IRRIGATION SYSTEM COST COMPARISON MODEL

By

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To the Faculty of Washington State University:

The members of the Committee appointed to examine the thesis of ANJELA BEGMATOVA find it satisfactory and recommend that it be accepted.

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Chair

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IRRIGATION SYSTEM COST COMPARISON MODEL

Abstract

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The model presented in this thesis is a cost estimator, which was developed to assist growers, irrigation managers, and others with related interests with making system conversion decisions. It allows comparing costs for two irrigation systems of interest and calculating the potential gains/losses as a result of converting from one system to another. Model's capability of calculating and comparing not only the total costs of each system but also annualized cost savings, such as costs per unit area and costs per water amount used for irrigation, permits focusing on profit maximization while minimizing the farming costs.

Total farming costs, distribution uniformity (DU), irrigation efficiency (IE), and pumping plant efficiency (PPE) not only affect efficiency and profitability of irrigation systems but vary with irrigation methods as well. The results revealed that annual energy costs, cost/acre-year and total costs tend to decrease, and the cost/acre-in increases, when DU and IE increase, regardless the engine type. Electric pumps have advantages over the fuel pumps for all tested systems: even without improving DU and IE values, it is enough to upgrade the fuel pump to the electric pump to reduce system costs greatly.

The results of sensitivity analysis showed that total costs (TC) had the same degree of sensitivity to all management factors (PPE, DU, and IE) regardless of the system and

engine type. However, there were variations among the systems and pumps: TC were more sensitive to the parameters for the wheel-line than the center pivot irrigation system regardless of the engine type and, similarly, the costs had higher sensitivity to the parameters for the fuel pump than the electric pump regardless of the system. For the economic impact, TC were most sensitive to the labor costs and they were least sensitive to the pumping costs in all cases. However, the costs were more sensitive to changes in parameters for fuel pumps rather than electric pumps. Pumping costs showed the greatest variation and proved to be a dominant component of TC, which is explained by significantly different values of DU and IE of the two systems.

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Dedication

This thesis is dedicated to my family

CHAPTER 1

INTRODUCTION

In much of the Western portions of the United States climate conditions are such that natural precipitation does not provide adequate moisture for optimum production of agricultural crops. Many farms in the Yakima Valley use inefficient surface irrigation, particularly furrow/rill irrigation. These surface irrigation methods are popular because of their low costs, the lack of incentives to conserve, and the existing topography was amenable to furrows. Fuhrer et al., 2000 reported that today irrigation in the Yakima River Basin is accomplished using one of three methods: rill (furrow), sprinkler, or drip. Nowadays, most farmers in that area employ multiple best management practices (BMP) to reduce water use and to minimize soil erosion from their fields. One of the commonly used BMP is converting from rill irrigation to sprinkler or upgrading an older sprinkler system to a more efficient one. This provides many benefits to the farmer, including water conservation, reduced erosion, and decreased runoff. However, these upgraded systems are expensive and are not an operationally viable option for all crops. Recently, according to the National Association of Conservation Districts, growers are encouraged to convert from furrow irrigation methods to drip or sprinkler irrigation systems to improve water use but also to deal effectively with drought conditions. Converting to more efficient irrigation systems has the potential to result in more flexible irrigation scheduling, less water application, higher yields and an improvement of the environment. Previous studies showed that shifting to more sophisticated management was motivated by the idea that crops could also do well with limited water amounts (Burt et al., 1997).

Careful study of a system will indicate whether improvements can be made and will help with selecting possible modifications that may be both practical and economical. Improved water management on the farm may help conserve water, labor, and soil and may also increase yields of crops. Since profitability of a new system is closely related to the irrigation efficiency (IE), application efficiency (AE) and water distribution uniformity (DU) on the fields, many researchers have developed evaluation procedures for different irrigation systems (Merriam and Keller, 1978; ASABE Standards, 2006).

Mateos (2006) performed a simulation study, where he compared evaluation procedures for three irrigation methods (trickle, sprinkler and furrow) based on six performance factors: DU, Christiansen's uniformity coefficient, application efficiency, deep percolation ratio, tail water ratio and requirement efficiency. Evaluations were conducted based on model outputs and equations particular to each of the different irrigation methods. The author concluded that procedures used for trickle and sprinkle irrigation systems provided good estimates, whereas procedure applied for furrow irrigation was biased, and overestimated DU, particularly.

In evaluating the cost effectiveness of converting to a more advanced irrigation method, a number of engineering, agronomic and economic factors play a role. O'Brien, et al. (2001) concluded that the most important of these elements are: the purchase and installation costs of a new system, the expenses of possible renovations on the existing pumping plant, changes in irrigated crops and corresponding crop area, as well as labor savings. Long–term expectations of crop prices, differences in irrigated production costs and energy costs (including operation and maintenance) for the two systems should also be accounted.

A great contribution to the evaluation of the DU and IE in the Yakima Valley was done by California Polytechnic State University (Cal Poly) in collaboration with the Bureau of Reclamation in the summer 2001. Five typical irrigation systems were sampled (twenty fields in total) and later analyzed to estimate DU and IE using the AgWater software (developed by Cal Poly). The AgWater program is an interactive learning, teaching and pre-seasonal evaluation tool, which combines concepts of irrigation scheduling and DU. To examine problems and components that affect the DU for various irrigation methods, the ITRC Irrigation System Evaluation Software was applied. Developed by Cal Poly, the software estimates the global DU and the causes and relative importance of various factors influencing the non-uniformity. The program has an embedded library of printable optional “Recommendation Paragraphs”; the recommendations are selected by the program based upon data or observations entered by user.

However, farmers have to ensure that converting to the more water–efficient irrigation system will be profitable on their lands in terms of their location. It is possible that there is no motivation to shift, and that the current system is the most appropriate for the existing soil and water conditions. It would be helpful if farmers could easily compare (1) profitability of an existing system and the cost and management benefits of a more sophisticated and efficient one they are planning to convert to, and (2) the resources conservation and costs reduction for the existing system.

This thesis concludes research conducted in the Yakima Valley in the summer of 2007. The research purpose was to develop the needed tool described above and, in the future, have it placed on the Internet for use by growers to assist with making system conversion decisions. Technically, the tool is a model that calculates the above–mentioned expenses for a desired irrigation system. To help farmers make a final selection of the most suitable system, the model includes a full economic analysis for comparing existing irrigation systems with new ones, within the constraints and goals selected. This economic analysis is compared on an annualized cost basis with calculation of the potential gains as a result of converting to another irrigation system. The fairy simple interface of the tool makes it easy to use and requires farmers to enter only general parameters to obtain immediate results without help from specialists. Calculations behind the tool are based on analysis of data collected during evaluations of studied irrigation systems in the Yakima River Basin. To have a more precise and reasonable model built, data obtained from the field studies in 2007 were used, as well as data from the 2001 summer studies were adapted. Both studies focused on the evaluation of distribution uniformity and efficiency. Evaluation procedures followed both methods explicitly described by Merriam and Keller (1978) and techniques used by the Cal Poly State University, and use of the ITRC Irrigation System Evaluation Software.

CHAPTER 2

METHODS AND MATERIALS

The work was done in the summer 2007 on five (5) fields in the Yakima Valley, WA. Examined irrigation systems and crops cultivated were as follows: two (2) furrow irrigation with Concord grapes on each, one (1) solid set over pasture, one (1) hand-line over pasture, one (1) undertree sprinklers in cherry orchard.

The following steps were performed to complete the work:

1. Field selection and evaluation procedures for irrigation systems.
2. Economic analysis and model development.
3. Sensitivity analysis.

2.1.Field Selection and Evaluation Procedures for Irrigation Systems

This section provides technical description of the evaluation procedures and results for irrigation systems studied in the summer of 2007. The irrigation systems evaluated included: surface, sprinkler (hand-line and solid set) and undertree (orchard) sprinkler.

Growers in the Yakima Valley were selected in the order that they voluntarily signed up for the study. The evaluations were a part of a program initiated by the South Yakima Conservation District (SYCD) to encourage growers to improve their water use. Five examined fields were located mainly on the Yakama Indian Reservations in the Toppenish area.

There is not a single parameter which is sufficient for defining irrigation performance. Conceptually, the adequacy of irrigation depends on how much water is stored within the crop root zone, losses percolating below the root zone, losses occurring as surface runoff or tailwater the uniformity of the applied water, and the remaining deficit or under-irrigation within the soil profile following irrigation. Ultimately, the measure of performance is whether or not the system promoted production and profitability on the farm. Although many other factors were looked at during the system evaluations the most important were irrigation efficiency (IE) and distribution uniformity (DU). Evaluation procedures vary from system to system, but the definitions and terms remain the same. These definitions are explicitly described in the Terminology section of Appendix A.

Collected data was the analyzed and used in the model as defaults to familiarize users with typical parameters for each irrigation system. To cover a wide range of systems and corresponding values, additional DU's and IE's values were used. Those were results of the research done by Cal Poly in the summer of 2001, when twenty fields were examined in Roza and Sunnyside Irrigation Districts located in the Yakima Valley of Washington Sate (brief information is shown in TablesA-1 and A-2 of Appendix A). Detailed step-by-step procedures can be found in the guidelines by Merriam and Keller (1978), which were used as a primary source for the fieldwork.

The principal objective of evaluating **surface irrigation systems** is to identify management practices and system configurations that can be feasibly and effectively implemented to improve the irrigation efficiency. An evaluation may show that higher efficiencies are possible by reducing the duration of the inflow to an interval required to apply the depth that would refill the root zone soil moisture deficit. The evaluation may also show opportunities for improving performance through changes in the field size and topography. Evaluations are useful in a number of analyses and operations, particularly those that are essential to improve management and control. Evaluation data can be collected periodically from the system to refine management practices and identify the changes in the field that occur over the irrigation season or from year to year. The surface irrigation system is a complex and dynamic hydrologic system and, thus, the evaluation processes are important to optimize the use of water resources in this system.

Observations were recorded in the special printed forms for an easier data entry when analyzing. The first thing to do was to select four test furrows (named A, B, C and D) were selected – they may be either in one part of the field, alternate furrows for a better patrolling the streams without walking on wet soil, or in different parts of the field for a better characterizing of soil types, water delivery and other conditions. Stakes were set along each of the furrows, at 100-foot stations, starting from the furrow inlet, and soil moisture deficit (SMD[1]) was determined prior to the water was turned on. Each tested furrow was identified and the size of stream flowing past station zero in each furrow was recorded. Plotting advance and recession curves is a good tool to reflect the movement of water along the furrows. Recession occurs right after the water stream is turned off and starts exactly where the advance ends. From Figure 2.1 it is obvious that streams in Furrows B and C were large enough to reach the lower end but could cause erosion, while the stream in the Furrow A was so small that it could not make it to the lower end resulting in high percolation rates, especially within the first 100 feet. Although the highest flow rate was in the Furrow D, the water in it did not advance to the very end due to large wet perimeter of the furrow and lack of time; it could have advanced further if the evaluation was run for a longer time (duration of that particular evaluation was 3 hours, or 181 minutes). The cease was recorded for Furrows B and C only as only they had water

[1] See explicit definition in the Terminology section of Appendix A

reached the lower end. Therefore, furrow use, soil structure, and moisture content importantly affect stream size, intake rate, and advance rate. When a field with a uniform slope, soil and crop density receives steady flow at its upper end, a water front will advance at a monotonically decreasing rate until it reaches the end of the field. If it is not diked, runoff will occur for a time before recession starts following shutoff of inflow.

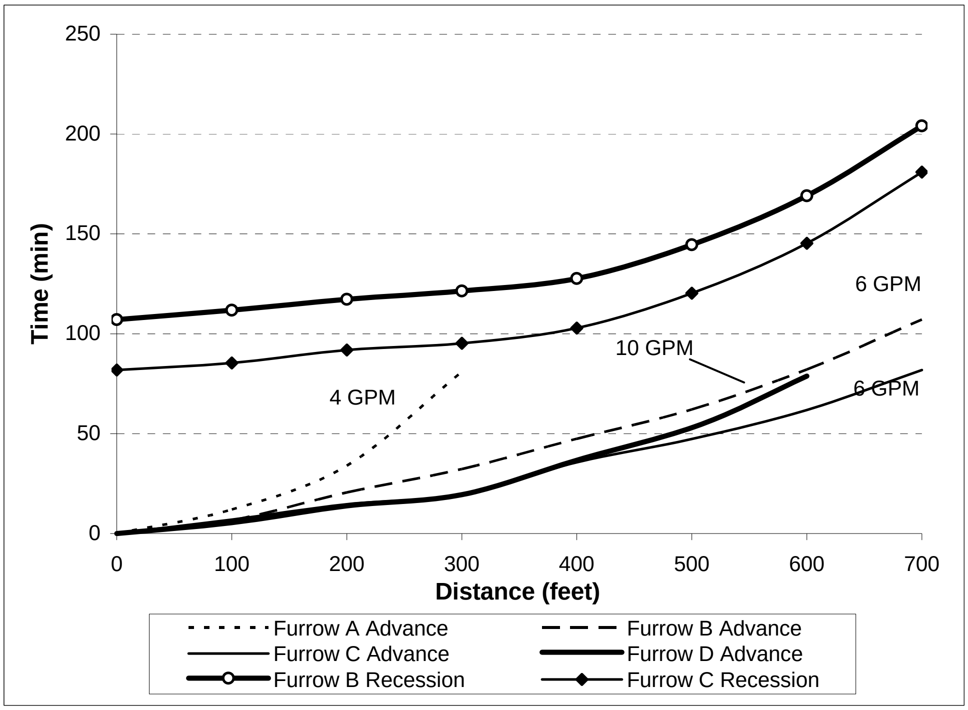

Figure 2.1. Advance and recession curves for the surface irrigation systems (four furrows tested), obtained practically during the fieldwork

Another task was to measure the infiltration rate (Figure 2.2), for which flow measuring devices (weirs were used in this research) were set at the zero station and first station (first 100 feet) on two out of four test furrows. Infiltration rates plotted on Figure 2.2. show a general profile of a tested furrow. The intake rate is very high in the beginning (within first 20–25 minutes) and rapidly declines after the soil is fully saturated. The intake rate finally remains at same level, graphically reflecting a straight line. DU for this surface irrigation system was calculated to be 0.83, which agreed with the value calculated by the Evaluation software.

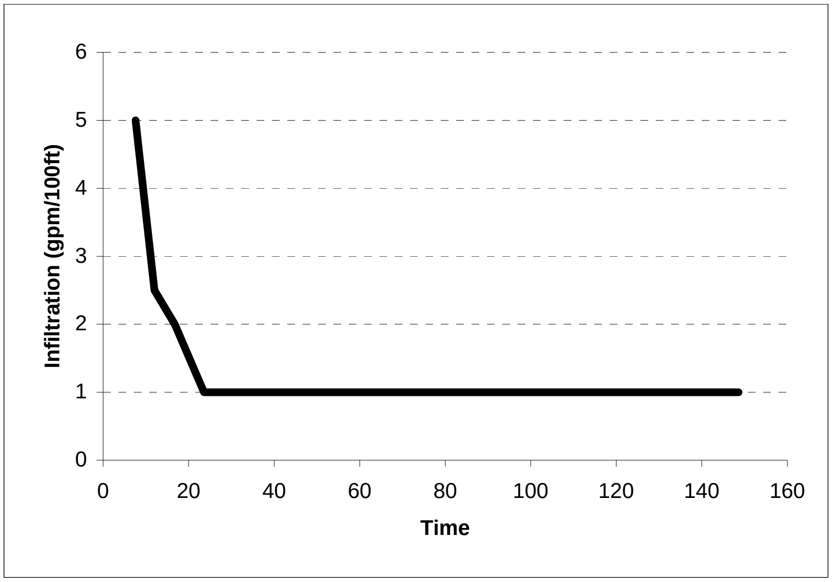

Figure 2.2. Intake rates along the profile of a furrow

Based on this system evaluation some recommendations given by the Evaluation software to the farmer include: 1) a stronger irrigation strategy to use the applied irrigation water effectively needed to be developed for a better regulation of water supply (scheduling); 2) the timing of an irrigation should be determined by the water volume available in the crop root zone and the rate that the water is being removed from root zone by the crop (evapotranspiration); 3) the irrigation water should be shut off when the depth of water infiltration equals to the depth of water removed from the root zone by the crop.

There are similarities between the procedures and evaluation of all types of **sprinkle irrigation systems**. Both hand-line and solid set systems are classified under sprinkler irrigation systems, and therefore their evaluations followed similar procedures. The estimation of DU requires a catch can test to see how evenly the water is distributed on the field; the evaluations were completed by utilizing the data collected, for which volumes of water caught in the containers had to be converted to rates and recorded in units of inches per hours (iph). Figures 2.3 and 2.4 reflect water distribution within the grid with cans for hand-line and solid set, respectively. Topological plots are very useful for visual observation as they are not only in two dimensions (length and width of the grids) but also has a third dimension (perpendicular to the plot). A color intensity helps to distinguish amount of catch collected (in): each color represents a particular applied water depth, varying from the highest catch in the very center (brighter circles at the bottom on plots) to the lowest further away from the center (darkest shades in the corners). The pattern in Figure 2.3 is due to the overlapping of neighboring sprinklers in the hand-line lateral's middle (lateral is represented by a vertical straight line with catch cans placed on both sides from it). It is also due to different sprinkler nozzle sizes. Higher depths at the bottom of the line (first sprinkler) are caused by a larger nozzle size, while much lower depths above (last two sprinklers) were caused by the smaller nozzles. The darkest spots are the areas short with water (did not receive any or the smallest depths of water). Wind distortion observed during the evaluation negatively affected the water application pattern of sprinklers along the laterals, which is noticeable on below. While wind speed and direction are not controlled variables, their effect on irrigation uniformity is significant, and sprinkler system design must be done with anticipated wind conditions in mind. Different sizes of sprinklers nozzles produce coverage (see Figure 2.4) similar to the pattern for the hand-line system. Other reasons, variation of operating pressures from sprinkler to sprinkler, sand wear on nozzles, non-rotating sprinklers, plugged nozzles and small leakages detected during the test, also play a significant role in DU and application efficiency. The calculated DU's were 0.56 and 0.46 for the hand-line and solid-set irrigation systems, respectively.

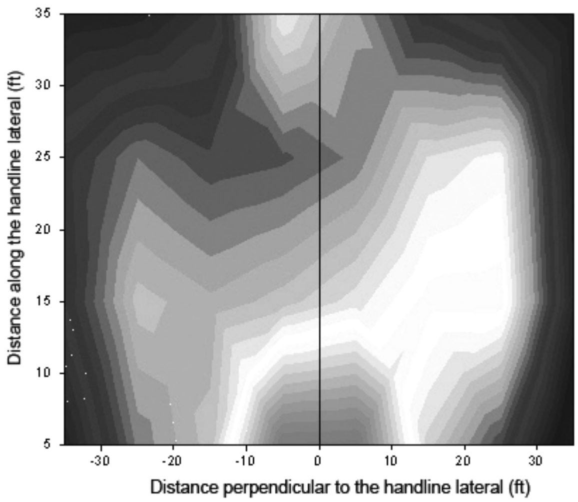

Figure 2.3. DU of irrigation water along the hand-line irrigation system
Vertical straight line is the hand-line lateral

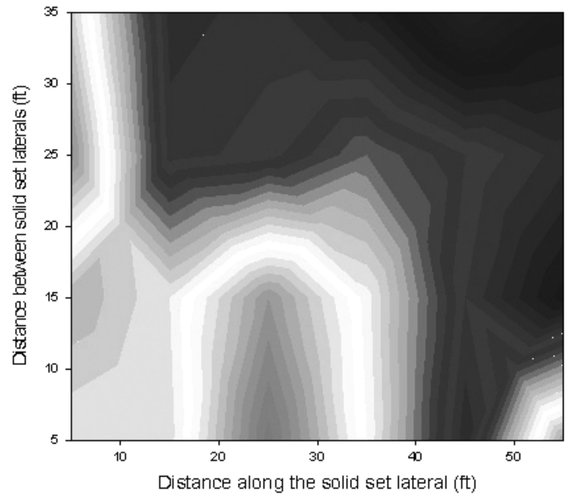

Figure 2.4. DU of irrigation water for the solid set irrigation system
The plot represents a grid of catch cans

Recommendations for both hand-line and solid-set systems given by the Evaluation software include: 1) use same-size nozzles; otherwise it causes non-uniform discharge of water as well as changes in the throw patterns of sprinklers and, therefore, a non-uniform overlap, 2) use sand separators to remove sand, 3) filters could be a solution to avoid plugging of some sprinklers, 4) properly choose time of day of the irrigation and plan the irrigation so that the same parts of the field are not irrigated at the same time of day each time they are irrigated.

Evaluation of an **undertree (orchard sprinkler) irrigation system** was performed to obtain information about application losses (i.e., runoff, deep percolation, wind drift), how much water was being applied, and where that water was going. In order to make decisions, infiltration was observed by the means of a catch can test. Catch cans needed to be placed in a radial row were set along a radius of the sprinkler's wetted circle, so that the water was caught from only one sprinkler. Assuming that water collected in cans was equal to the water applied to the ground, Figure 2.5 can be used to check the distribution of water application along a radial distance from the sprinkler. Because the radial rows with cans were set in three different spots, an average of each can was calculated and plotted (see Figure 2.5). The highest catches were within the first seven feet with a further decrease towards the last can.

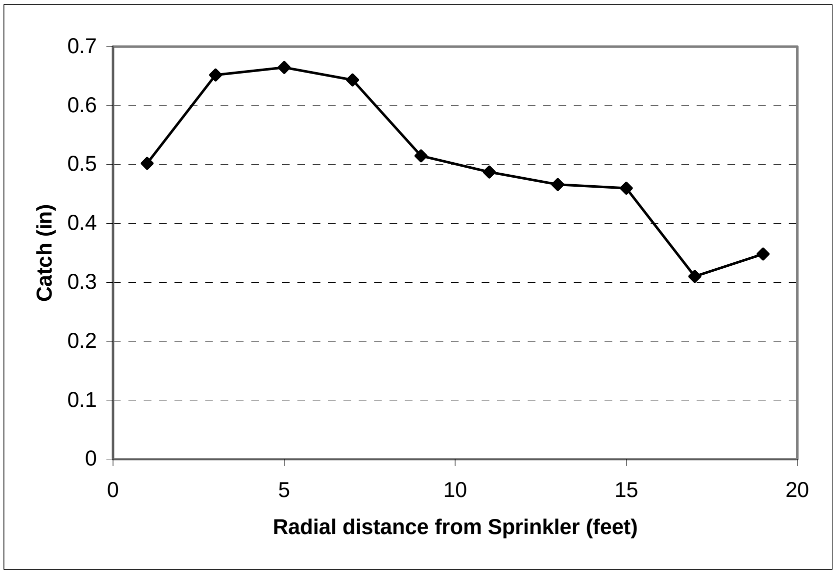

Figure 2.5. Catch can test (average depth of three sets) for the undertree irrigation system
Zero on an axis represents a position of sprinklers (first can was set one foot away from it, other cans were placed two feet apart)

The average application rates (iph) are shown on Figure 2.6. Again, the rates vary from the highest in the beginning of rows with cans (first seven feet) to the lowest at the end of rows (furthermost couple of feet). The average application rate for the shown sprinkler was 0.12 iph and is represented by a bold straight line. The DU on the tested area is 0.62.

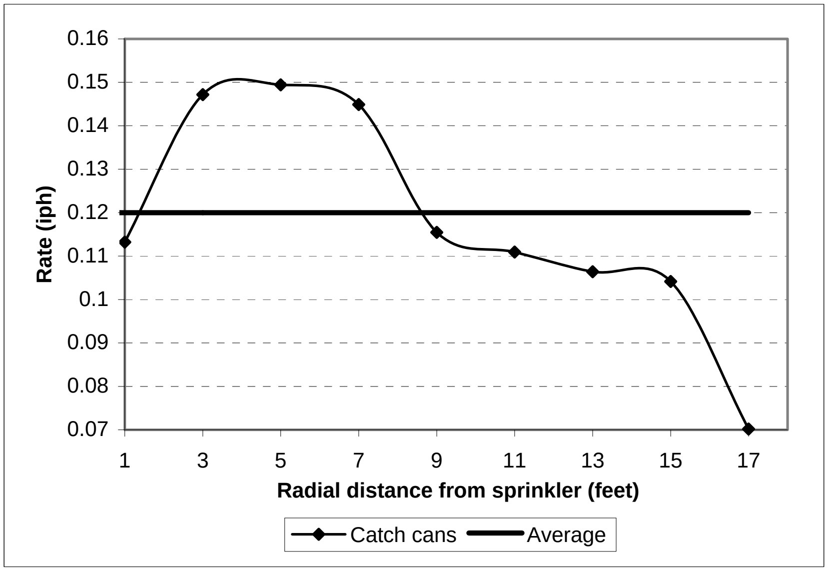

Figure 2.6. Profile of water application rates along the sprinkler radius

To reflect the real operation of the system, sprinklers were tested simultaneously with different adjustments and pressures. The crop type, field characteristics, root depth and MAD[2] were checked and recorded in special forms. SMD[2] in the area of the pattern[3] that would receive full irrigation as well as soil texture, available soil moisture capacity in the root zone were also estimated. During the experiment, the height of jet trajectory, tree and wind interference, and characteristics of sprinkler rotation were observed. Sprinkler pressure (using a pitot tube and pressure gauge connected to the sprinkler riser), wetted diameter, and total discharge including any leakage from the test sprinkler and from two or three other sprinklers spaced throughout the system were measured.

DU Estimation

To define if the *distribution uniformity*[4] (DU) is adequate, the average amount of water per can was calculated. To determine the DU for the irrigation system, the catch can

[2] See explicit definition in the Terminology section of Appendix A
[3] This area should represent half or more of the sprinkler pattern and should not be affected by overlap or tree drip (Merriam and Keller, 1978)
[4] See explicit definition in the Terminology section of Appendix A

data were sorted in descending order in Excel, which allowed to obtain the lower quarter of readings (DU_{LQ}) and then find the average of these readings. All DU values were averaged as well. Then the equation was used to calculate the DU by dividing the average lowest quarter depth (in) by the average total depth (in), kept in decimals or converted to percentage:

$$DU = \frac{DU_{LQ}}{DU_{total}} \tag{2.1}$$

where: *DU* is a distribution of uniformity (decimals);

DU_{LQ} is an average lower quarter depth (in);

DU_{total} is an average total depth (in).

2.2. Economic Analysis and Model Development

Originally, the model was built in the MS Excel spreadsheet for simplicity of development and use. It has a fairly simple interface, allowing users to enter various inputs (initial values, etc.) and get prompt results. The spreadsheet consists of three parts: Inputs, Calculations, and Outputs. **Inputs** are the variables in a form of characteristics of irrigation systems and equipment, as well as economic components, entered by users. For every question[5], users are given options to either choose from defaults or customize options by entering their own values. The inputs are used in the **Calculations**, which compute farm irrigation system costs and result in the displayed **Outputs**. Because of the model's economic purpose, the Outputs are given in terms of costs ($) that growers could spend or save if preferred another irrigation system. Additionally, motor (engine)

[5] Questions (inputs) prepared for the users is attached are listed in Table B-1 in Appendix B

horsepower and water horsepower required for a certain system are calculated and offered to the users to compare with ones they already use.

As the model's main function is to estimate costs and provide comparative results of two systems, it has to be able to compare an existing system to a possible one a farmer may shift to, or to the same but upgraded system. The existing system is introduced as the "base", while being compared to the same upgraded system ("system 1") and a completely new system ("system 2"). Pumping/electricity costs, labor costs, and maintenance & repair costs are the most essential factors as they vary with a system. Together they create the total costs and provide a motivation for decision making. These costs are described in details further below.

2.2.1. Farm Irrigation System Costs

In the design and management of irrigation systems, efficient water use and good crop production are major goals. Determining the expected annual costs of owning and operating feasible alternative designs is an important part of irrigation system design. These data are used by the landowners to asses the feasibility of irrigating the field, for selecting the most suitable irrigation system, and in determining the optimal crop mix for the field.

Total costs are made up of variable costs, which vary according to quantity produced such as raw materials, and fixed costs, which are independent of quantity produced such as expenses for assets.

$$\text{Total costs} = \text{Total fixed costs} + \text{Total variable costs} \qquad (2.2)$$

(i) Total Fixed Costs (Total Ownership Costs) associate with owning a fixed input. These are the costs that are incurred even if the input is not used. Depreciation of equipment and land, insurance, taxes, and interest are fixed costs. Repairs and maintenance may also be included. Fixed costs do not change as the level of production changes in the short run but can change in the long run as the quantity of the fixed input changes. By definition, there need to be any fixed costs exist only in the short run and are equal to zero in the long run. Therefore, fixed costs reflect a long-term commitment that can be recovered only by wearing them out in the production of goods and services for sale.

Total fixed costs are the summation of the several types of the fixed costs and are calculated as follows:

$$\textit{Total fixed costs} = \textit{ADIC} + \textit{Tax\&Insurance}(\$) + \textit{Water Right} \qquad (2.3)$$

where: *ADIC* is annualized costs depreciated over an analysis period with the consideration of interest rate ($);

Taxes&Insurance is taxes and insurance costs the farmers pay ($);

Water Right is an operation and maintenance assessment that farmers pay for their water rights($).

- **Annual Depreciation and Interest Costs (ADIC)** in the calculations include both depreciation and interest costs. James, L. G. (1988) provides an example of ADIC calculations, formulas from where are used in this model (equations (2.4) to (2.8) in this Chapter).

  Eq. (2.4) is used to compute ADIC using a capital recovery factor for the life of various system components and the nominal interest rate:

$$ADIC = CRF\sum_{j=1}^{NC} PW_j = CRF\left(PW_1 + PW_2 + ... + PW_j\right) \qquad (2.4)$$

where: *ADIC* is annual depreciation and interest costs;

CRF is a capital recovery factor, calculated in Eq. (2.5);

NC is a number of system components;

$PW_{,j}$ is present worth value of individual components ($), calculated further in Eqs. (2.6), (2.7) and (2.8).

Capital recovery factor (CRF) converts a present value into a stream of equal annual payments over a specified time, at a specified discount rate (interest), and is calculated for every component with respect to its own useful life. In other words, CRF is the amount of equal (or uniform) payments to be received for *n* years such that the total present value of al these equal payments is equivalent to a payment of one dollar at present if *i* interest rate is *i*:

$$CRF = \frac{i(1+i)^{AP}}{(1+i)^{AP} - 1} \qquad (2.5)$$

where: *CRF* is a capital recovery factor;

i is an annual interest rate (decimal), entered by users;

AP is an analysis period (years), entered by users.

Present worth (PW), an estimated current value of a future amount to be received or paid out by the end of the analysis period and discounted at an appropriate interest rate, must be invested at the beginning of the analysis period. There are three scenarios of present worth calculation, based on the correlation between the asset's useful life and analysis period. The first scenario takes place when the analysis period equals the component's useful life. Then PW is computed using Eq. (2.6):

$$AP = UL: \qquad PW = IC - SV\left(\frac{1+r}{1+i}\right)^{AP} \tag{2.6}$$

where: *PW* is the present worth of a component ($);

IC is the initial cost of a component ($);

SV is the salvage value of a component ($);

r is the expected annual rate of cost escalation (decimal), entered by users;

AP is the analysis period (years);

UL is a component's useful life (years).

Second term in Eq. (2.6) gives the present worth of the salvage value considering the effect of cost escalation.

Usually farmers have information on prices prior to the purchase, and as the prices and useful lives vary from year to year and component to component, it is more reliable if the users enter these values themselves. Hence, terms such as the salvage value (*SV*), expected annual rate of cost escalation (*r*), analysis period (*AP*) and the component's useful life (*UL*) are input values. Escalation rate is a percentage an annual change in the price levels of the goods and services occurs or is expecting to occur in the future.

The second scenario happens when the component's useful life exceeds the analysis period, then the component will not be fully depreciated at the end of the analysis period and will still be operating for some time beyond the analysis period. In this case, calculation of present worth is similar to the Eq. (2.6), except that it requires using the final salvage value of the component at the end of analysis period, which accounts for the undepreciated and salvage values. The Eq. (2.7) uses the straight-line depreciation method over the useful life to estimate the undepreciated value at the end of the analysis period:

$$AP < UL: \qquad SV = SV_f = IC - (IC - SV)\frac{AP}{UL} \tag{2.7}$$

$$PW = IC - SV_f\left(\frac{1+r}{1+i}\right)^{AP}$$

where: UL is a component's useful life (years), entered by users;

SV_f is a final salvage value of component ($).

When the analysis period exceeds useful life, the component needs to be replaced one or more times during the analysis period. Eq. (2.8) is used in such situations:

$$AP > UL: \qquad PW = IC + \left(IC - SV\right)\left[\sum_{j=1}^{N}\left(\frac{1+r}{1+i}\right)^{(j)(UL)}\right] - Z\left(\frac{1+r}{1+i}\right)^{AP} \tag{2.8}$$

where: N is an integer portion of $\dfrac{AP-1}{UL}$

$$Z = IC - (IC - SV)\left(\frac{AP - (N)(UL)}{UL}\right)$$

The second term and third terms in Eq. (2.8) represent the present worth of the replaced component cost and the final salvage value, respectively.

Because farming is a capital intensive industry, a farmer is allowed cost recovery or depreciation on machinery, equipment, and buildings. *Depreciation* is defined as the annual loss in value due to use, wear, tear, age, and technical obsolescence. Investments that have an indefinite *useful life* such as water rights and land are not depreciated. The depreciation of a system component that has a finite life is the difference between the item's initial cost and its salvage value.

A *salvage value* is the estimated value of an asset at the end of its useful life and generally is some positive value. However, it may be zero if the asset is used until it is completely worn out and has no scrap or junk value at that time. There is a relationship between useful life and salvage value: the shorter the useful life, the higher the salvage value, and vice versa. The values of useful life vary for each asset, equipment or system component. Some useful live values for particular systems are given in Table A-4; and in a larger range are given in Table A-5 in Appendix A. Depreciable items in addition to those in Table A-4 in the Appendix A include fuel storage facilities, buildings for housing or storing pumps and other equipment, farm road and drainage facility construction, etc.

Interest, a fee paid on borrowed capital, is a product of an average asset value and the interest rate, where the average asset value is an average value of a purchase price and a salvage value. This common computation gives the interest charged for the average value of the item over its life and reflects that it is decreasing in value over time. Interest rate forms the percentage paid over a certain period of time which is charged or paid for the use of money. Interest cost is determined by the interest rate and the total initial costs of the irrigation system; the initial cost of all depreciable components and items such as water rights and land (all not depreciated) are included in the system cost.

Mentioned common methods for calculations of depreciation and interest rate are acceptable when someone needs to compute them separately, not linked to each other. However, in this study, a single ADIC equation (Eq. 2.4) used considers both depreciation and interest rate, which makes calculations easier and faster as well as helps avoid repetition.

- **Annual taxes and insurance** can be estimated as a percent (normally ranging from 1.5 to 2.5%) of the average value of the asset or the dollar amount paid.

$$Annual\ taxes\ \&\ insurance = (1.5\ to\ 2.5\%) \times \sum_{j=1}^{NC} IC_j \tag{2.9}$$

where: *IC* is a initial cost of component ($);

NC is a number of system components.

As these percents are approximate estimates and normally vary with taxing entities and insurance companies, it would be more precise if the users had a chance to enter their actual values; otherwise, a default of average 2% is used to compute the annual costs of taxes and insurance.

- **Annual water costs**

Generally, irrigators/growers are charged for the water they use, especially this is true in the locations served by irrigation districts. There are three major approaches to water pricing: area-based, volumetric, and market-equilibrium. Volumetric water pricing is an approach that charges based on the volume of water used by the farmer; unlike area-based pricing, it encourages farmers to better control their water use. As water costs may vary from district to district as well as in time, it is entered as an input by the users.

(ii) Total Variable Costs (Total Operating Costs) are those costs over which the manager has control, or in other words, the costs that can be varied flexibly as conditions change. Total variable costs can be found by summing individual variable costs, each of which is equal to the quantity of the inputs purchased times its price per unit. These costs include the costs of energy, maintenance and repair, and labor. The cost of professional services for irrigation scheduling and fertilizer recommendations should also be included.

- **Annual energy costs** include the costs of all energy used to operate the irrigation system: energy used for pumping, moving equipment within and between fields, injecting fertilizers and other chemicals into the system, etc. When energy costs over an extended analysis period are annualized, they should be adjusted to account for inflation and rising energy prices; to do this an equivalent annual cost factor (EACF) is used in the model when comparing the relative economics of two systems.

  High pumping costs usually result from poor maintenance, excessive wear, or mismatched components. As pumps are common in irrigation systems, pumping costs are often the largest component of energy costs, and are therefore the subject of great interest and attention.

  Pumps and Pumping Costs

  Many times, growers think in terms of unit costs. They know about how many dollars per acre to cultivate, how many dollars per acre to harvest, how many tons per acre of production to expect, etc. It is also important to know unit-costs for water pressure, which is simply the costs to pump one acre-foot of water through a sprinkler system, or back up a tailwater return system. A handy unit-cost is the money required to increase water pressure 10 pound-per-square-inch (psi), or how much it costs to pump one acre-foot at a given pressure.

The major factors that influence the pumping cost per volume are: fuel price, pumping plant efficiency and total dynamic head (TDH). TDH is the total hydraulic resistance against which the pump must operate. A grower needs other information as well such as acres irrigated, discharge rate, total application depth, and fuel price/unit.

Irrigation systems do not apply water with 100% uniformity or at 100% efficiency. Losses which occur include deep percolation of water below the expected maximum rooting depth of the crop, surface runoff, evaporation, and wind drift (that is why the system evaluation is needed to estimate these losses). To determine how much water out of total water applied was beneficially used on the field (gets stored in the plant root zone and is available for the plant to use), irrigation efficiency of irrigation water must be considered. This irrigation efficiency is multiplied by the total irrigation water applied to the field over the entire irrigation season, reflected by the Eq. (2.10).

$$Net\ water = Area \times Water\ requirement \tag{2.10}$$

where: *Net water* is amount of irrigation water that actually reached the ground (acre-inches);

Area is acres irrigated (acres), entered by users;

Water requirement is season irrigation requirement (inches), entered by users.

From this we can calculate the total amount of irrigation water applied to the field:

$$Total\ water = \frac{Net\ \ water}{DU \times IE / 100} \tag{2.11}$$

where: *Total water* is total gross amount of irrigation water applied to the field (acre-inches);

Net water is calculated in Eq. (2.10) (acre-inches);

IE is an irrigation efficiency of water applied (%), chosen and entered by users from the provided range of IE's for corresponding irrigation systems;

DU is distribution uniformity of water applied (decimals), chosen and entered by users from the provided range of DU's) for corresponding irrigation systems;

100 is a constant that converts percents (%) to decimals.

Eq. (2.11) includes some important considerations for various irrigation systems, which are reflected in the model as well. As described by Burt et al. (1997), to express DU in terms of infiltrated depth, some water, which does not contribute to infiltrated depth (intercepted by the crop, evaporation to reduce transpiration and fractions of distributed water) is ignored for the surface irrigation systems. However, incorporation of these fractions could improve the estimate of DU for the sprinkler, undertree or drip irrigation systems, where accumulated water during the catch can test includes the infiltration, canopy interception, and reduction of transpiration during the irrigation. Therefore, the DU term in the denominator in Eq. (2.11) is not used for the surface systems (as IE already account for losses of water), but is included for the rest of the systems.

Dividing the total water amount by the flow rate maintained in the system, seasonal hours of pumping are found:

$$Hours = \frac{Total\ \ water}{Flow / 452.567} \tag{2.12}$$

where: *Hours* is the seasonal hours of operation (hours);

Total water is calculated in Eq. (2.11) (acre-inches);

Flow is the flow rate for a system, entered by users;

452.567 is a conversion constant (1 acre-in/hr = 452.567 gallons per minute).

Pumping plant efficiency is an essential factor that affects energy bill (and, hence, total costs) if the evaluated system uses a pump; wear and changes in pumping conditions over time can cause substantial loss and result in excessive energy use and, hence, higher costs. Pumps do not operate at the same efficiency at every combination of flow/pressure, i.e., pumping plant efficiency changes with pressure and flow output of the pump as well as varies from pump to pump, and cannot be calculated very precisely. To avoid problems with computations, users are asked to give the best estimates of the pump characteristics and enter them as inputs. The equation to use is:

$$PPE = \frac{ME \times Power\ \ transmission \times PE}{1000000} \tag{2.13}$$

where: *PPE* is the pumping plant efficiency (decimals);

ME is the motor/engine efficiency (%), entered by users;

Power transmission is the bulk transfer of electrical power (%), entered by users;

PE is the water pump efficiency (%), entered by users;

1000000 is the constant that converts percents (%) to decimals.

Although, the users enter the motor horsepower and water horsepower as inputs themselves, they can also check with the precisely calculated horsepower values (included in the model and shown in the Outputs section) and to make sure if those they have match the actual characteristics.

Water horsepower (measured in horsepower or HP) is the amount of power required to move a given volume of water to a specified total head (the amount of work done on the water) and is calculated by:

$$WHP = \frac{TDH \times Flow}{3960} \quad (2.14)$$

or:

$$WHP = \frac{(Pressure \times 2.31 + Losses) \times Flow}{1717} \quad (2.15)$$

where: *WHP* is water horsepower required (HP);

TDH is the total dynamic head (feet), entered by users;

Flow is the discharge rate (gallons per minute), entered by users;

Pressure is the operating pressure of the system (psi), entered by users;

Losses is the water lift & friction losses in the system (feet), entered by users;

3960 and 1717 are constants to correlate HP and GPM;

2.31 is a constant to convert feet to psi.

Eqs. (2.14) and (2.15) are for calculating the water horsepower and are interchangeable. If the TDH value is not known, it can usually be estimated by adding total pumping lift and pressure at the pump. Since pressure is usually measured in (psi), it needs to be converted to (feet) by multiplying (psi) by 2.31.

Motor/engine horsepower can be found using water horsepower as:

$$HP = \frac{WHP}{PPE} \tag{2.16}$$

where: *HP* is the required horsepower of motor/engine (HP);

WHP is water horsepower, calculated in Eqs. (2.14) and (2.15);

PPE is pumping plant efficiency, calculated in Eq. (2.13).

Horsepower can be converted into kilowatts. One kilowatt is equivalent to 1.34 horsepower. Besides horsepower or kilowatts, the time the pump is in operation also influences energy costs. So, electricity used is measured in kilowatt-hours and the consumer pays a unit energy cost per kilowatt-hour. Fossil fuel energy used by gas or diesel engine driven pumps is measured in gallons of fuel used per hour and the hours of operation. To reduce electrical energy use, the kilowatt-hours must decrease because of fewer kilowatts or less operating time, or both.

Economic analysis also includes an option of *power unit selection* and allows the users to calculate pumping costs based on the motor chosen. The model considers two types of power unit: electric motors and internal-combustion engines (hereafter called fuel pumps). Burt et al. (2000) mentioned that *electric motors* offer the advantage of long life, ease of maintenance, and dependability. Other advantages of electric motors include their delivery of full power throughout their life and endurance to damages by fluctuations in pump loading. A major consideration in choosing electric power is the accessibility to and cost of electricity at the pump site. *Internal-combustion engines* used in irrigation are generally higher in initial cost and more difficult to maintain than electric motors, and their fuel costs are usually higher (i.e., costs per unit of water horsepower developed). However, where portability is desired or where source of electricity is expensive, internal-combustion engines are the only option. Types of fuel used in this case are: diesel (compression-ignition) and natural gas/ liquefied petroleum gas /gasoline (spark-ignition).

Since calculations of costs differ for different power units, the users are asked to enter inputs for the types of engine/motor they use. For electric engines, kilowatt demand is calculated prior to the computation of a total seasonal bill:

$$kW\ \ demand = HP \times 0.746 \tag{2.17}$$

where: *kW demand* is a kilowatt demand for the system (kW);

HP is calculated in Eq. (2.16);

0.746 is a constant.

Kilowatt demand is needed to measure an average load over a given period (analysis period) and is expressed in kilowatts. This measurement is used by utilities and wholesalers to determine a customer's average requirement.

Total power used is energy used over a certain period of time, and, hence, is a product of kilowatt demand and total seasonal hours:

$$Total\ \ power\,(E) = kW\ \ demand \times Hours \tag{2.18}$$

where: *Total power(E)* is total power used during the entire irrigation season for electric pumps (kW-hour);

kW demand is calculated in Eq. (2.17);

Hours is seasonal hours of operation, calculated in Eq. (2.12).

How big and what type of pump are critical questions because one pump might pump enough water, but not at the right pressure. And another pump might build up enough pressure, but not produce adequate flow. Additionally, if using electricity as the power source, it is important to know if there is enough power to pump water to the desired height.

Depending on how they use electricity, electric utility customers are charged for different electric services; these charges determine the energy bill. Most customers pay for the energy they use – *energy charge* (measured in kilowatt-hours); larger users of electricity are also charged for demand (measured in kilowatts). *Demand charge* covers the costs associated with maintaining sufficient electrical facilities at all times to meet each customer's highest demand for energy, and is based on the greatest amount of electricity used by the user. The demand charge is expressed as a dollar per kilowatt (*kW*) rate and is applied to the customer's maximum kW demand, or the highest rate at which the customer required energy during the month. It costs more to serve the higher-demand customer, since the company must have facilities in place to serve the highest demand at any given moment. The demand charge reflects this higher cost and provides an incentive for customers to manage their loads to lower their demand. The demand charge portion of the customer’s power bill does not change, regardless of the operating time. However, the energy charge portion of the power bill depends on the amount of time the pump runs. A customer who is careful and does not run the pump more hours than necessary will save money on the energy bill.

The cost of electricity depends on the location, utility company, how much, and possibly when is used. Many companies charge a lower rate for power use above the cutoff usage (or a threshold) in kW-hr; the cutoff happens when overall demand reaches the threshold level. The model accounts for all of these conditions by comparing the kW demand to the kW cutoff and calculates the appropriate rates with respect of total power used (kW-hr) to the cutoff (kW-hr).

Having demand and energy charges known, total seasonal bill for electric engines is determined by summing the two charges, such as:

$$Total\ energy\ bill = Demand\ charge + Energy\ charge \qquad (2.21)$$

where: *Total energy bill* is total seasonal energy bill reported to the users ($/year);

Demand charge is demand charges, determined by utility companies, by comparing the kW demand to the kW cutoff;

Energy charge is energy charges, determined by utility companies, by comparing total power used (kW-hr) to the cutoff (kW-hr).

Calculation procedures for fuel pumps are done in different order and with different equations. Total power used is just a product of operating hours per season and a motor horsepower, and has units of HP-hour compared to the kW-hour for electric engines:

$$Total\ \ power\,(F) = HP \times Hours \qquad (2.22)$$

where: *Total power (F)* is total power used during the entire irrigation season for fuel pumps (HP-hour);

HP required horsepower of motor/engine (HP), calculated in Eq. (2.16);

Hours is seasonal hours of operation, calculated in Eq. (2.12).

Fuel cost is calculated by multiplying total power used by the energy value. The latter is an input entered by users in BTU/gallon of fuel, which is a measure of heat content of a fuel and indicates the amount of energy contained in the fuel. But for the convenience in further computations the energy value is converted to HP-hour/gallon:

$$1\ (HP - hr / gal) = 1\ \frac{BTU / gal}{2544.43} \tag{2.23}$$

Now, having matched units, fuel required to drive the motor is easily found:

$$Fuel = \frac{Total\ \ power(F)}{Heat\ content} \tag{2.24}$$

where: *Fuel* is the amount of fuel required to drive the motor (gallons);

Total power(F) is total power used during the entire irrigation season for fuel pumps (HP-hour), calculated in Eq. (2.22);

Heat content is a measure of heat content of a fuel (HP-hour/gallon), an input converted from the units of BTU/gallon.

Finally, the total seasonal fuel costs are determined by multiplying total fuel amount by the price per each gallon:

$$Total\ \ fuel\ bill = Fuel \times Fuel\ cost \tag{2.25}$$

where: *Total fuel bill* is total fuel costs in a season ($/year);

Fuel is the amount of fuel required to drive the motor (gallons/year);

Fuel cost is the price of fuel per one gallon ($/gallon), entered by users.

Procedures in the next part of calculations further below – Eqs. (2.25) and (2.26), are good for both types of engines and reflect a good base for the cost comparison. In order to observe savings in costs, it is more practical to focus on annualized costs per unit area or water amount used for irrigation rather than total costs spent on the system. To accomplish this goal, either total energy or fuel costs found in Eqs. (2.21) and (2.25), respectively, is divided by the total gross amount of irrigation applied to the field to obtain the cost spent per unit volume of water applied:

$$Cost / acre - in = \frac{Total\ energy\ bill\ or\ Total\ \ fuel\ bill}{Total\ water} \qquad (2.26)$$

where: *Cost/acre-in* is the cost per unit volume of water applied to the field ($/acre-in);

Total energy bill or *Total fuel bill* is the total seasonal energy costs ($/year) or the total seasonal fuel costs ($/year) depending on the type of motor, calculated in Eqs. (2.21) and (2.25), respectively;

Total water is total amount of irrigation water applied to the field (acre-inches), calculated in Eq. (2.11).

The second comparative measure is the annualized cost per unit area of the field, calculation of which is similar to Eq. (2.26), except that the parameter of interest now is the unit area:

$$Cost / acre - year = \frac{Total\ energy\ bill\ or\ Total\ \ fuel\ bill}{Area} \qquad (2.27)$$

where: *Cost/acre-year* is the annualized cost per unit area of the field ($/acre-year);

Total energy bill or *Total fuel bill* is the total seasonal energy costs ($/year) or the total seasonal fuel costs ($/year) depending on the type of motor, calculated in Eqs. (2.21) and (2.25), respectively;

Area is acres irrigated (acres), entered by users.

The values of total seasonal energy/fuel costs (Eqs. (2.21), (2.25)), cost per volume of water applied to the field (Eq. (2.26)) and annualized cost per unit area (Eq. (2.27)) as well as water horsepower (Eq. (2.14) or (2.15)) and motor horsepower (Eq. (2.16)) are displayed in the **Outputs** section available for a cost comparison between two systems. To provide total costs spent for each of the systems and their difference are also shown.

- **Annual maintenance and repair costs**

Maintenance and repair costs depend on a number of hours the irrigation system operates, the operating environment, and the quality of maintenance. In addition, there is substantial variation in the prices paid for parts and supplies, and in the wages paid to repair and maintenance personnel. These costs should be based on local data whenever possible; however, when local data is not available, annual maintenance and repair costs for an irrigation system component can be approximated as a percentage of the components initial cost (see ranges listed in Tables A-4 and A-5 in Appendix A). The total annual maintenance and repair cost for the system is the sum of the component costs.

As only the farmers know how much his/her annual maintenance and repair costs are, they are asked to enter these as inputs. If users are not sure about the value to enter, they can approximate the costs using Tables A-4 and A-5 in Appendix A.

- **Annual labor costs**

The labor required to operate an irrigation system depends on many factors, such as the type of application system, the degree of automation, the crop, the frequency and number of irrigations, and the terrain. As Burt et al. (2000) pointed out, it is hard to define labor costs as they are so highly dependent upon the design, the type of crop, and the quality of installation as well as the attitude, sophistication, and management style of both the owner and operators/workers. For example, a very high performance (high DU) can be reached with a minimum of labor, but the system must be installed correctly with the proper filtration, flushout valves, and chemigation system.

As labor costs form a big portion of costs that determine a decision-making process of choosing an appropriate irrigation system, all factors should be included for more accurate calculations. The model considers that besides regular hours the workers get paid for, they may need to work extra hours during a season. The owner/farmer is asked to enter the value that represents these approximate costs the best. A simple equation used is then:

$$Total\ labor\ costs = Annual\ \ labor\ costs + Additional\ labor\ costs \qquad (2.28)$$

where: *Total labor costs* is total annual labor costs ($);

Annual labor costs is annual labor costs/wages ($), entered by users;

Additional labor costs is annual additional labor costs paid for extra hours ($), calculated in Eq. (2.29).

Note that all terms in Eq. (2.28) are annualized, i.e., already consider all working hours during the entire irrigation season.

Additional labor costs depend on the man-hours spent and are computed as follows:

$$Additional\ labor\ costs = Additional\ time \times OTR \qquad (2.29)$$

where: *Additional labor costs* is annual additional labor costs paid for extra hours ($);

Additional time is additional time per season (hours), calculated in Eq. (2.30);

OTR is over time rate ($/hour).

And:

$$Additional\ time = Weeks \times Moves \times Extra\ time / 60 \qquad (2.30)$$

where: *Additional time* is additional time per season (hours);

Weeks is extra weeks per season, entered by users (weeks/season);

Moves is a number of moves made every week (moves/week), entered by users;

Extra time is additional time per move (min/move), entered by users;

60 is a constant, converts minutes to hours.

Equations (2.29) and (2.30) are skipped on some systems that do not require moves, such as surface irrigation and solid-set. Instead, the users need to enter their best estimate for additional labor costs for these systems.

Equivalent annual cost factor (EACF)

Total variable (operating) costs are adjusted for estimated inflation by using the EACF of escalating costs taking into account the time value of money over the life cycle. The effect of escalating costs is included by multiplying estimated annual costs for the initial year of operation by the EACF. The EACF is defined by the following:

$$EACF = \left(\frac{(1+r)^{AP} - (1+i)^{AP}}{(r-i)} \right) \left(\frac{i}{(1+i)^{AP} - 1} \right) \qquad (2.31)$$

where: *EACF* is the equivalent annual cost factor;

i is the annual interest rate (decimal), entered by users;

r is the expected annual rate of cost escalation (decimal), entered by users;

AP is the analysis period (years).

2.3. Analysis: Change of system costs with improvement of DU and IE

Various designs of irrigation systems can result in varying degrees of uniformity, whereas management practices may cause losses of irrigation water. A number of techniques in the system design and practices can be used to increase the DU and IE of the systems, respectively. For example, for pressurized systems, these techniques may include using larger pipe sizes to minimize pressure differences due to friction losses, using pressure regulators to minimize pressure differences due to elevation differentials, using close sprinkler spacing, or trickle emitters with low manufacturing variations. All these changes will increase the costs of the system, and in general, the costs of the irrigation systems will go up with the DU. But since higher DU's correlate with higher IE's, there are some savings in water and energy costs associated with the higher uniformity systems.

The goal of this analysis was to observe how the system costs changed with change in DU and IE, keeping other inputs constant. Another interest was to observe a role of the engine type. For this, three irrigation systems (surface/rill, center pivot and wheel-line) were tested, changing both DU and IE at a time and recording corresponding water and energy costs in a tabular form (see Results). The typical ranges of DU and IE for each system were used from the results of experiments completed by Cal Poly (Tables A-2 and

A-3). To capture the affect of DU and IE on energy costs in terms of rill, the system was assumed to operate by the pump.

2.4. Performance of Sensitivity Analysis

Total farming costs and Distribution Uniformity (DU), Irrigation Efficiency (IE) and Pumping plant efficiency (PPE) not only affect efficiency and profitability of irrigation systems but vary with irrigation methods as well. Sensitivity analysis is used to determine how "sensitive" a model is to changes in the value of the parameters of the model and to changes in the structure of the model (i.e., to determine how different values of an independent variable will impact a particular dependent variable under a given set of assumptions). If a small change in a parameter results in relatively large changes in the outcomes, the outcomes are said to be sensitive to that parameter. This may mean that the parameter has to be determined very accurately or that the alternative has to be redesigned for low sensitivity. The sensitivity analysis technique is detailed described by Breierova and Choudhari (1996) and is performed by repeating an evaluation using different input values. By testing the percentage change in the output corresponding to specified percentage change in input values, the most critical parameters can be identified (variable-by-variable approach). These variables should receive the most focus to improve the accuracy of the model. Variables (parameters) selected for the sensitivity analysis are:

- *Distribution uniformity* (*DU*), *Irrigation efficiency* (*IE*) and *Pumping plant efficiency* (*PPE*) and their significance are explicitly described in Chapter 2;
- *Total costs* are total costs of the irrigation system, and are made up of variable costs (vary according to quantity produced) and fixed costs (expenses for assets);

- *Pumping costs* are total energy costs or total fuel costs for electric engine or liquid fuel driven engine, respectively. These costs directly depend on DU and IE as well as engine efficiency;
- *Labor costs* include permanent salaries and over time salaries;
- *Maintenance and Repair costs* (*M&R*) is another component of the *Total costs* and consists of expenses for operation and maintenance of the irrigation system, (re)installation of equipment, etc.

The following steps were performed to complete the analysis:

1. First, the inputs of interest were selected. The sensitivity analysis was performed to see: (1) an impact of management practices (*PPE, DU*, and *IE*) on *Total costs*, and (2) the economic impact (the impact of changes in cost variables (*Labor costs, Pumping costs* and *M&R costs*) on *Total costs.*
   (1) The first group was interesting to learn how management practices may change *Total costs*, while the second group's target was the relationship between the main cost components and *Total costs*. Two systems, wheel-line and center pivot, each with operating electrical and powered by liquid fuel driven engines, were randomly selected for the comparison. It was interesting to observe differences in management practices and engine types (pumps), each within same system and between two systems;
   (2) For the second group, since the objective was to compare how changes in chosen parameters impact *Total costs*, it was interesting to see how these changes affect both fuel and electric pump systems.

2. For each parameter boundaries were defined (-40% and 100%) and increments (steps) in costs or range of variation were selected. Thus, the step size of 10% was chosen for variation of *PPE*, *DU*, and *IE*, within typical ranges for selected irrigation systems/methods. For the costs, the fixed step size was 20% between the values. With the changes in parameters set, the model was run for each value, recording new corresponding changes in the *Total costs* and calculating their relative change (increments in percents) as well. Converting all real values to a relative change (%) allowed plotting of the multiple parameters on the same graph by matching the scales. Percentage change was calculated by the difference between two values (user's input and a desirable value) divided by the initial value (user's input) and converted to percentage;
3. The next step was to plot the data obtained in Part Two. The graphs were arranged in a few ways: all parameters compared for a single system, one parameter at a time compared for a single system, comparison of one parameter for both systems, or comparison of one parameter for both engine types;
4. The sensitivity of the *Total costs* to each parameter was observed and interpreted. In the plotted results, steeper curves generally indicate a higher degree of sensitivity to deviations from the original estimates. This is explained by a greater change in parameter (steeper slope) for a fixed change in percentage along the axis.

CHAPTER 3

RESULTS AND DISCUSSION

3.1. Analysis: Change of system costs with improvement of DU and IE

The results presented in Tables 3.1, 3.2 and 3.3 revealed that annual energy costs, cost/acre-year and total costs decrease when the DU and IE increase, regardless of the engine type. However, the cost/acre-in increased for higher DU and IE in most cases, but the difference is not significant. This change is practically explained: high DU and IE permit water applied to reach further down to the desired depth and distributed more evenly, with fewer losses (e.g., runoff, deep percolation). Then less water should be applied to bring the actual efficiency to the desired one, which, in turn, requires shorter duration of irrigation and less irrigation water to pump. The systems with initial DU and IE being quite low (wheel-line and surface irrigation systems) serve good examples to reflect how dramatically the improved DU and IE values may change the costs.

Table 3.1. Change of costs with improvement of DU and IE for the wheel-line irrigation system

DU	IE	annual energy ($)	cost/acre-in ($)	cost/acre-yr ($)	total costs ($)
Fuel pump (Water HP = 23.7 HP; Motor HP = 94.4 HP)					
0.62	66	6641.11	10.87	132.82	26286.41
0.85	80	3996.38	10.87	79.93	21818.96
Electric pump (Water HP = 23.7 HP; Motor HP = 36.6 HP)					
0.62	66	1459.89	2.39	29.20	17534.34
0.85	80	909.79	2.47	18.20	16605.11

Another observation is that electric pumps have advantages over the fuel pumps for all tested systems, which is verified by lower costs of the outputs. Even without improving the DU and IE values, it is enough to upgrade the fuel pump to the electric pump to reduce system costs greatly. This change will result in decrease of pumping costs, and hence energy and total costs too, and help modify pump characteristics (e.g., reduce motor horsepower).

Table 3.2. Change of costs with improvement of DU and IE for the center pivot irrigation system

DU	IE	annual energy ($)	cost/acre-in ($)	cost/acre-yr ($)	total costs ($)
Fuel pump (Water HP = 23.7 HP; Motor HP = 94.4 HP)					
0.80	80	4246.16	10.87	84.92	76253.16
0.85	90	3552.34	10.87	71.05	75081.17
Electric pump (Water HP = 23.7 HP; Motor HP = 36.6 HP)					
0.80	80	966.65	2.47	19.33	70713.44
0.85	90	808.70	2.47	16.17	70446.63

Table 3.3. Change of costs with improvement of DU and IE for the surface irrigation system

DU	IE	annual energy ($)	cost/acre-in ($)	cost/acre-yr ($)	total costs ($)
Fuel pump (Water HP = 23.7 HP; Motor HP = 94.4 HP)					
0.92	20	13587.71	10.87	271.75	38087.41
0.90	47	5782.00	10.87	115.64	22030.44
Electric pump (Water HP = 23.7 HP; Motor HP = 36.6 HP)					
0.92	20	2777.73	2.22	55.55	19827.28
0.90	47	1296.91	2.44	25.94	14454.26

3.2. Sensitivity Analysis

Impact of management practices on the Total costs

Evaluating an impact of change in management practices on *Total costs* for a wheel-line system, it is obvious that all three parameters give same degree of sensitivity to deviations from the original estimates (see Figure 3.1). Shapes of curves expose identical slopes: there is no difference in ratios of relative change in *Total costs* to relative change in each parameter (*PPE*, *DU*, or *IE*) due to the inverse relationship of all three parameters and *Total costs*. This means that changing only one of three parameters at a time is enough to result in a change in *Total costs*; it can be mathematically verified by Eqs. (2.12), (2.14), (2.19), and (2.23) in Chapter 2.

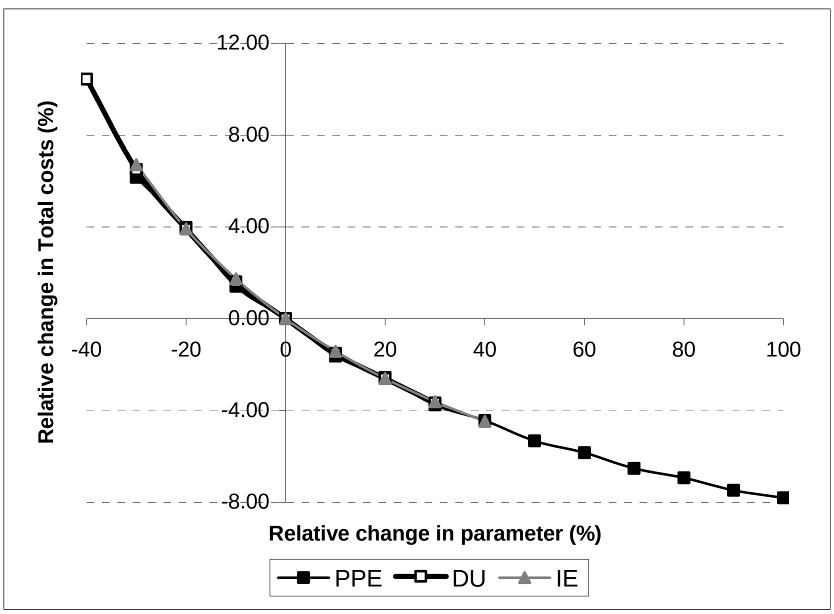

Figure 3.1. Sensitivity of *Total costs* to *PPE, DU,* and *IE* for the wheel-line with a fuel pump

The dependence described above was observed on other graphs as well (Figures 3.2, 3.3, and 3.4): *Total costs* are sensitive to change in parameters to the same degree within a single system, regardless of the engine type.

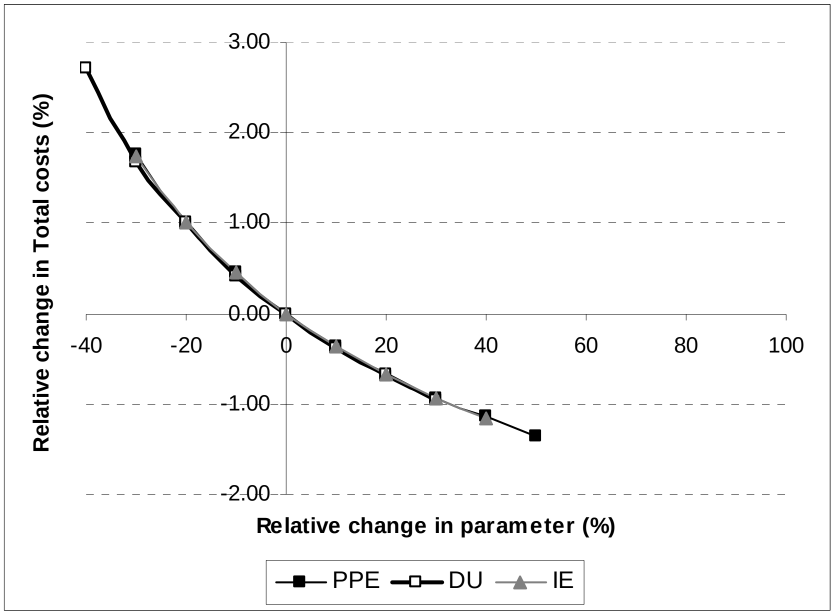

Figure 3.2. Sensitivity of *Total costs* to *PPE*, *DU*, and *IE* for the wheel-line with an electric pump

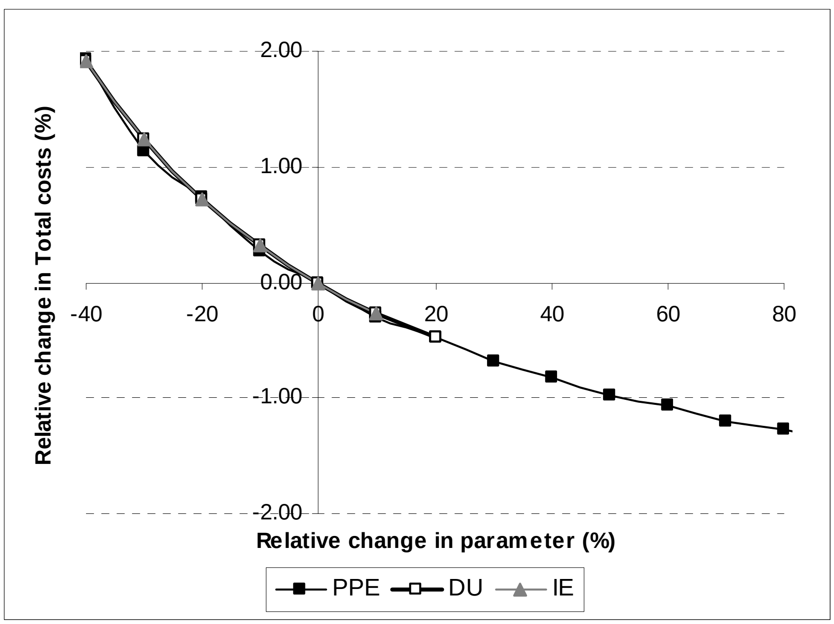

Figure 3.3. Sensitivity of *Total costs* to *PPE*, *DU*, and *IE* for the center pivot with a fuel pump

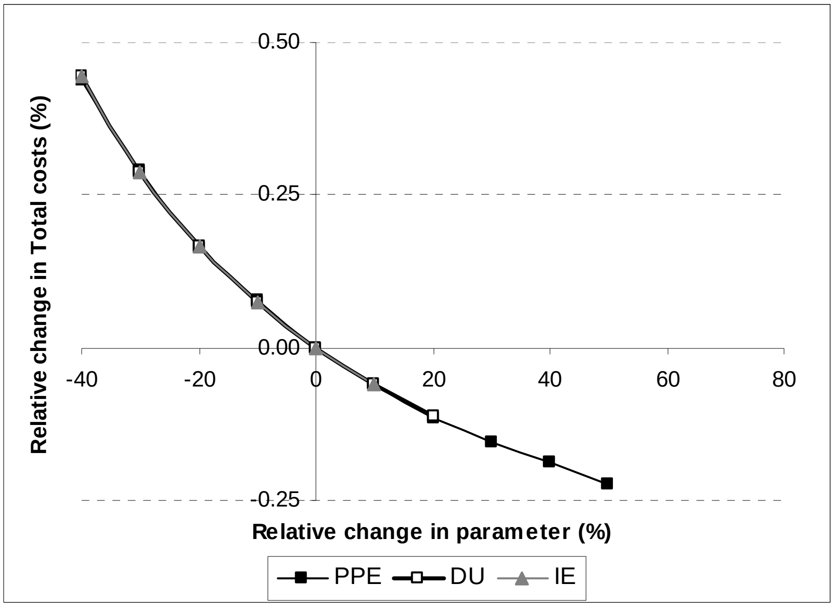

Figure 3.4. Sensitivity of *Total costs* to *PPE*, *DU*, and *IE* for the center pivot with an electric pump

Noticeable ranges of relative change in *Total costs* (Y-axis) support the idea of the effect of engine types (liquid fuel driven engine or electric engine) on the costs. To observe this relationship, change in *Total costs* (%) and change in one of three parameters

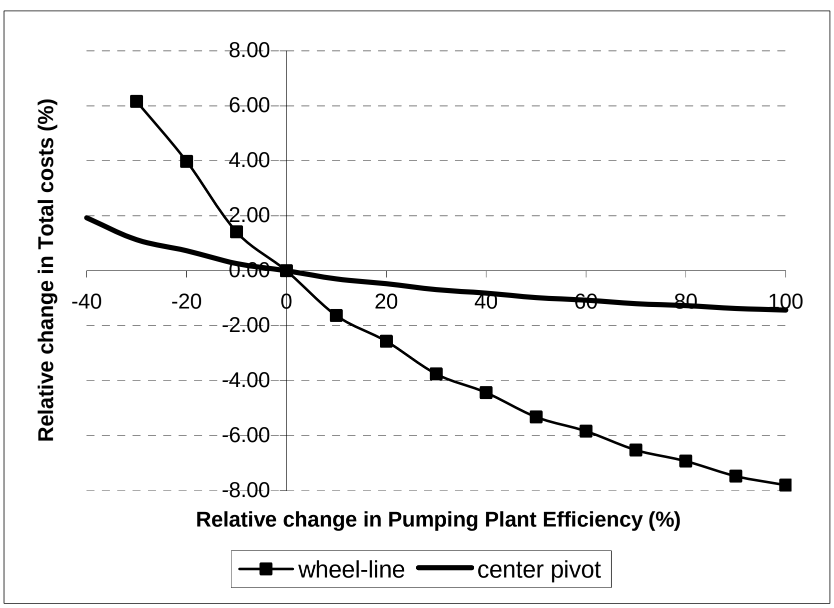

Figure 3.5. Sensitivity of *Total costs* to *PPE* for wheel-line and center pivot, both with fuel pumps

(%) were plotted for each engine type, in comparison between two systems. Figures 3.5, 3.6 reveal an evident difference between two systems: *Total costs* are more sensitive to change in *PPE* in terms of the wheel-line rather than the center pivot irrigation system. The rest of graphs plotted for other two parameters (*DU* and *IE*) depict similar patterns (see Figures B.1, B.2, B.3 and B.4 in Appendix B).

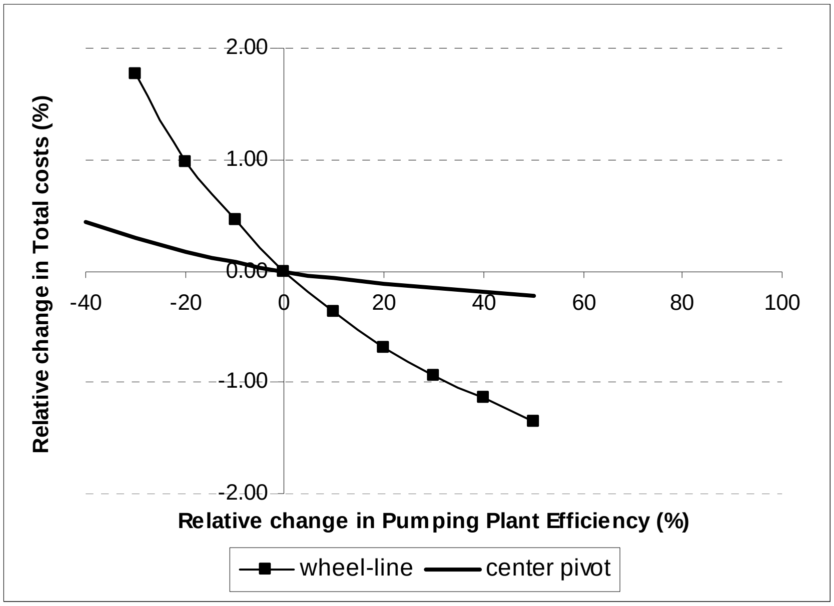

Figure 3.6. Sensitivity of *Total costs* to *PPE* for wheel-line and center pivot, both with electric pumps

Although, the engine types did not reflect a significant effect on the degree of sensitivity of *Total costs* with respect to chosen parameters within the same system, comparing pumps to each other would reveal some differences. Notably different slopes represent various degrees to sensitivity of *Total costs* to the *PPE* (Figures 3.7 and 3.8): *Total costs* are more sensitive to change in powered by liquid fuel driven engine (fuel pump) rather than to change in electric pump. This statement is meaningful from a practical point of view: the center pivot system has higher values of *DU* and *IE*. However, it is true for both systems that incrementally improving the *PPE* will help reduce the costs, no matter if the system performs poorly or well. The same relationship was found between the costs and other two management factors (*DU* and *IE*); those graphs are reported in Appendix B (Figures B.5, B.6, B.7 and B.8). In general, calculations supported the common knowledge of electric pumps having higher efficiency than the fuel pumps.

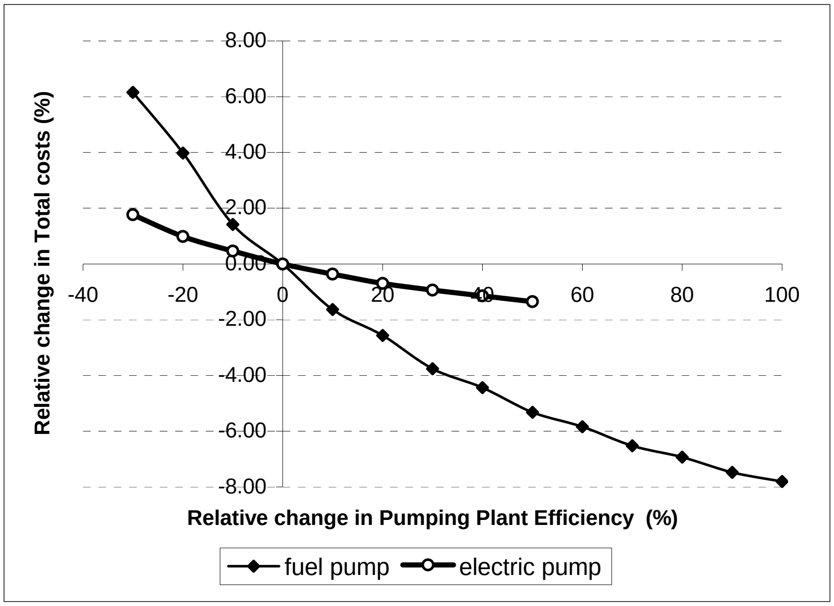

Figure 3.7. Sensitivity of *Total costs* to *PPE* for the wheel-line with fuel pump and electric pump

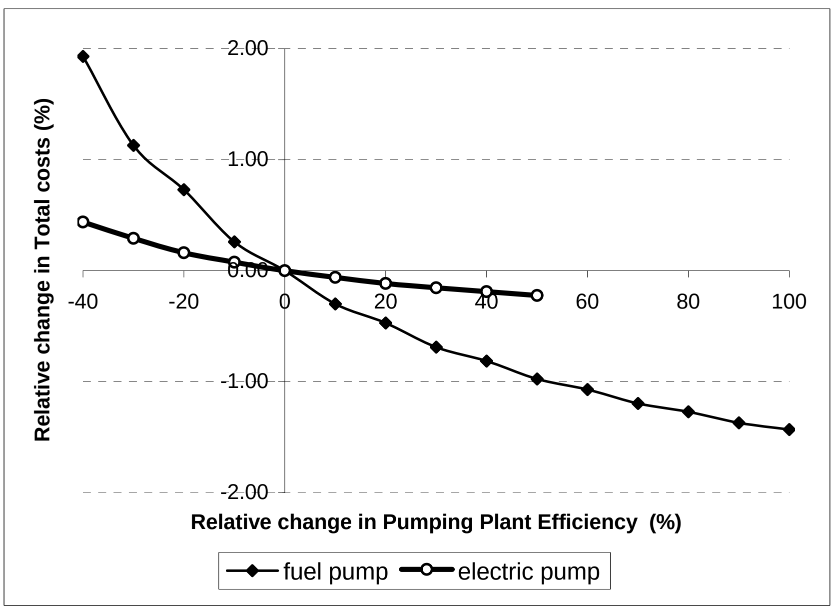

Figure 3.8. Sensitivity of *Total costs* to *PPE* for the center pivot with fuel pump and electric pump

Economic impact on the Total costs

Different slopes of the lines shown on Figure 3.9 are interpreted as follows: *Total costs* are most sensitive to *Labor costs* and they are least sensitive to *Pumping costs*.

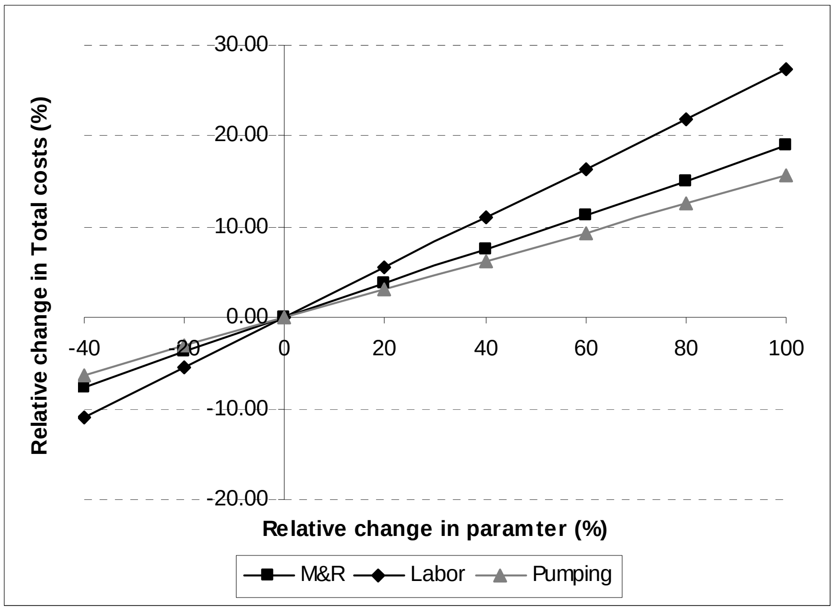

Figure 3.9. Sensitivity of *Total costs* to four cost components for the wheel-line with a fuel pump

Similarly to Figure 3.9, *Labor costs* caused the highest changes in *Total costs* for the center pivot system with a fuel pump; *Pumping costs* caused the least changes (Figure 3.10). It was also noted that the range of change in *Total costs* was much narrower than for the wheel-line system. The lower position of the *Pumping costs* line for the center pivot may be explained by its significantly different values of DU and IE, which determine duration of irrigation and amount of water for irrigation. Generally, systems with poor DU and IE values require longer irrigation sets (i.e., longer runs of pumps) and more water to pump, resulting in increase of the pumping costs.

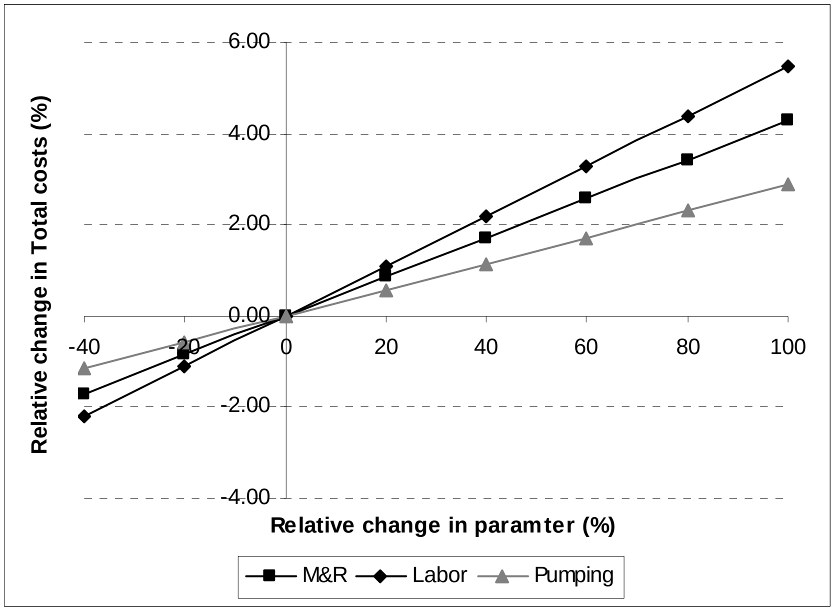

Figure 3.10. Sensitivity of *Total costs* to four cost components for the center pivot with a fuel pump

Testing degrees of sensitivity of the parameters for electric pumps, same trends as for fuel pumps are observed: *Total costs* are most sensitive to *Labor costs* and they are least sensitive to *Pumping costs* (Figures 3.11 and 3.12). Noticeable shift of the *Pumping*

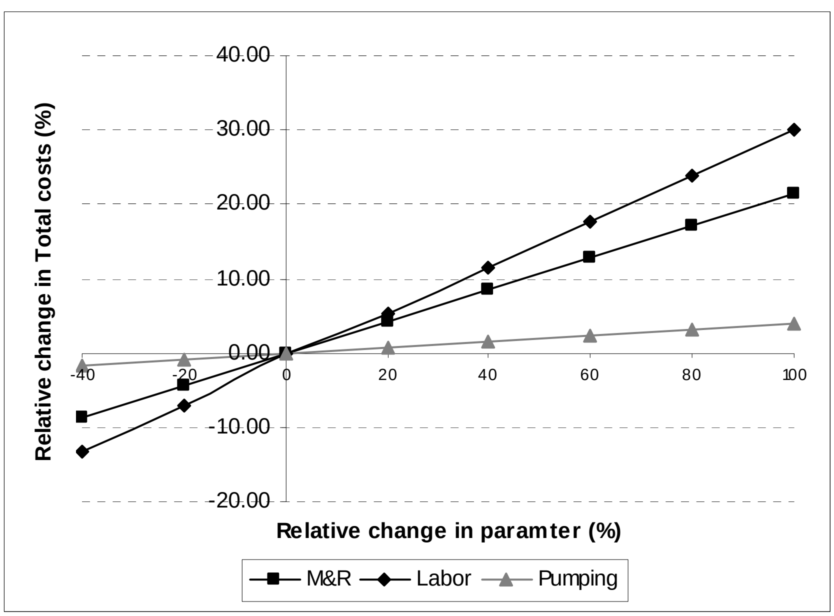

Figure 3.11. Sensitivity of *Total costs* to four cost components for the wheel-line with an electric pump

costs lower towards the X-axis may be explained by the effect of DU and IE values, which surely differ between the examined systems. The highest sensitivity to the *Labor costs* reflected on Figures 3.9– 3.12 is due to different initial labor inputs in two systems (center pivot was assumed to require less of labor costs). In general, the labor costs vary not only with systems, but also account for expenses the farmers/managers have available to attract workers.

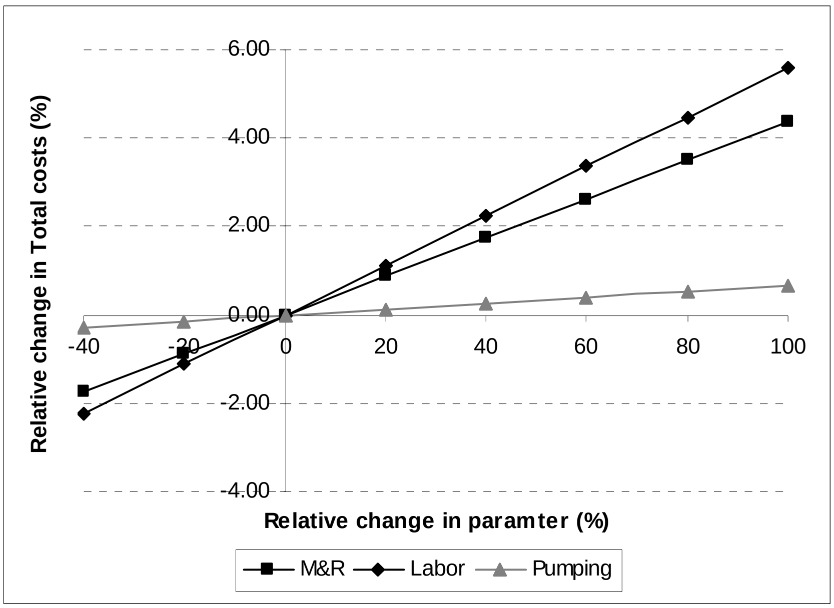

Figure 3.12. Sensitivity of *Total costs* to four cost components for the center pivot with an electric pump

The *Pumping costs* were chosen to test *Total costs* in comparison between two engine types (Figures 3.13 and 3.14). Choosing the *Pumping costs* has a duel effect: they determine *Total costs* to a greater extent as well as consider systems' DU and IE and efficiencies of the pumps. Both figures depict significantly higher degree of sensitivity for the systems driven by the fuel pumps.

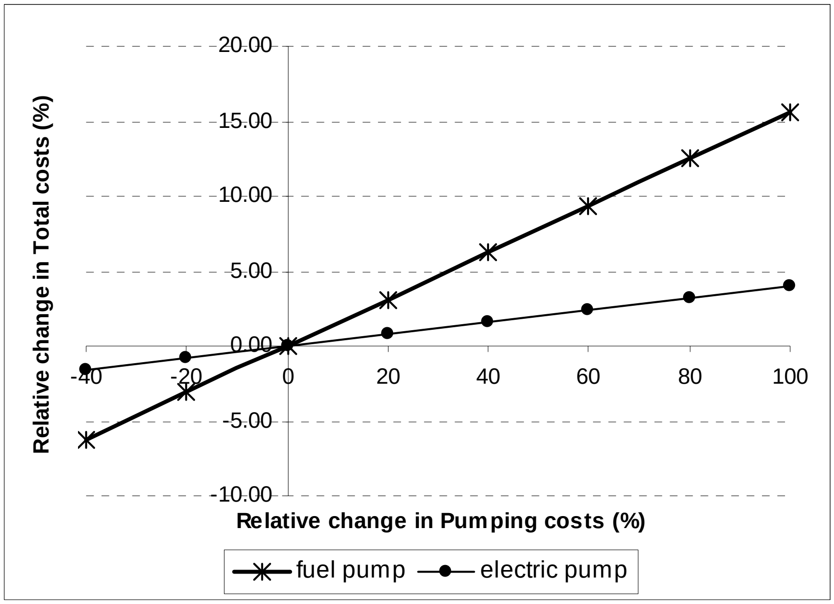

Figure 3.13. Sensitivity of *Total costs Pumping costs* for the wheel-line with both electric pump and fuel pump

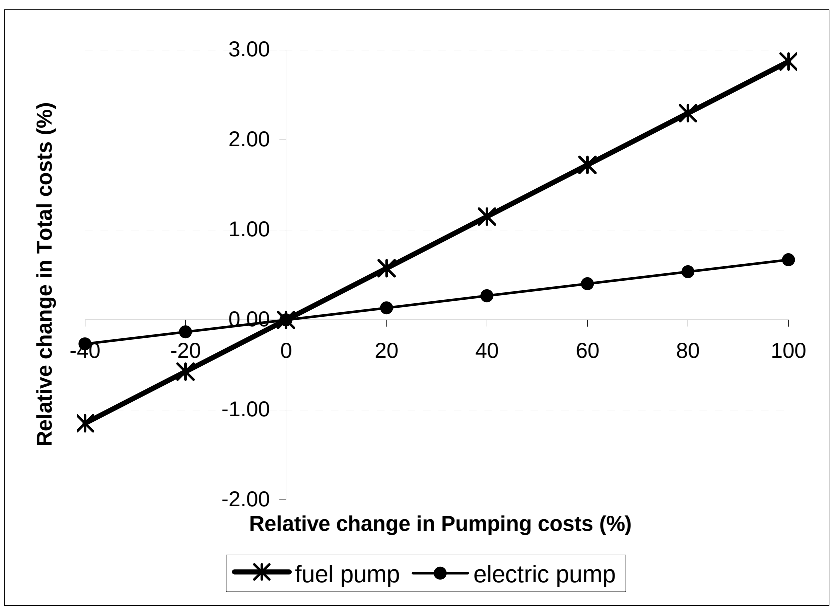

Figure 3.14. Sensitivity of *Total costs Pumping costs* for the center pivot with both electric pump and fuel pump

CHAPTER 4

CONCLUSIONS

4.1. Analysis: Change of system costs with improvement of DU and IE

The results of the analysis revealed that annual energy costs, cost/acre-year and total costs tend to decrease, and the cost/acre-in increases, when the DU and IE increase, regardless of the engine type. In general, systems with low DU and IE have higher costs as higher water applications are needed. Electric pumps have advantages over the fuel pumps for all tested systems; even without improving the DU and IE values, it is enough to upgrade the fuel pump to the electric pump to reduce system costs greatly. This change will result in decreasing of pumping costs, and hence energy and total costs too, and will also help to modify pump characteristics (e.g., reduce motor horsepower).

4.2. Sensitivity Analysis

1. *Impact of management practices on the Total costs (TC). Total costs* had same degree of sensitivity to all management factors (*PPE*, *DU*, and *IE*) regardless of the system and engine type. However, results revealed significant variations among the systems and pumps. *Total costs* were more sensitive to the parameters for the wheel-line than the center pivot irrigation system regardless of the engine type, which is explained by the higher values of DU and IE of the center pivot system. Similarly, TC had higher sensitivity to the parameters for the fuel than the electric pump regardless of the system, again as a result of higher efficiency.

2. *Economic impact on Total costs.* In general, the sensitivity pattern was found to be similar regardless of the irrigation system and the engine type: TC values were most sensitive to *Labor costs* and they were least sensitive to *Pumping costs* in all cases. However, the results showed that the costs were more sensitive to changes in parameters for fuel pumps rather than electric pumps. *Pumping costs* showed the greatest variation and proved to be a dominant component of TC. This variation may be explained by significantly different values of DU and IE of the two systems compared, which determine duration of irrigation and amount of water for irrigation. Generally, systems with poor DU and IE values require longer irrigation sets (i.e., longer runs of pumps) and more water to pump, resulting in increasing of the *Pumping costs*.

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APPENDIX A

DATA FROM RESEARCH BY CAL POLY

Table A-1. Field Information

Field #	Irrigation District	Irrigation System	Crop	Acres
1	SVID	Wheel-line	Asparagus	16.3
2	SVID	Overvine Sprinklers	Concord Grapes	34.6
3	RID	Micro Sprayers	Pears	20.0
4	RID	Buried Drip	Apples	55.0
5	RID	Drip	Apples and Cherries	36.0
6	RID	Drip	Hops	21.8
7	SVID	Overvine Sprinklers	Concord Grapes	17.0
8	RID	Overvine Sprinklers	Concord Grapes	3.5
9	SVID	Overvine Sprinklers	Wine Grapes	7.5
10	RID	Overvine Sprinklers	Niagara Grapes	33.0
11	SVID	Buried Drip	Hops	22.0
12	SVID	Buried Drip	Hops	32.0
13	SVID	Wheel-line	Alfalfa	70.0
14	RID	Overvine Sprinklers	Wine Grapes	17.0
15	SVID	Overvine Sprinklers	Niagara Grapes	15.2
16	SVID	Overvine Sprinklers	Concord Grapes	30.0
17	RID	Wheel-line	Mint	32.0
18	RID	Undertree Sprinklers	Apples	22.0
19	RID	Overvine Sprinklers	Concord Grapes	3.0
20	SVID	Rill	Corn	5.0

Table A-2. Actual and Improved Irrigation Efficiency Values. Water Destination by Each Field

Field #	DU		IE, %	Irrigation Water Applied, in	Evapora-tion Losses, in	Irrigation Water Infiltrated, in	Actual ET, inches			ET Deficit, inches			Deep Percolation, inches		
							Wettest	Average	Driest	Wettest	Average	Driest	Wettest	Average	Driest
1	0.81	Actual	53	12.7	1.3	11.4	13.5	12.5	11.4	1.9	3.9	5.0	6.1	4.7	3.4
	0.85	Improved	72	17.3	1.7	15.6	16.2	16.2	15.3	0.0	0.0	0.9	3.7	0.9	0.8
2	0.76	Actual	70	25.6	1.0	24.6	19.1	19.1	18.5	0.7	0.7	1.3	13.0	6.6	1.6
	0.86	Improved	80	21.9	0.9	21.0	19.8	19.8	19.8	0.0	0.0	0.0	6.9	3.6	0.0
3	0.90	Actual	45	30.0	3.0	27.0	17.1	17.0	16.9	1.0	1.1	1.3	16.1	13.5	11.0
	0.92	Improved	84	20.1	2.0	18.1	18.1	18.1	18.1	0.0	0.0	0.0	2.7	1.3	0.0
4	0.87	Actual	83	36.5	2.2	34.3	32.9	32.9	32.1	0.1	0.1	0.9	8.4	3.8	0.4
	0.90	Improved	82	37.6	2.3	35.4	33.0	33.0	33.0	0.0	0.0	0.0	6.5	4.0	1.6
5	0.84	Actual	44	16.0	1.0	15.0	8.6	8.6	8.6	0.0	0.0	0.0	8.8	6.4	4.0
	0.90	Improved	69	9.9	0.6	9.3	8.6	8.6	8.6	0.0	0.0	0.0	1.8	0.9	0.2
6	0.93	Actual	90	22.5	0.0	22.5	25.8	24.8	23.8	3.7	4.7	5.7	2.8	2.3	1.9
	0.93	Improved	93	29.2	0.0	29.2	29.5	29.5	29.5	0.0	0.0	0.0	3.9	1.9	0.5
7	0.49	Actual	87	14.4	0.4	14.0	18.7	14.5	8.7	1.1	5.3	11.1	2.9	1.5	0.7
	0.80	Improved	74	23.1	0.7	22.4	19.8	19.8	19.8	0.0	0.0	0.0	10.3	5.4	0.0
8	0.31	Actual	93	10.6	0.3	10.3	16.6	11.8	5.9	3.8	8.5	14.4	1.4	0.4	0.0
	0.75	Improved	69	24.3	0.7	23.6	20.3	20.3	20.3	0.0	0.0	0.0	13.1	6.8	0.0
9	0.47	Actual	21	54.0	1.6	52.4	12.6	12.6	12.6	0.0	0.0	0.0	70.1	41.5	12.8
	0.82	Improved	75	13.5	0.4	13.1	12.6	12.6	12.6	0.0	0.0	0.0	5.3	2.9	0.0
10	0.79	Actual	97	17.1	0.5	16.6	19.2	18.9	15.9	0.6	1.0	3.9	3.8	0.0	0.0
	0.84	Improved	77	22.0	0.7	21.4	19.8	19.8	19.8	0.0	0.0	0.0	8.5	4.5	0.0
11	0.37	Actual	66	52.0	0.0	52.0	34.7	34.7	24.8	0.0	0.0	10.0	48.8	17.6	0.9
	0.93	Improved	93	36.2	0.0	36.2	34.7	34.7	34.7	0.0	0.0	0.0	4.7	2.2	0.2
12	0.76	Actual	44	62.5	0.0	62.5	31.9	31.9	31.9	2.9	2.9	2.9	49.9	34.9	19.9
	0.80	Improved	80	40.5	0.0	40.5	34.7	34.7	34.7	0.0	0.0	0.0	15.7	7.6	0.2
13	0.63	Actual	82	11.8	1.2	10.6	17.0	14.7	11.4	22.6	25.0	28.2	2.4	0.9	0.2
	0.85	Improved	74	52.9	5.4	47.5	41.4	41.4	38.7	0.0	0.0	0.0	17.7	8.4	2.0
14	0.79	Actual	73	15.9	0.6	15.2	12.6	11.8	10.1	0.0	0.8	2.7	7.5	3.7	0.3
	0.84	Improved	83	12.3	0.5	11.8	12.6	12.6	12.6	0.0	0.0	0.0	3.8	1.6	0.0
15	0.84	Actual	59	27.8	0.8	27.0	19.8	19.8	19.8	0.0	0.0	0.0	15.5	10.7	5.5
	0.85	Improved	80	21.7	0.6	21.0	19.8	19.8	19.8	0.0	0.0	0.0	7.3	3.7	0.0
16	0.76	Actual	52	35.0	1.4	33.6	15.1	15.1	15.1	4.8	4.8	4.8	23.9	15.3	6.6
	0.78	Improved	76	21.9	0.9	21.0	19.8	19.8	19.8	0.0	0.0	0.0	7.9	4.3	0.0
17	0.62	Actual	66	26.3	2.7	23.6	22.2	22.2	17.9	9.7	9.6	13.9	15.8	6.0	1.3
	0.85	Improved	80	23.8	2.4	21.4	23.7	23.7	21.6	7.8	7.8	9.6	6.3	2.2	0.3
18	0.68	Actual	58	39.7	1.2	38.5	23.0	23.0	22.0	0.0	0.0	0.9	31.9	18.9	5.3
	0.93	Improved	85	23.2	0.7	22.5	23.0	23.0	23.0	0.0	0.0	0.0	4.9	2.9	0.0
19	0.67	Actual	71	20.8	1.2	19.6	18.5	16.9	14.6	1.4	2.9	5.3	9.2	4.8	0.8
	0.85	Improved	76	23.4	1.4	22.0	19.8	19.8	19.8	0.0	0.0	0.0	8.2	4.2	0.0
20	0.92	Actual	20	126.6	65.8	60.8	26.0	26.0	26.0	0.0	0.0	0.0	40.5	35.6	30.8
	0.90	Improved	47	53.3	27.7	25.6	26.0	26.0	26.0	0.0	0.0	0.0	2.6	0.6	0.0

Table A-3. Actual DU values, Causes of Non-uniformity and Recommendations, Improved DU values by Systems and Fields

System	field	Actual DU	Improved DU	Main Causes of non-uniformity	Recommendations
Overvine sprinklers	8	0.31	0.75	Very low pressure. Lack of nozzles Plugging with rocks from the well	Switch to already existing pressurized; Change/add same size nozzles; District turnout; Install a small tubular screen filter
(General observations: plugging was noticeable in almost all the systems evaluated. All these boxes have simple screens, and in some cases it is only filtration method thy have, small gravity overflow screens can be recommended)	9	0.47	0.82	Low pressure. Plugging. The system operates by gravity	Need pump and filters; Improve District turnout design
	7	0.49	0.80	Low overlap uniformity. Different nozzle sizes Interference between sprinklers and grapes	Check and replace all the different nozzles to the same size; All risers should be at the same height
	19	0.67	0.85	Plugging problems; not enough filtration	Be careful when cleaning tabular filters
	2	0.76	0.86	Plugging problems; not enough filtration	Be careful when cleaning tabular filters
	16	0.76	0.84	Interference between sprinklers and the grapes	Check and control the growth of vines in the rises
	10	0.79	0.84	Sprinkler pressure differences	Install pre-set pressure regulator at the base of each sprinkler
	14	0.79	0.84	Sprinkler pressure differences Low catch can DU	Install an additional gate valve at the entrance to each lateral and adjust the pressure
	15	0.84	0.85	Very good for a solid-set system	All risers should be at the same height
Drip – Microspray	11	0.37	0.93	Buried system. Root intrusion. Worms	Abandon the buried tape
(General observations: chemical injection must be upstream from the filters)	12	0.76	0.80	Plugged emitters. Silt, bacterial growth Pressure differences	Improve bacterial growth control. Regularly inject chlorine; Adjust pressure accordingly at the Dorot valves
	5	0.84	0.90	Plugged emitters. Silt	Require individual points of improvement districts
	4	0.87	0.90	Pressure differences. Timing/Spacing. Slight plugging	Irrigate different spacing blocks for different wet durations
	3	0.90	0.92	Pressure differences. Barb leaks	Adjust pressure accordingly at the Dorot valves; Check for leaks
	6	0.93	0.93	Very good	Improve bacterial growth control. Regularly inject chlorine
Wheel-line	1	0.81	0.85	Low overlap uniformity. Pressure differences along line	Install pre-set pressure regulator at the base of each sprinkler
	13	0.63	0.85	Low pressure. Different nozzle sizes. Nozzle wear	Raise pump pressure. Use alternate sets. Use levelers; Replace any worn nozzle and insure all nozzles are same size
	17	0.62	0.85	Low overlap uniformity. Pressure differences along the wheel-line. Different nozzle sizes	Use alternate sets. Use pre-set pressure regulators on wheel-lines and Flow Control nozzles on hand move systems. Replace any worn nozzles
Undertree Sprinklers	18	0.88	0.94	Low overlap uniformity. Plugging Pressure differences along the laterals	Install an extra ON-OFF valve at the head of each lateral. Adjust the pressure at the first sprinkler of each lateral. Start same pressure
Rill	20	0.92	0.92	Very high DU	Reduce the set duration to 20 hours to improve efficiency

Table A-4. Annual Maintenance and Repairs, and Depreciation Guidelines for Irrigation System Components
(*Source*: L. James, "Principles of farm irrigation system design", 1988, pp. 100; G. Thompson, L. Spiess, J. Krider, "Farm Resources and System Selection", 1980, pp. 58)

Component	**Depreciation (h)**	**Period (yr)**	**Annual Maintenance and Repairs (Percent[6])**
Wells and casings	—	20–30	0.5–1.5
Pumping plant structure	—	20–40	0.5–1.5
Pump, vertical turbine			
Bowls	16,000–20,000	8–10	5–7
Column, etc.	32,000–40,000	16–20	3–5
Pump, centrifugal	32,000–50,000	16–25	3–5
Power transmission			
Gear head	30,000–36,000		5–7
V-belt	6,000	3	5–7
Flat belt, rubber and fabric	10,000	5	5–7
Flat belt, leather	20,000	10	5–7
Prime movers			
Electric motor	50,000–70,000	25–35	1.5–2.5
Diesel engine	28,000	14	5–8
Gasoline engine			
Air cooled	8,000	4	6–9
Water cooled	18,000	9	5–8
Propane engine	28,000	14	4–7
Open farm ditches (permanent)		20–25	1–2
Concrete structure		20–40	0.5–1.0
Pipe, asbestos – cement and PVC buried		40	0.25–0.75
Pipe, aluminum, gated surface		10–12	1.5–2.5
Pipe, steel, waterworks class, buried		40	0.25–0.50
Pipe, steel, coated and lined, buried		40	0.25–0.50
Pipe, steel, coated, buried		20–25	0.50–0.75
Pipe, steel, coated, surface		10–12	1.5–2.5
Pipe, steel, galvanized, surface		15	1.0–2.0
Pipe, steel, coated and lined, surface		20–25	1.0–2.0
Pipe, wood, buried		20	0.75–1.25
Pipe, aluminum, sprinkler use, surface		15	1.5–2.5
Pipe, reinforced plastic mortar, buried		40	0.25–0.50
Pipe, plastic, trickle, surface		10	1.5–2.5
Sprinkler heads		8	5–8
Trickle emitters		8	5–8
Trickle filters		12–15	6–9
Landgrazing[7]		None	1.5–2.5
Reservoirs[7]		None	2.0
Mechanical move sprinklers		12–16	5–8
Continuously moving sprinklers		10–15	5–8

[6] Annual maintenance and costs are expressed as a percentage of the initial cost.
[7] Various stages of expected life, from 7–50 years have been applied to land grading and reservoir costs. If adequate maintenance is practiced, these items will remain unaffected by depreciation. For economic analysis, interest on the investment will cover the costs involved. Life may be limited for reservoirs if watershed sedimentation will reduce its usefulness. Costs associated with water rights can also be handled by an interest charge.

Table A-5. Typical Economic Lives and Maintenance Costs for Irrigation System Components
(*Source*: C.M. Burt, A.J. Clemmens, R. Bliesner, J.L. Mirriam, and L. Hardy. "Selection of irrigation methods for agriculture', 2000, pp. 24)

Component	Economic Life (yrs)	Maintenance (% of Cost)
Surface Irrigation		
Buried pipe	30	1
Gated pipe, aluminum	10–20	3
Gated pipe, PVC	5–10	5
Sprinkler Irrigation		
Lateral		
Hand move	15	2
End-tow	10	3
Side roll	15	2
	15	4
Hose fed	5/20	3
Traveling gun	10	6
Center pivot		
Standard	15	5
w/ corner	15	6
Linear move	15	6
Solid set		
Portable	15	2
Permanent	20	1
Drip/Microirrigation		
Orchard		
Drip or Microspray	15/25	5
Row-crop		
Multiple year emitters or tape	6/15	6
Disposable tape	1/(3–15)	10
Other components		
Buried PVC mainline	20–40	1
Steel mainline	10–20	1
Aluminum mainline	10-20	2
Electric pumps	15	3
Diesel/gas pumps	10	6
Wells	25	1

Notes:

Where two lives are shown with a slash, the first number is for above ground components and the second for below ground components. These values are approximate. Local experience and local operating conditions should be considered when available.

Terminology and definitions used

Evaluation procedures vary from system to system, and therefore have different approaches. But the indicator definitions and terms remain same for every single application method, and are explicitly described below:

Distribution Uniformity (*DU*), Low quarter (*DU_{LQ}*)

DU is a measure of the uniformity with which irrigation water is distributed to the plants in a field, i.e., how evenly water soaks into the ground across a field during the irrigation. *DU* includes the concept of reasonable use and beneficial use and can be applied to all irrigation methods. Ideally, at higher *DU*'s variation in the depths of water applied at different points on the field differ less from the average depth. This is an important factor, particularly for high value crops, where small variations in *DU* may cause declines in crop quality. An irrigation system with good *DU* saves water because it allows to avoid oveirrigating parts of the field, but it concentrates on putting adequate water on dry or other problem areas instead. Uniformity is generally measured using grids or lines of catch cans/containers under sprinkler systems (all types of sprinkler systems), by extensive monitoring of soil moisture from the head to the tail end of the run (for surface irrigation), or by measuring emitter flow rates at several points (for drip/trickle systems). The higher the *DU*, the better the performance of the system.

Mathematically *DU* is expressed as the following equation (Merriam and Keller, 1978):

$$DU = \frac{average\ low\ quarter\ depth\ of\ water\ infiltrated}{avgerage\ depth\ of\ irrig.water\ infiltrated} \times 100 \qquad \text{(A.4)}$$

The low-quarter distribution uniformity, DU_{LQ}, is defined as:

$$DU_{LQ} = \frac{d_{LQ}}{D_{avg}} = \frac{average\ low\ quarter\ depth\ of\ irrig.water\ applied\ to\ elements}{avgerage\ depth\ of\ irrig.water\ accumulated\ in\ all\ elements} \quad (A.5)$$

Where the average of the lowest 1/4 of the values, rather than the absolute minimum values is used as a “minimum” value. *DU* is expressed as a ratio rather than a percentage to avoid confusion with the efficiencies. Water depth is measured for each “element” area; an “element” is the smallest area in the field that requires water, but within which the variation of distributed water is not important. The concept of “element scale” is needed when evaluating sprinkler or undertree systems: DU_{LQ}=1 implies that equal element areas (not every portion of the field) received the same amount of water.

The practice of using the least watered 25% of the area (low quarter) as the reference standard has gained wide acceptance. The uniformity described by DU_{LQ} leaves about 1/8 of the area at less than the value of the numerator. This “under irrigation” varies from zero at the 1/8 point to the minimum depth applied at the extreme.

Evaluating *DU* is a fairly straightforward, although a statistical sampling, process, which involves a very famous and widely-used in the sprinkler industry Christiansen Uniformity Coefficient (*CU*) method – it is a measure of the average of the lowest 1/2 of the field. For normally distributed data it is not recommended in making comparisons between irrigation methods. The coefficient of variation (*CV*) is another statistical expression of water application uniformity requiring a large number of sampling points and has typically been used in the drip/micro irrigation industry to describe one small component of field uniformity – that of manufacturing variation of emitters.

$$CV = \frac{Std.Dev.\ of\ accumulated\ water\ depths\ (weighted\ by\ area)}{mean\ water\ depth} \quad (A.6)$$

For normally distributed data, *CV* is related to DU_{LQ} by the following relationship (Burt et al., 2000):

$$DU_{LQ} = 1 - 1.27CV \qquad \text{(A.7)}$$

Irrigation Efficiency (*IE*) is defined as the percent of water supplied to the farm that is beneficially used for irrigation on the farm:

$$IE = \frac{irrigation\ water\ beneficially\ used}{irrigation\ water\ applied - irrigation\ water\ stored} \times 100\% \qquad \text{(A.1)}$$

Expression in the denominator in Eq. (A.1) represents the total volume (both beneficial and nonbeneficial uses) of irrigation water that leaves the boundaries within a specified time interval. If, at the end of the time period the irrigation water content within the designated region is the same as it was at the start, *storage* term is equal to 0, meaning that all the water applied has left the region. The beneficial uses include the water consumed to achieve an agronomic objective. Then Eq. (A.1) is simplified to:

$$IE = \frac{irrigation\ water\ beneficially\ used}{irrigation\ water\ applied} \times 100\% \qquad \text{(A.2)}$$

Low on-farm *IE*'s can result in excess pumping, fertilizer leaching, low crop yields, water quality degradation, drainage problems, excess water costs, reduction in the acreage that can be irrigated with a fixed volume of water available on a farm. *IE* may be defined in terms of depth rather than volume, where depth is defined as the total irrigation water volume divided by the area enclosed by the boundary.

A relationship between *DU* and *IE* may be expressed as:

- *DU* and *IE* are tightly related and result in application efficiency (*AE*): system may have uniform irrigation (high *DU*) but not efficient (low *IE* due to runoff, deep percolation), the system is said to have a low *AE*. However, high *AE* can be achieved if the *DU* is high (Burt et al, 1997);

- There must be good *DU* before there can be good *IE,* if the crop is to be sufficiently watered;
- Good *DU* is no guarantee of good *IE*;
- If the whole field is to be sufficiently watered, then the *DU* becomes the theoretical upper limit to *IE*. That is why *DU* is the first aspect examined when trying to improve irrigation performance.

Application Efficiency (*AE*) describes how evenly an application system distributes water over a field and is based on the concept of how well the irrigation system meets a target irrigation depth. In any event, the *AE* is represented as:

$$AE = \frac{avg.depth\ of\ \ irrig.water\ contributing\ to\ target}{avg.depth\ of\ \ irrig.water\ applied} \times 100\% \qquad \text{(A.3)}$$

The “target depth” may be the soil-moisture deficit (*SMD*), it may also contain a leaching fraction, or it may simply be a target irrigation depth. It is important to assume that the target depth is uniform over the subject area. Since *AE* does not consider the uniformity of application, it is more useful as an irrigation management tool then an evaluation tool in comparing irrigation methods. *AE* is used for field irrigation, whereas *IE* may be used for a field, farm, irrigation district, or basin. *AE* is also used for a single irrigation event, whereas *IE* can be used for a variety of time intervals.

Soil moisture deficit (*SMD*) is the difference in the depth of water actually stored in the crop root zone at any given time and the depth of water stored in that crop root zone at field capacity. *SMD* is expressed numerically as a depth (in inches) indicating the dryness of the root zone at the time of measurement. This depth is identical to the depth of water to be replaced by irrigation under normal management. For this reason, the idea of moisture deficit in the root zone is preferable to the commonly used concept of depth of water currently in the soil. Knowledge is needed of how dry the soil moisture tension at that *SMD* and how well the crop will grow under that stress, to monitor soil moisture to determine when to irrigate and how much water to apply. Applying too much water causes excessive runoff and/or deep percolation. As a result, valuable water is lost along with nutrients and chemicals, which may leach into the ground water. The "feel and appearance method" is one of several irrigation scheduling methods used in Irrigation Water Management (IWM) to measure the *SMD*.

Management allowed deficit (*MAD*) is the desired *SMD* at the time of irrigation. It is an expression of the degree of dryness that the manager believes the plants in a given area can tolerate and still produce the desired yield. The *MAD* is related to *SMD* and resulting crop stress. It may be expressed as the percent of the total available soil moisture in the root zone or the corresponding depth of water that can be extracted from the root zone between irrigations to produce the best economic balance between crop costs and returns of irrigation. The irrigator must carefully estimate the *SMD*; if it is the same as *MAD* or greater, the soil is dry enough to start irrigating.

APPENDIX B

MODEL INPUTS AND GRAPHICAL RESULTS

1. Model Inputs

Table B-1 below includes all questions (i.e., inputs) the users are asked to enter to run the model. Cells shaded in grey are designated for a better visual perception: [enter] stands for the entered input, [calculated] is for displayed automatic computation, [choose from a dropdown menu] gives an option to choose from a dropdown menu with fixed inputs, and [automatically picked] displays default values corresponding to the system chosen from the dropdown menu. Because sometimes the default values may not characterize an irrigation system, the users are given a choice to enter the actual values – those options are *italicized.*

Table B-1. Section 1: Inputs of the model

1	Field area	[enter]	(acres)
2	Season irrigation requirement	[enter]	(depth, inches)
3	Analysis period	[enter]	(years)
4	Annual water right cost	[enter]	($)
	What would you like to do? - upgrade an existing system (Go to Q5) - convert to a new system (Go to Q25)		
	Existing irrigation system upgrade		
5	Your existing irrigation system	[choose from a dropdown menu]	(see the reference list with assumptions below)
	Or enter your system:	[enter]	
6	Corresponding DU	[automatically picked]	(see the reference list with assumptions below)
	Or enter your value:	[enter]	(decimal)
7	Corresponding IE	[automatically picked]	(see the reference list with assumptions below)
	Or enter your value:	[enter]	(%)

Table B-1 (continued)

Farming costs (annualized)

8 Type in what you would like to purchase/upgrade:

Component	Qnty	Initial cost ($)	Useful life (yrs)	Salvage value ($)

	Total purchase costs:	[calculated]	
9	Annual interest rate	[enter]	(decimal)
10	Maintenance and Repair	[enter]	($)
11	Labor costs	[enter]	($)
12	Additional labor costs (<u>leave blank if does NOT apply</u>)		
	Additional time per move	[enter]	(min/move)
	Moves per week	[enter]	(moves/week)
	Weeks per season	[enter]	(weeks/season)
	Labor costs per hour	[enter]	($/hour)
	Or enter your value:	[enter]	($/hour)
13	Taxes and insurance	[enter]	($)
	(By default, 2% of initial costs of components)		
14	Other costs	[enter]	($)
15	Expected annual rate of escalation	[enter]	(decimal)

	Electric pump costs			**Fuel pump costs**		
16	*Demand charge*			*Fuel charges*		
	Cutoff:	[enter]	(kW)	Cost/gallon	[enter]	($)
	Cost < Cutoff:	[enter]	($/kW)	Energy/gallon	[enter]	(BTU/gal)
	Cost > Cutoff:	[enter]	($/kW)			
17	*Energy charge*					
	Cutoff:	[enter]	(kW)			
	Cost < Cutoff:	[enter]	($/kW)			
	Cost > Cutoff:	[enter]	($/kW)			

	System		
18	Operating pressure	[enter]	(psi)
19	Flow rate	[enter]	(gpm)
20	Water lift and friction losses	[enter]	(feet)
	<u>OR</u> Total dynamic head (TDH)	[enter]	(feet)
	Motor and pump characteristics		
21	Engine/motor efficiency	[enter]	(%)
22	Pump efficiency	[enter]	(%)
23	Power transmission efficiency	[enter]	(%)
24	Motor horsepower (MHP)	[enter]	(HP)

Table B-2 summarizes default values (assumptions) for various irrigation systems, obtained by performing evaluation as described in Chapter 2. All values given in this table are averaged data of DU and IE values obtained both during fieldwork in the summer of 2007 and the summer of 2001 (research by Cal Poly).

Table B-2. Assumptions of DU and IE for various irrigation systems

Irrigation systems to choose:	DU values:	IE values:
Buried drip	0.90	95
Center pivot	0.85	85
Drip	0.90	90
Hand-line	0.75	70
Micro sprayers	0.90	90
Overvine	0.70	68
Solid set	0.75	75
Surface	0.60	35
Undertree	0.75	75
wheel-line	0.75	70

2. Additional Graphical Results

Some additional graphs that were not included in Chapter 3 are shown below.

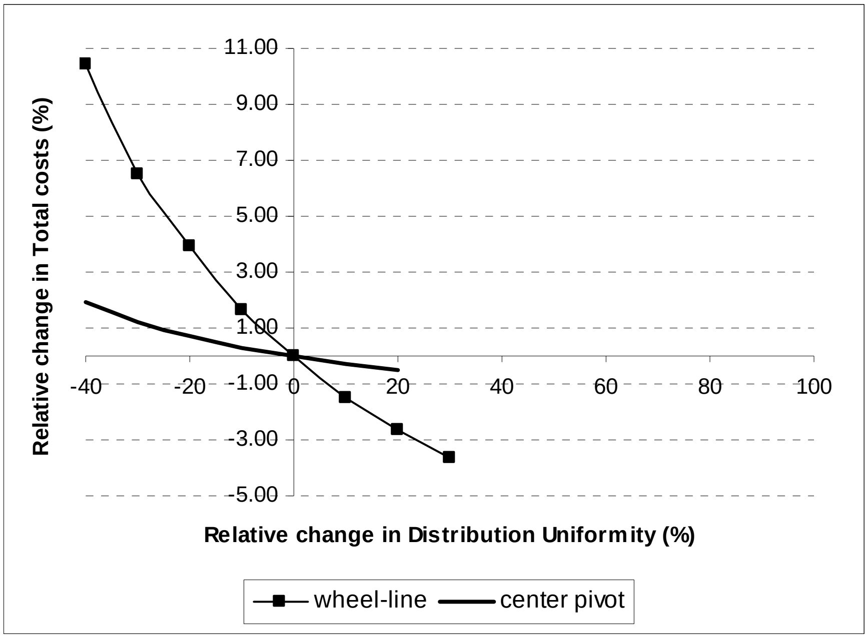

Figure B.1. Sensitivity of *Total costs* to *DU* for wheel-line and center pivot, both with fuel pumps

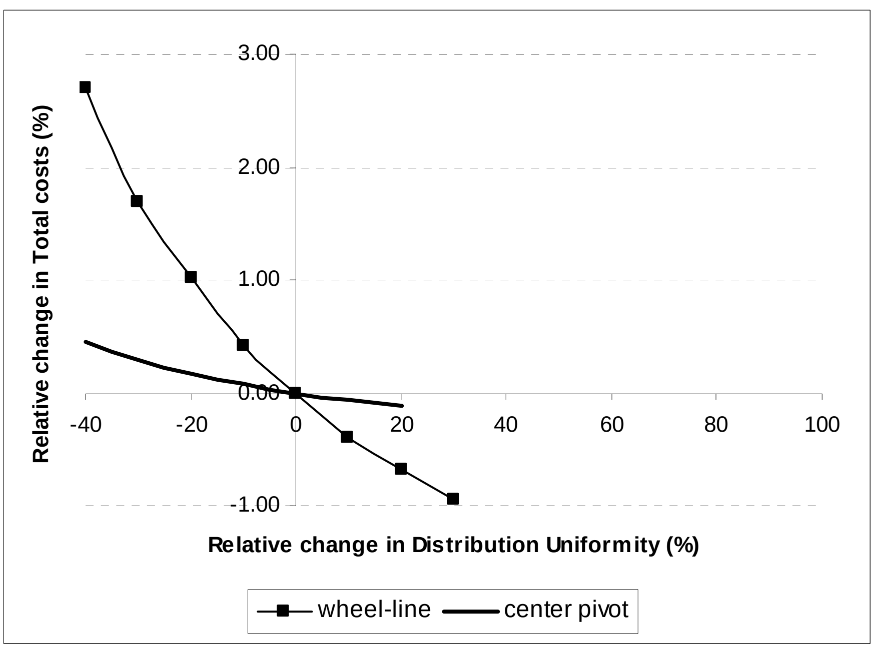

Figure B.2. Sensitivity of *Total costs* to *DU* for wheel-line and center pivot, both with electric pumps

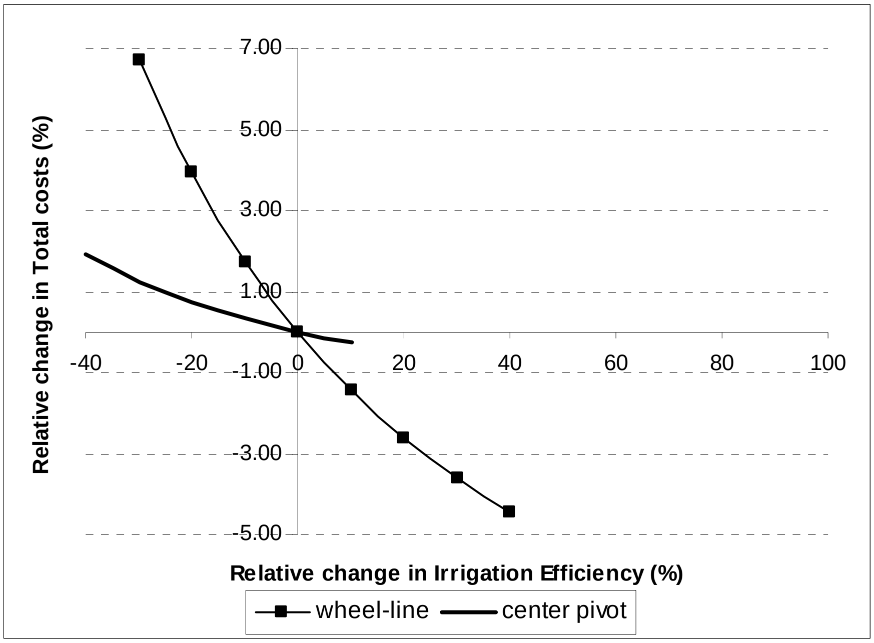

Figure B.3. Sensitivity of *Total costs* to *IE* for wheel-line and center pivot, both with fuel pumps

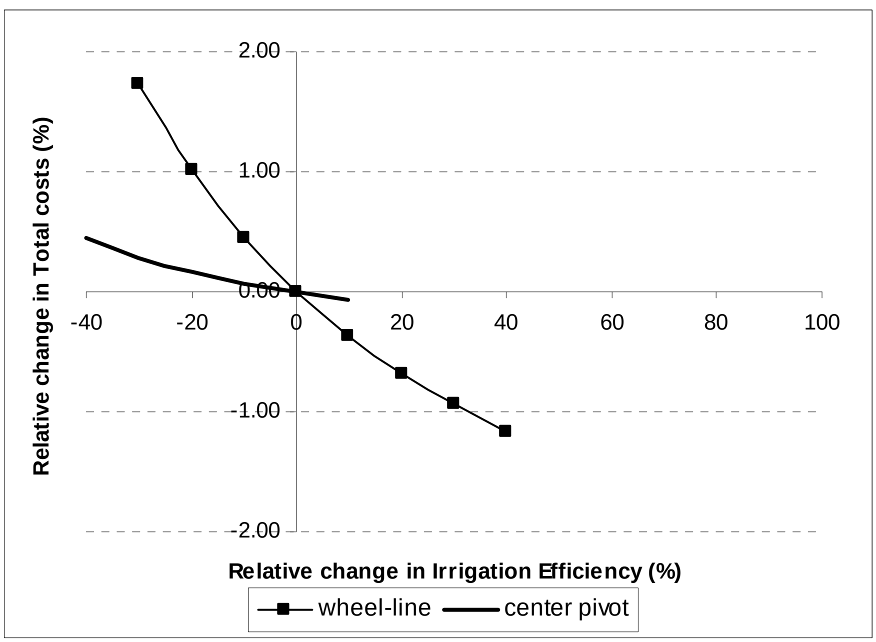

Figure B.4. Sensitivity of *Total costs* to *IE* for wheel-line and center pivot, both with electric pumps

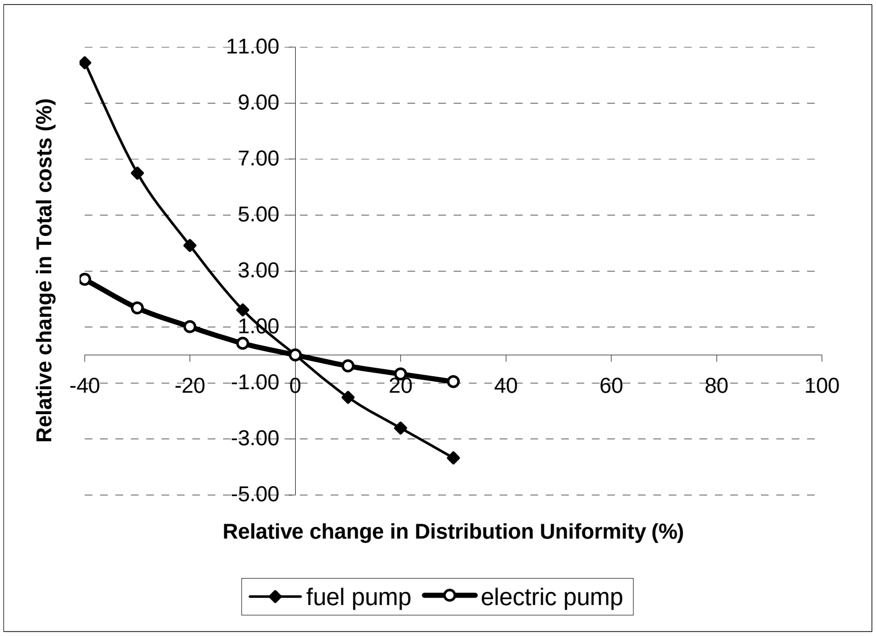

Figure B.5. Sensitivity of *Total costs* to *DU* for wheel-line with fuel pump and electric pump

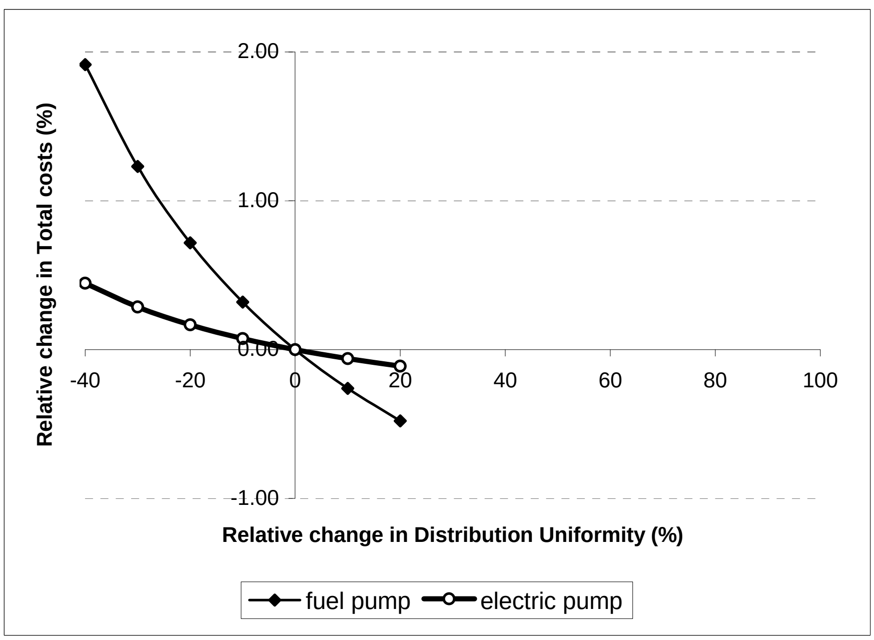

Figure B.6. Sensitivity of *Total costs* to *DU* for center pivot with fuel pump and electric pump

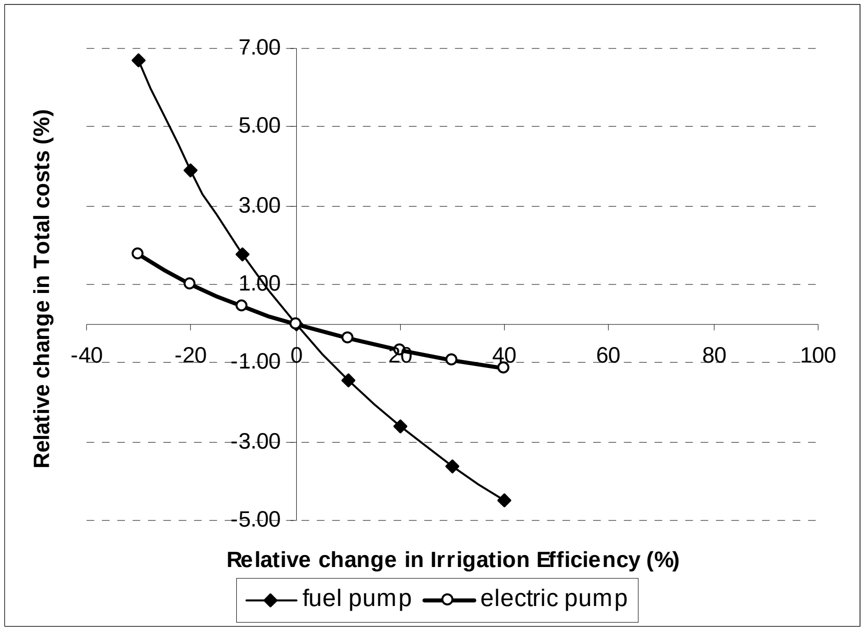

Figure B.7. Sensitivity of *Total costs* to *IE* for wheel-line with fuel pump and electric pump

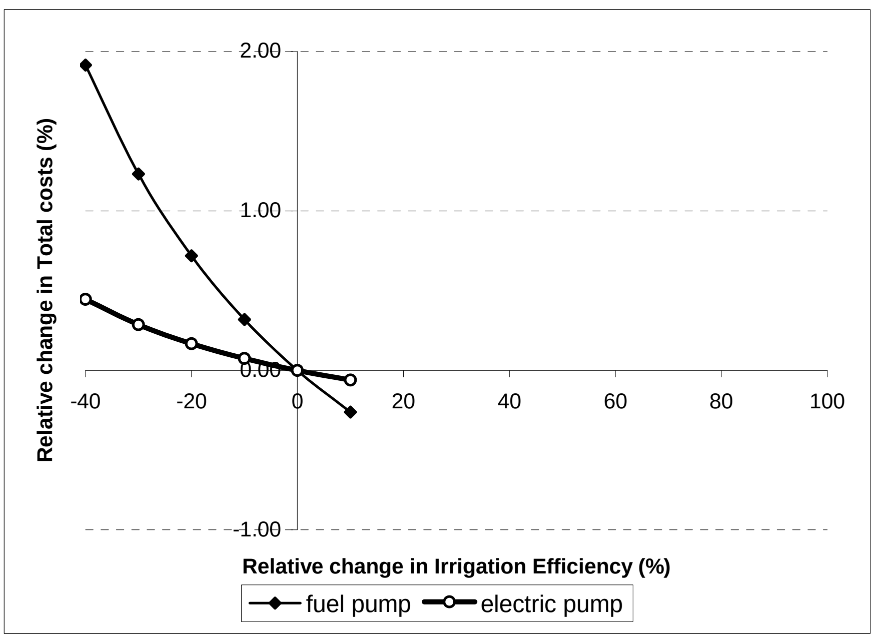

Figure B.8. Sensitivity of *Total costs* to *IE* for center pivot with fuel pump and electric pump