A Knowledge Based System for Irrigation Planning in Virginia

by

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Thesis submitted to the Faculty of the
Virginia Polytechnic Institute and State University
in partial fulfillment of the requirements for the degree of
Master of Science
in
Agricultural Engineering

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July 5, 1990
Blacksburg, Virginia
LD 5655
WB 55
1990
K852
C. 2
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(ABSTRACT)

Problems associated with irrigation in humid regions include uncertainty of whether irrigation will be necessary in a given year, and the question of whether crop response will be sufficient to make the required investment profitable in the long run. A prototype knowledge based system (KBS) has been developed to determine the economic feasibility of a range of irrigation systems for site specific conditions. The KBS uses information input by the user to determine possible irrigation alternatives and provides an economic evaluation of suitable systems based on domain-specific knowledge about soils, crops, irrigation costs, and agricultural drought in Virginia. Irrigation systems considered by the KBS include center-pivot, traveling gun and portable pipe systems. Crops considered are field corn, soybeans, and peanuts.

Preliminary evaluation showed that the KBS was able to effectively determine if portable pipe, traveling gun and center pivot irrigation systems were suitable, and provide an economic evaluation of these systems for site specific situations in Virginia. The KBS developed in this study provides a basic framework which can be used to build a more comprehensive system which would address a larger domain, considering additional systems and crops.
Acknowledgements

I am grateful to Dr. T. A. Dillaha for his guidance during my M.S program. I would like to thank Dr. C. D. Heatwole for his help and guidance throughout the course of this study. Grateful acknowledgement is extended to Dr. B. B. Ross who gave so generously of his time and whose expertise in irrigation provided me with insights into the irrigation planning process. Drs. D. B. Taylor and P. W. Weckler provided helpful comments.

Thanks are extended to Jeaan, Vijay, Sebastian and Marcel for their help in evaluating the user-interface. To my parents, sister and brother, whose love and affection have tided me over many difficult times, I will always owe a debt of gratitude.
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INTRODUCTION

Background

One of the most significant risk factors in agriculture is weather. Seldom is rainfall adequate to obtain optimum crop production - even in humid areas. Irrigation aims to achieve a high standard of production over the growing season of a crop, irrespective of rainfall availability. The real value of irrigation is not so much in preventing a total crop loss as in getting the maximum return on investment by optimizing crop yields (Turner and Anderson, 1980). Irrigation increases yields in four main ways:

- Assures a better stand.
- Allows higher plant populations.
- Improves efficiency of fertilizer use.
- Allows planting of improved varieties developed for use with irrigation.

The extent of irrigation in Virginia has been measured by various surveys and studies. Taylor et al. (1985) report that these efforts have attempted to catalog irrigation development by system use during the time of the survey and fluctuations in the reported figures parallel the general climate at the time of the survey. They attribute this fluctuation, in part, to labor intensive systems not being used significantly during wetter than average growing seasons. Ross et al. (1982) reported that the irrigated area in Virginia increased from 12,800 hectares (32,000 acres) to 32,800 hectares (82,000 acres) over the period 1962-1982. Table 1 shows the
irrigated area in Virginia from 1983 to 1989. The decrease in irrigated area in 1989 can be largely attributed to the fact that it was an extremely wet year.

Ross et al. (1982) state that although irrigated cropland constitutes only a small percentage of Virginia’s total cropland, it contributes a proportionally larger share of the total value of Virginia’s agriculture. They also state that increased competition from other Southeastern states and economic necessity in many cases will create pressures on producers in Virginia to investigate irrigation possibilities. Problems of irrigation in humid regions include uncertainty of whether irrigation will be necessary in a given year, and the question of whether crop response to irrigation will be sufficient to make the required investment profitable in the long run (Lea, 1985). Taylor et al. (1985) developed a methodology for assessing the economic feasibility of large scale riparian irrigation systems in Virginia, considering agronomic and engineering constraints. Application of the method to the Pamunkey river area in the Hanover and King William counties of Virginia identified many feasible sites for irrigation expansion.

Excellent guides are available to assist in irrigation planning (Turner and Anderson, 1980; USDA, 1976; Veltidis, 1985). However, it is unlikely that the typical farmer/extension agent interested in irrigation development would initially have all the information needed to effectively use the guides. It is also unlikely that they would have the expertise to evaluate the economic feasibility of irrigation systems. Consequently, there is a need for a system which provides preliminary or ‘first-cut’ information about suitable irrigation systems, including an economic evaluation of these systems, for a given site-specific situation in Virginia. In the context of this study, an irrigation system is said to be suitable for a given site-specific situation if engineering/agronomic constraints do not prevent its use. Engineering constraints refer to factors such as area to be irrigated, field slope, and field shape. Agronomic constraints refer to factors such as crop type and soil characteristics.

Bennett et al. (1988) point out that the planning of irrigation development requires both expert and analytical evaluations. One means of employing both analytical and expert evaluations when planning an irrigation development is through the use of Knowledge Based Systems (KBSs), also known as Expert Systems (ESs). McKinlon et al. (1985) define an ES as

**INTRODUCTION**
Table 1. Irrigated area in Virginia, 1983-1989 (Ross, 1990).

<table>
<thead>
<tr>
<th>Year</th>
<th>Irrigated Area (hectares)</th>
</tr>
</thead>
<tbody>
<tr>
<td>1983</td>
<td>34,000</td>
</tr>
<tr>
<td>1984</td>
<td>35,000</td>
</tr>
<tr>
<td>1985</td>
<td>36,200</td>
</tr>
<tr>
<td>1986</td>
<td>33,920</td>
</tr>
<tr>
<td>1987</td>
<td>33,680</td>
</tr>
<tr>
<td>1988</td>
<td>33,900</td>
</tr>
<tr>
<td>1989</td>
<td>30,900</td>
</tr>
</tbody>
</table>
a computer program capable of carrying out reasoning and analysis functions in a narrowly
defined area at proficiency levels approaching that of a human expert.

Objectives of Study

The overall project objective was to develop a KBS to provide preliminary information
on suitable irrigation systems and an economic evaluation of these systems for site-specific
situations in Virginia. The preliminary information would include a short description of suitable
systems and a summary of their water and labor requirements. The economic evaluation
would assess the feasibility of the system, that is, whether the average, long-term returns from
the irrigation system exceed the returns under dryland production. Irrigation systems to be
included in the KBS are the three major systems in Virginia: center pivot, traveling gun (hose
tow) and portable pipe. The KBS will consider selected crops (field corn, soybeans, and pean-
nuts) for which yield and cost of production figures are readily available. The specific objec-
tives are:

1. Develop a KBS to determine suitable irrigation alternatives and provide an economic
evaluation of these systems for site specific situations in Virginia.

2. Assemble crops, soils, and agricultural drought databases required by the KBS.

3. Evaluate the KBS by running a range of sample scenarios through it and have the results
   assessed by an expert.

4. Carry out a sensitivity analysis of the irrigation cost models to identify input parameters
   that have the greatest effect on model output.
The KBS developed in this study will allow the inclusion of additional crops and irrigation systems. In an expanded form, the KBS will be suitable for use by farmers and/or extension agents exploring irrigation development in Virginia.
LITERATURE REVIEW

Irrigation Systems in Virginia

Farm irrigation systems can be classified based on the way water is applied to the soil. A common classification (Thompson et al., 1980) is to divide systems into:

- **Surface irrigation methods**: where small open channels or overland flow is used to distribute the water over a cropped field.
- **Sprinkler irrigation methods**: where water is distributed serially to the cropped field.
- **Trickle irrigation methods**: where small point applicators are used to apply the water.
- **Subsurface irrigation methods**: where water is supplied to the root zone by artificially regulating the groundwater table elevation or by applicators which apply the water below the soil surface.

Sprinkler irrigation accounts for about 90% of the total irrigated area in Virginia - the rest being irrigated by trickle methods. Recently, there has been some interest in subsurface irrigation in the Coastal Plain region of Virginia. Table 2 shows the irrigated area in Virginia by system and crop. Three types of sprinkler irrigation systems (center pivot, traveling gun and portable pipe) account for 85% of the total irrigated area. A brief review of these systems based on the descriptions provided by Taylor et al. (1985) follows. Detailed descriptions of these and other systems may be found in Carl and Anderson (1980), Jensen (1980), and Cuenca (1989).
Table 2. Irrigated area in Virginia by system and crop (Ross, 1990).

<table>
<thead>
<tr>
<th>Irrigation system</th>
<th>Area (hectares)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Sprinkler</td>
<td></td>
</tr>
<tr>
<td>Center pivot</td>
<td>8,800</td>
</tr>
<tr>
<td>Portable pipe</td>
<td></td>
</tr>
<tr>
<td>Medium pressure</td>
<td>4,800</td>
</tr>
<tr>
<td>High pressure</td>
<td>4,800</td>
</tr>
<tr>
<td>Traveling gun</td>
<td>8,000</td>
</tr>
<tr>
<td>Towline/Side roll/Lateral</td>
<td>1,000</td>
</tr>
<tr>
<td>Solid set</td>
<td>300</td>
</tr>
<tr>
<td>Trickle</td>
<td>3,200</td>
</tr>
<tr>
<td>Crop</td>
<td></td>
</tr>
<tr>
<td>Corn</td>
<td>8,000</td>
</tr>
<tr>
<td>Cotton</td>
<td>100</td>
</tr>
<tr>
<td>Pasture/Hay crops</td>
<td>400</td>
</tr>
<tr>
<td>Peanuts</td>
<td>400</td>
</tr>
<tr>
<td>Potatoes</td>
<td>4,000</td>
</tr>
<tr>
<td>Small fruits/nuts</td>
<td>1,000</td>
</tr>
<tr>
<td>Soybeans</td>
<td>1,200</td>
</tr>
<tr>
<td>Tobacco</td>
<td>8,800</td>
</tr>
<tr>
<td>Tree fruits</td>
<td>1,200</td>
</tr>
<tr>
<td>Vegetables</td>
<td>5,800</td>
</tr>
</tbody>
</table>
Center Pivot

The center pivot system consists of sprinklers mounted on a single lateral arm which moves in a circular motion. The lateral is usually of painted or galvanized steel pipe connected by flexible couplings. The lateral is anchored at one end in the center of the field to a swivel joint (called the center pivot) and supported by an under-truss system and towers which are made mobile by wheels. The span between towers varies from 30-60 m (100-200 ft) and the length of the lateral may be as much as 790 m (2630 ft). The lateral rotates continuously about the center pivot when irrigating, wetting a circular area of up to 200 hectares (500 acres) - depending on the length of the lateral. Water is supplied at the center pivot from a well located at the center of the field or from a mainline supply. As sprinklers toward the pivot center cover much less field area than the ones toward the outer end, sprinklers at the outer end are either increased in size or placed closer together. Although early center pivots used medium pressure (operating at about 345 KPa or 50 psi) or high pressure (operating at about 480 KPa or 70 psi) sprinklers, most systems now use low pressure spray heads (operating at about 210 KPa or 30 psi). The lateral is driven by power units at each tower, which allows each tower to travel at different speeds, thus ensuring that the lateral rotates uniformly and in a straight line. Figure 1 shows a schematic of the field layout for a center pivot system.

Center pivot systems may be adapted to irrigating the corner areas of a square field either with large end guns or corner systems. Large end guns are pre-set to operate when the lateral is travelling past the corner. Corner systems essentially consist of a retractable arm on the end of the center pivot which can move automatically along the boundaries of an irregularly shaped field. Both end gun and corner attachments on center pivot systems generally require less investment, per additional unit area, than the basic system.

Especially adaptable to the irregularly shaped fields in Virginia, is the towable center pivot. This system is essentially towed to a pivot point by a farm tractor, the circle pattern irrigated, and then towed to an adjacent pivot point for additional irrigation. In this manner, long
Figure 1. Field layout for a center pivot system.
narrow fields can be irrigated, although labor requirements are increased over the fixed center pivot system. Two moves (three pivot points per system) is the generally accepted maximum for effective irrigation management. Equipment costs for towable center pivot systems are usually less than for fixed center pivot systems because additional area is being covered by a smaller system. However, towable center pivot systems require more mainline pipe.

**Traveling Gun**

The traveling gun, (hose-pull) irrigation system consists of a single big gun sprinkler mounted on a moving cart which irrigates rectangular strips, 45-105 m (105-350 ft) wide and up to 420 m (1400 ft) long. Water is fed to the big gun, and the gun cart itself is towed, by a flexible polyethylene 5-13 cm (2-5 in) inside diameter hose. The hose is stored on, and unwound from, a moveable reel, mounted on a trailer. When preparing to irrigate, the unit is moved into position, and the gun cart and hose are pulled to the starting point by a farm tractor. During irrigation, the unit automatically pulls the gun cart back to the reel while winding the hose with an auxiliary engine, water turbine or water piston. The unit is then repositioned to irrigate another rectangular strip. Figure 2 shows a schematic of the field layout for a traveling gun system.

Energy requirements for the traveling gun system are high. The pressure requirements of a big gun are on the order of 590 KPa (85 psi), and high flow velocities in the usually undersized polyethylene lateral hose result in high friction losses.

**Portable Pipe**

The portable pipe system is a hand moved system of risers and sprinklers connected by quick coupling lateral piping and submains. Based on design characteristics and field condi-
Figure 2. Field layout for a traveling gun system.
tions, a given arrangement of laterals and sprinklers, or set, must be available to be moved around the field. A portion of the total area is irrigated by each set for an established duration, and the entire area irrigated within the total time allowed for completing the irrigation cycle. Figure 3 shows a schematic of the field layout for a portable pipe system with two laterals. The number of laterals depends on the design characteristics of the system.

Portable pipe systems may be medium pressure or high pressure. The sprinklers in medium pressure systems operate at about 345 KPa (50 psi), while the sprinklers in high pressure systems operate at about 480 KPa (70 psi). The high pressure portable pipe system (also known as a stationary big gun system) allows wider sprinkler spacings and results in less in-field equipment. Although the labor requirements for the high pressure system are considerably less than for the medium pressure system, the energy requirements are substantially higher.

**Irrigation Planning**

Numerous considerations influence a crop producer's attitude toward irrigation. The decision to convert from nonirrigated to irrigated farming requires evaluation of many factors (Vellidis et al., 1985). Thompson et al. (1980) state that the planning process for selecting a farm irrigation system requires an inventory of the resources available to the farmer. The evaluation of these resources is necessary to identify the production potentials, and the physical and operational constraints which affect the selection of viable alternative farm irrigation systems. Thompson et al. (1980) identify the following factors for evaluation to determine viable irrigation systems for a given farm:

- Farm water supply: sources, water quantity and quality.
Figure 3. Field layout for a portable pipe system.
• Soils: soil texture, soil structure, soil profile/depth, soil salinity, drainage, topography and erodibility factors.
• Climate-crop-system interactions: the irrigation system selected must be applicable to the crops to be grown, as well as the physical constraints of the farm.
• Capital and labor: available capital, available labor and technical skill.
• Energy: energy availability and energy requirements.

Once suitable systems have been determined, it is necessary to carry out an economic feasibility evaluation. Kibler et al. (1981) remark that the irrigation of crops in humid regions is ultimately constrained by the question of economic feasibility. The economic feasibility evaluation assesses the economic viability of the planned development and assists in selecting a specific farm irrigation system from among adaptable alternatives; that is, it establishes the justification for irrigation development (Thompson et al., 1980).

**Knowledge Based Systems**

Knowledge based systems are the most widespread application of artificial intelligence research. Schmoldt et al. (1986) reported that there were more than 150 ESs being used or under development. Batchelor and McClendon (1989) have described several KBSs developed for agricultural applications. Rolston (1988) characterizes ideal KBSs as including the following:

• Extensive specific knowledge from the domain of interest.
• Application of search techniques.
• Support for heuristic knowledge.
• Capacity to infer new knowledge from existing knowledge.
• Symbolic processing.
• An ability to explain its own reasoning.

A KBS is typically composed of three basic elements (Walters and Nielsen, 1988):

• The knowledge base, containing the expert’s factual and relationship knowledge represented in one or more different ways.
• A knowledge-independent inference engine, containing instructions to reason with the information contained in the knowledge base.
• A group of interfaces, connecting the inference engine to the user, external databases, and to external programs.

Rolston (1988) and Walters and Nielsen (1988) describe several techniques for knowledge representation. Production rules are the most commonly used scheme. A production rule consists of a series of condition elements and an action portion. The condition elements of the rule describe the conditions that must be true for the rule to be applicable and the action portion describes the actions to be taken when the rule executes.

Knowledge acquisition is the collection and analysis of information from one or more domain experts and other sources leading to the production of a number of documents which form the basis of a functioning knowledge base (Greenwell, 1988). The reader is referred to Hart (1985) and Greenwell (1988) for information on knowledge acquisition techniques.

Knowledge base verification refers to the testing of the knowledge base, or rule set, for consistency and completeness (Hayes-Roth, 1985). Nguyen et al. (1987) discuss potential problems that may lead to inconsistencies or incompleteness in the knowledge base. They also describe an algorithm for knowledge base verification.

An important aspect of KBS development is validation. O’Keefe et al. (1988) state that validation refers to substantiating that the system performs with an acceptable level of accuracy. They discuss problems that may arise in validation and present qualitative and quantitative methods for validation of KBSs.
One of the main reasons for the rapid growth in the rate of KBS development is the support of a rich set of powerful development tools (Rolston, 1988). According to Gevarter (1987), development tools make it possible to develop a KBS in an order of magnitude less time than would be required with the use of computer languages traditionally used for KBS development. Gevarter (1987) reviews the capabilities that make development tools such an asset and discusses various commercially available tools in terms of their incorporation of these capabilities.

Bennett et al. (1988) developed an ES for the planning and design of irrigation systems for conditions found in the Piedmont and Coastal Plain regions of North Carolina. Their approach was to develop a system to be used as a teaching tool in irrigation design while also serving as a means to supply farmers and other end users with relevant data and information necessary in planning and evaluating an irrigation system for their particular needs. However, their ES does not evaluate the economic feasibility of irrigation systems.

Hart et al. (1989) developed two ESs for the selection of irrigation systems appropriate to conditions in Arizona. The first ES uses user input to rate irrigation systems from the most favorable to the least favorable. The second ES analyzes input information and recommends either the most appropriate system or several systems which seem to be equally appropriate. The ESs are strictly for system selection and do not contain components for design or economic evaluation.
KNOWLEDGE BASE

The knowledge base structure and information flow is illustrated in Figure 4. The knowledge base has three major components:

- A rule-base for obtaining site-specific information, for determining suitable irrigation systems, and for controlling information flow.
- Databases for providing soils, crops, and drought information.
- Irrigation cost models for determining average annual costs of irrigation for different systems.

Dr. B. B. Ross, irrigation specialist in the Department of Agricultural Engineering at Virginia Polytechnic Institute and State University provided the expertise for the study. He gave extensive support through personal interviews and provided access to relevant irrigation literature.

Rule Base

The rule-base was developed using the LEVEL5 Expert System Development Tool (Information Builders, Inc., New York), running under the MS-DOS operating system. LEVEL5 has a built-in inference engine with the capability of interfacing with external programs and database files. The rule-base contains over 400 rules written in Production Rule Language (PRL),
Figure 4. Knowledge base structure and information flow.
the application development language of LEVEL5. PRL uses 'IF(condition)....THEN(conclusion)'
rules as the basic construct for knowledge representation. These rules, together with a set of
PRL statements and operators, make it possible to develop a rule-base for an application in
a relatively short time. The rule-base, when processed by the LEVEL5 inference engine que-
ries the user through a customized user interface, evaluates rules to establish conclusions,
accesses external databases, and executes external programs.

The rule-base provides a framework for controlling information flow, accessing data-
bases, and running external programs. It requires the LEVEL5 development system to run.
The present rule base was written so that it can be easily expanded to include other crops
and/or irrigation systems. Crops currently included are corn, soybeans, and peanuts. Irri-
gation systems currently evaluated are center-pivot, traveling gun, and portable pipe. LEVEL5
allows modular development of the rule-base and partitioning of the domain knowledge into
separate rule-bases that are chained together. A discussion of the six PRL files that make
up the rule-base follows.

**Input information (FILE1.PRL)**

A flow chart of the rule-base in FILE1 is given in Figure 5. The rule-base in FILE1 has two
functions. First, it displays the input information that will be required during an interactive
session, and if the user wants additional information on input requirements, this is also dis-
played. The rule-base then prompts for the user's county name which is used to determine the
geographical area to be used when obtaining agricultural drought information.
Figure 5. Flow chart of rule-base for input information (FILE1).
Agronomic Analysis (FILE2.PRL)

A flow chart of the rule-base in FILE2 is given in Figure 6. The rule-base first prompts the user for the major soil type in the area to be irrigated. The soil databases are then accessed to obtain information on available water capacity, infiltration rate, and whether drainage is necessary for the soil to be suitable for irrigation. If the major soil type is not known, the user is presented with a textural description of soils and asked to select the description that best fits the soil. The required soil information for these generic soil groups are coded in the rules. If artificial drainage is necessary for the soil the user is asked if a drainage system already exists in which case no drainage costs are added to the capital cost of the irrigation development. If a drainage system does not exist, the user is asked if the cost of providing drainage is to be input - if not, a default value is used.

The rule-base then prompts the user for the crop to be grown. The crop databases are accessed to obtain information on growing season, peak consumptive use, and root zone depth. The user may input values for dryland/irrigated yields and cost of production, otherwise default values in the database are used. If the user selects the ‘Crop not listed’ option, the crop databases are not accessed and the the user is prompted for all required crop information.

The user is then prompted for the area to be irrigated, the average slope of the area, and maximum/minimum crop prices expected in a dry (1 in 10 year drought) and a normal (5 in 10 year drought) year, and annual interest rate. The rule-base finally checks to see if clearing costs are to be included in the capital cost of irrigation development.
Figure 6. Flow chart of rule-base for agronomic analysis (FILE2).
Drought Days Determination (FILE3.PRL)

A flowchart of the rule-base in FILE3 is given in Figure 7a. The rule-base in FILE3 does not require any user interaction. The rule-base accesses the drought days database and obtains the long-term, average number of drought days expected in a 'dry' (1 in 10 year drought) and a 'normal' (5 in 10 year drought) season. A 'drought day' is defined as one in which soil moisture is depleted to the extent that crop growth is adversely affected, and irrigation becomes desirable. The number of drought days depends on the irrigation basis (depth of water to be replaced at each irrigation), geographical location in Virginia, and growing season of the crop. The irrigation basis is computed as follows:

$$d_s = AWC \times RZD \times TP$$  \hspace{1cm} (1)

where:

- $d_s =$ basis, or net depth of irrigation, mm (in)
- $AWC =$ available water capacity of soil, mm/m (in/in)
- $RZD =$ root zone depth of crop, m (in)
- $TP =$ trigger point in decimal notation

The trigger point refers to the amount of plant available water allowed to be depleted from the root zone depth, expressed as a fraction, before lack of soil moisture is considered sufficient to cause undue plant stress. The trigger point may vary according to the soil type, crop, and irrigation system. Generally, it is assumed constant across all soils and crops and is varied only for different irrigation systems. For sprinkler systems, a value of 0.5 is considered satisfactory, while a lower value (e.g. 0.25) is used for trickle systems which are designed for more frequent, smaller application depths. The rule-base obtains dry and normal season drought days for values of irrigation basis calculated using both 0.5 and 0.25 as trigger points. Since drought days are only available for integer values of $d_s$, to obtain the drought days for any non-integer value of $d_s$, the database is accessed twice to obtain the drought days for $d_s$. 
equal to the two integer values closest to the non-integer value, and linear interpolation is employed to obtain the actual number of drought days as follows:

\[ D_r = D_j + (D_{j+1} - D_j)(r - j) \]  

where:

- \( r \) = any non-integer value of basis
- \( j \) = nearest integer value of basis smaller than \( r \)
- \( D_r \) = number of drought days for basis \( r \)
- \( D_j \) = number of drought days for basis \( j \)
- \( D_{j+1} \) = number of drought days for basis \( j+1 \)

**System Selection (FILE4.PRL)**

A flowchart of the rule-base in FILE4 is given in Figure 7b. The rule-base determines suitable irrigation systems based on the area to be irrigated, infiltration rate, and field slope and shape. The criteria used for determining system suitability are given in Table 3. The field shape criterion is used to determine which types of center pivot systems are suitable from the fixed, two-point and three-point towable systems. If the field is square, the towable systems are eliminated. If the field is rectangular, the rule-base prompts the user for the field dimensions, and depending on the length to width (L/W) ratio, selects either the fixed center pivot (L/W < 1.5), two-point towable (1.5 \( \leq \) L/W \( \leq \) 2.5), or three-point towable (L/W > 2.5). For irregularly shaped fields, all three center pivot systems are considered and the rule-base prompts the user for the diameters of the biggest single, biggest two, and biggest three circles that would fit in the field.
Table 3. Irrigation system selection criteria.

<table>
<thead>
<tr>
<th>Irrigation system</th>
<th>Maximum slope (percent)</th>
<th>Minimum required soil intake rate (mm/h)</th>
<th>Minimum area (ha)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center pivot</td>
<td>20</td>
<td>5</td>
<td>4</td>
</tr>
<tr>
<td>Traveling gun</td>
<td>10</td>
<td>6</td>
<td>4</td>
</tr>
<tr>
<td>Portable pipe</td>
<td>20</td>
<td>3</td>
<td>N/A</td>
</tr>
</tbody>
</table>

N/A: Not applicable, no minimum area
Figure 7. Flow chart of rule-base for a) drought days determination (FILE3), b) system selection (FILE4).
Engineering Factors (FILE5.PRL)

A flowchart for the rule-base in FILE5 is given in Figure 8. The rule-base computes the pumping demand (system capacity), total labor and water requirements (for both normal and dry seasons) for all suitable systems, using the following expressions:

\[ D_i = \frac{d_b}{C_u} \]  

\[ d_s = \frac{d_b}{E_s} \]  

\[ T_i = D_i N_h \]  

\[ Q_s = \frac{K d_a A}{T_i} \]  

\[ CPS = \frac{D_d}{D_i} \]  

\[ W_i = d_s \times A \times CPS \]  

\[ L_n = I_1 \times A \times CPS \]

where:

- \( D_i \) = days per irrigation cycle  
- \( C_u \) = crop consumptive use, mm/day (in/day)  
- \( d_s \) = gross depth of irrigation, mm (in)  
- \( E_s \) = system efficiency, decimal notation  
- \( T_i \) = time per irrigation cycle, hr  
- \( N_h \) = number of irrigation system operating hours per day  
- \( Q_s \) = system capacity, l/s (gpm)
\[ K = \text{constant for consistent units, 0.0028 (453)} \]

\[ A = \text{area to be irrigated, hectares (acres)} \]

\[ CPS = \text{number of irrigation cycles per season} \]

\[ D_s = \text{number of drought days in season} \]

\[ W_t = \text{total water requirements, hectare-mm (acre-in)} \]

\[ L_n = \text{total labor requirements for season, hours} \]

\[ l_1 = \text{labor requirements for irrigation system per unit area per irrigation cycle, hours} \]

The user is asked if labor requirements for an irrigation system are a critical factor (that is, whether the user is limited to a maximum labor supply). If so, the user is asked to enter the maximum labor expected to be available per week (for operating the irrigation system) over the growing season. The maximum available labor is compared to the labor requirements for each system. Irrigation systems which have a higher labor requirement in a normal season than that available are eliminated. However, irrigation systems for which adequate labor is not available only during dry years are still considered and a warning displayed in the output for this system.

The user is then asked if water from an existing source is to be used. If not, the cost of developing the water source is included in the capital cost of all feasible irrigation systems. The user may input a value for the cost of developing the water source (per hectare-mm or acre-foot), otherwise a default value is used. If a water source does exist, the user is asked if any estimate of the maximum allowable extraction rate (if the source is a stream or a well) or maximum available storage (if the source is a pond) is available. If no estimate is available, the extraction rate or available storage is assumed sufficient for all systems. However, the user is advised that since water source development costs may represent a significant part of the total capital costs, the allowable extraction rate/available storage should be obtained in the event that additional storage is required. If requested by the user, the rule-base will provide instructions on how to obtain this information.

If an estimate of the allowable extraction rate/maximum available storage is available, an external FORTRAN routine is activated to check if the available extraction rate/total storage
Figure 8. Flow chart of rule base for engineering factors (FILE5).
Figure 9. Flow chart of routine for water source assessment.
is sufficient for all systems that have been determined to be feasible. A flowchart of the routine is given in Figure 9. Available total storage is compared with the requirements in a dry year. If the extraction rate/total water requirements for one or more systems is not being met, the routine asks the user if he/she is willing to consider the cost of providing additional storage. If so, the cost of water source development is added to the capital cost for these systems. Again, the user may input a value for the cost of water development, otherwise a default value is used. If the user is not willing to consider the cost of developing the water source, the area to be irrigated by systems for which the pumping demand/total water requirements is not being met is reduced according the available extraction rate or total storage.

Finally, the user is prompted for the horizontal and vertical distance of the water source (existing or proposed) to the field. This data is passed to the next rule-base for use in the economic analysis. The rule-base writes all user input, and suitable irrigation systems, including a brief description of each system, the pumping demand, the water requirements and labor requirements to a disk file and/or printer.

**Economic Evaluation (FILE6.PRL)**

A flow chart of the rule-base in FILE6 is given in Figure 10. The rule-base writes the information required by the irrigation cost models to a file and activates the external cost model routine. The output is written to a file and may be viewed or printed. The user may then change selected input parameters and re-run the irrigation cost models, start a new session or exit to the operating system. The rule-base also allows the user to view and/or print current values of input parameters that can be changed before running the irrigation cost model.

Only selected input parameters may be changed if the user wants to re-run the cost models. Parameters that would affect the selection of an irrigation system (e.g. area to be irrigated) cannot be changed.
Figure 10. Flow chart of rule-base for economic evaluation (FILE 6).
Databases

Databases were constructed using dBXL, a dBase III PLUS compatible database management system (WordTech Systems Inc., California). Five database files were used: two each for soils and crops and one for agricultural drought.

Soils

Information in the soils databases was obtained from the Virginia Guide to Supplemental Irrigation (USDA, 1976). The soils database file descriptions are given in Table 4. In the SOILS1 database, a record is selected by matching the soil name given by the user with the entry in the SOIL field. In the SOILS2 database, a record is selected based on the irrigation soil group (ISG) obtained from the SOILS1 record.

All major soil types in Virginia (approximately 400) were included in SOILS1. A cost of $25 per hectare (Vellidis, 1985) was assumed if sub-surface drainage was necessary for the soil to be suitable for irrigation. This cost was assumed constant across all soil types.

Crops

Information in the crops databases was obtained from Taylor et al. (1985) for corn and from "Economic Indicators of the Farm sector" (USDA, 1985) for soybeans and peanuts. The crops database file descriptions are given in Table 5. To access a record in the CROPS1 database, the crop selected by the user is matched with entries in the CROP field. Once a match is made, the geographical location (GEOGLOC) field is checked to see if it matches the geographic location of the user. If the GEOGLOC field does not match, the next record with a
Table 4. Soil database files.

**Filename: SOILS1.DBF**

<table>
<thead>
<tr>
<th>Field</th>
<th>Abbreviation</th>
<th>Field type</th>
<th>Length</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil name</td>
<td>SOIL</td>
<td>Character</td>
<td>30</td>
<td>N/A</td>
</tr>
<tr>
<td>Irrigation soil group</td>
<td>ISG</td>
<td>Numeric</td>
<td>3</td>
<td>N/A</td>
</tr>
<tr>
<td>Drainage cost</td>
<td>DC</td>
<td>Numeric</td>
<td>5</td>
<td>$/ha</td>
</tr>
</tbody>
</table>

**Filename: SOILS2.DBF**

<table>
<thead>
<tr>
<th>Field</th>
<th>Abbreviation</th>
<th>Field type</th>
<th>Length</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Irrigation soil group(^2)</td>
<td>ISG</td>
<td>Numeric</td>
<td>3</td>
<td>N/A</td>
</tr>
<tr>
<td>Soil intake rate</td>
<td>INR</td>
<td>Numeric</td>
<td>4(2)</td>
<td>mm/hr</td>
</tr>
<tr>
<td>Available water at 150 mm(^4)</td>
<td>AVWATC1</td>
<td>Numeric</td>
<td>4(2)</td>
<td>mm</td>
</tr>
<tr>
<td>Available water at 300 mm</td>
<td>AVWATC2</td>
<td>Numeric</td>
<td>4(2)</td>
<td>mm</td>
</tr>
<tr>
<td>Available water at 450 mm</td>
<td>AVWATC3</td>
<td>Numeric</td>
<td>4(2)</td>
<td>mm</td>
</tr>
<tr>
<td>Available water at 600 mm</td>
<td>AVWATC4</td>
<td>Numeric</td>
<td>4(2)</td>
<td>mm</td>
</tr>
</tbody>
</table>

1 Parentheses show number of decimal places for numeric fields
2 Defines the intake rate and available water capacity of the soil.
3 Amount of moisture the soil will hold between field capacity and permanent wilting point at the stated soil depth.
N/A: Not applicable
### Table 5. Crop database files.

<table>
<thead>
<tr>
<th>Field</th>
<th>Abbreviation</th>
<th>Field type</th>
<th>Length(^1)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop type</td>
<td>CROP</td>
<td>Character</td>
<td>15</td>
<td>N/A</td>
</tr>
<tr>
<td>Geographical location</td>
<td>GEGGLOC</td>
<td>Character</td>
<td>2</td>
<td>N/A</td>
</tr>
<tr>
<td>Growing season</td>
<td>GROSEAS</td>
<td>Character</td>
<td>3</td>
<td>N/A</td>
</tr>
<tr>
<td>Peak consumptive use</td>
<td>PEAKCU</td>
<td>Numeric</td>
<td>5(2)</td>
<td>mm/day</td>
</tr>
<tr>
<td>Weeks in growing season</td>
<td>WEEKS</td>
<td>Numeric</td>
<td>3</td>
<td>N/A</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Field</th>
<th>Abbreviation</th>
<th>Field type</th>
<th>Length(^1)</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Crop type</td>
<td>CROP</td>
<td>Character</td>
<td>15</td>
<td>N/A</td>
</tr>
<tr>
<td>Moisture control (root zone)</td>
<td>MCD</td>
<td>Numeric</td>
<td>6(1)</td>
<td>cm</td>
</tr>
<tr>
<td>Non-irrigated yield (dry year)</td>
<td>DL1</td>
<td>Numeric</td>
<td>7(1)</td>
<td>AU/ha</td>
</tr>
<tr>
<td>Non-irrigated yield (normal year)</td>
<td>DL2</td>
<td>Numeric</td>
<td>7(1)</td>
<td>AU/ha</td>
</tr>
<tr>
<td>Cost of dryland production</td>
<td>CDP</td>
<td>Numeric</td>
<td>6(1)</td>
<td>$/AU</td>
</tr>
<tr>
<td>Cost of irrigated production</td>
<td>CIP</td>
<td>Numeric</td>
<td>6(1)</td>
<td>$/AU</td>
</tr>
<tr>
<td>Irrigated yield</td>
<td>!RY</td>
<td>Numeric</td>
<td>7(1)</td>
<td>$/AU</td>
</tr>
</tbody>
</table>

\(^1\)Parentheses show number of decimal places for numeric fields

N/A: Not applicable

AU: Appropriate yield unit of crop
matching CROP field is checked until a record with both the CROP and GEOGLOC fields matching is found. In the CROPS2 database, a record is accessed once an entry in the CROP field matches the crop selected by the user.

The growing season (GROWSEAS) field in CROPS1 contains entries with a letter/number combination that defines the start/end of the growing season. For example, 'A' stands for April 1, 'B' for April 15, 'C' for May 1 and so on. '1' stands for September 31, '2' for September 15, '3' for August 31 and so on. The crop growing season is used in determining the number of drought days expected in a normal and dry season.

Peak consumptive use (PEAKCU) is the product of pan evaporation and crop factor at peak demand. The crop factor incorporates both the crop coefficient and pan coefficient. PEAKCU was assumed to be the same for a given crop in all geographical locations. However, PEAKCU will generally vary with geographical location, since pan evaporation rates will be different.

WEEKS is the number of weeks in the growing season, truncated to the nearest integer. WEEKS is used for computing total labor required to operate an irrigation system during the growing season (when the user indicates labor requirements are a critical factor and provides the maximum labor available per week).

Drought Days

Information in the drought days database was obtained from Vellidis et al. (1985), who assessed agricultural drought probability in Virginia on a site-specific basis based on a 54 year climatic record. They present tables which allow estimates of the minimum number of drought days to be expected at given probabilities, when the irrigation basis, growing season and geographical location are known. The irrigation basis can be any integer value between 1 and 5 inches and geographical location was defined as being one of the five areas used in the study, as shown in Figure 11. The tables provide estimates of the minimum number of
Figure 11. Location map of areas used for determining monthly drought probabilities (Vellidis et al., 1985).
drought days for 1-, 2-, 3-, and 5-in-10 year droughts. In this study, only the drought days for a 1-in-10 year drought (which was regarded as a dry year) and a 5-in-10 year drought (which was regarded as a normal year) were used.

The drought days database file description is given in Table 6. A record is accessed by obtaining a match in both the LOCBA and GROWSEAS fields. The LOCBA field contains entries with a letter/number combination that defines the geographical location and irrigation basis to be used for determining the number of drought days (e.g. ‘A1’ represents Area A with a Basis of 1 in). Hence for a given GROWSEAS, there will have to be 25 LOCBA entries (A1 through E5). GROWSEAS entries follow the same convention as the CROPS2 file. Any new GROWSEAS entry in the CROPS2 file must be supported by corresponding GROWSEAS entries in the drought days database file.

**Irrigation Cost Models**

The irrigation cost models were based on the models reported by Taylor et al. (1985). The models were originally developed to assess the feasibility and potential expansion of large scale riparian irrigation in Virginia. These models were modified to allow their use for the economic evaluation of irrigation systems on a site specific basis. The models use quasi-design equations and algorithms to size and cost irrigation system components and should not be used to obtain the actual design specifications of irrigation systems. The models were written in FORTRAN and compiled into an executable program which can be activated from the LEVEL5 rule-base. Appendix A contains a glossary of all variable names in the program. A program listing is given in Appendix B and a flowchart of the main program is given in Figure 12.

The main program (ECONEV.FOR) reads input data from two files. The ECONEV.INP file contains parameters generated by the KBS during the interactive session with the user. An ex-
Table 6. Drought days database file.

<table>
<thead>
<tr>
<th>Field</th>
<th>Abbreviation</th>
<th>Field type</th>
<th>Length</th>
<th>Units</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographic location and Irrigation basis</td>
<td>LOCBA</td>
<td>Character</td>
<td>4</td>
<td>N/A</td>
</tr>
<tr>
<td>Growing season</td>
<td>GROWSEAS</td>
<td>Character</td>
<td>3</td>
<td>N/A</td>
</tr>
<tr>
<td>Drought days (normal year)</td>
<td>NODN</td>
<td>Numeric</td>
<td>3</td>
<td>N/A</td>
</tr>
<tr>
<td>Drought days (dry year)</td>
<td>NODD</td>
<td>Numeric</td>
<td>3</td>
<td>N/A</td>
</tr>
</tbody>
</table>

N/A: Not applicable
Figure 12. Flowchart of main program in irrigation cost model.
ample ECONEV.INP file with parameter definitions is given in Appendix C. The COST.INP file contains updateable cost parameters used in the cost models. A listing of the current COST.INP file is given in Appendix D.

An economic evaluation of non-irrigated production is obtained by calling subroutine DRYAN. Then, depending on which irrigation systems have been determined to be feasible (this information is contained in the ECONEV.INP file), an economic evaluation of production with center-pivot, traveling gun, or portable pipe systems are obtained by calls to subroutines CENPIV, TGUN, and PPIPE respectively. Engineering and economic considerations which apply to cost models for all the irrigation systems are now presented, followed by a description of the individual irrigation cost models.

**Engineering Considerations**

A summary of the irrigation system design characteristics used in this study is given in Table 7. The following assumptions are made about field shape and pipe orientation:

- A square field is assumed for the traveling gun and portable pipe systems. For the center-pivot systems, a circular shaped field was assumed.
- Mainline pipe length is defined as the distance from the water source to the near edge of the field for all systems.
- The sub-main is the pipe which distributes water from the mainline to the field sub-mains. The field sub-mains are assumed to run through the field and distribute water to the laterals. Figure 13 will serve to clarify this terminology. Depending on the area to be irrigated, there may be no field sub-mains and the sub-main may simply be a continuation of the mainline in the irrigated field. In some cases, the field sub-mains may be a continuation of the sub-mains.
Table 7. Design characteristics of irrigation systems (Taylor et al., 1985).

<table>
<thead>
<tr>
<th>Irrigation system</th>
<th>E</th>
<th>N</th>
<th>L</th>
<th>P</th>
<th>A</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center pivot:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed</td>
<td>80</td>
<td>23</td>
<td>0.10</td>
<td>210</td>
<td>2.0</td>
</tr>
<tr>
<td>Towable, 2 position</td>
<td>80</td>
<td>22</td>
<td>0.20</td>
<td>210</td>
<td>2.5</td>
</tr>
<tr>
<td>Towable, 3 position</td>
<td>80</td>
<td>21</td>
<td>0.30</td>
<td>210</td>
<td>2.5</td>
</tr>
<tr>
<td>Traveling gun</td>
<td>75</td>
<td>20</td>
<td>0.30</td>
<td>590</td>
<td>4.0</td>
</tr>
<tr>
<td>Portable pipe:</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Medium pressure</td>
<td>70</td>
<td>16</td>
<td>1.50</td>
<td>345</td>
<td>1.0</td>
</tr>
<tr>
<td>High pressure</td>
<td>70</td>
<td>18</td>
<td>0.75</td>
<td>480</td>
<td>1.0</td>
</tr>
</tbody>
</table>

E: Application efficiency of irrigation system (%)
N: Operation time (hr/day)
L: Labor requirements (hr/acre/irrigation cycle)
P: Sprinkler operating pressure (KPa)
A: Area lost due to equipment operation and movement (% of total)
Figure 13. Mainline, sub-main, field sub mains and laterals.
• For the center-pivot systems, there are no field sub-mains and the sub-main is a continuation of the mainline from the edge of the field to the center-pivot. In the case of a fixed center-pivot system, the sub-main length is equal to the radius of the circular field. For towable center-pivot systems, the sub-main length is equal to the sum of the diameters of all but the furthest pivot circle, to which is added the radius of that circle - for this to be true, it is assumed that the towable center-pivot circles are adjacent to each other.

**Pipe Sizing and Friction loss**

An irrigation pipeline must be sized carefully to obtain the best operating economy when both initial and operating costs are considered. Too large a pipeline requires excessive initial investment, while too small a line may require excessive energy to overcome pipeline friction losses (Kruse et al., 1980).

Pipe sizing for mainlines, sub-mains, field sub-mains and laterals is, therefore, based on a given pipe size’s maximum allowable flow velocity which results in the most cost effective pipe size. These limits are primarily based on rule-of-thumb guidelines and vary for type of system and pipe material (Taylor et al., 1985). In the case of center-pivot and portable pipe laterals, these limits apply to velocities achieved in the lateral pipe before the first sprinkler is reached and flow is reduced.

Flow velocity in a pipe is obtained from the following form of the continuity equation:

\[
\text{v} = \frac{kQ_p}{d^2}
\]  

(10)

where:

\[\text{v} = \text{pipe flow velocity, m/s (ft/s)}\]

\[Q_p = \text{pipe discharge, l/s (gpm)}\]

\[d = \text{pipe diameter, mm (in)}\]

\[k = \text{constant for consistent units, 1,273 (0.408)}\]
To determine the pipe sizes for a pipe discharge, pipe diameter is incrementally increased until a pipe size is found which results in a pipe velocity less than the maximum allowable (see Table 8).

Friction loss estimates are determined by the following form of the Hazen-Williams friction loss equation for flow in circular pipes (Kruse et al., 1980):

\[ H_f = \left( \frac{v}{CC_1R^{0.63}} \right)^{1.852} \]  

(11)

where:

- \( H_f \) = friction loss in pipe, m/m (ft/ft)
- \( R \) = hydraulic radius, m (ft)
- \( C \) = a constant which depends on the system of units used, 0.0109 (1.318)
- \( C_1 \) = the Hazen-Williams friction loss coefficient

Table 8 shows the pipe material, maximum allowable pipe velocity and friction loss coefficients used for the mainline, sub-mains and laterals for each system.

**Pumping Requirements**

Pumping requirements are a function of the discharge necessary to meet the evaporative demand of the crop, and the total pumping head resulting from the given physical conditions (Taylor et al., 1985). The power requirement of the pumping unit is determined from the following equation:

\[ P_b = \frac{H_f Q_b}{K_I E_p} \]  

(12)

where:

- \( P_b \) = brake power of pumping unit, KW (HP)
- \( H_f \) = total pumping head, m (ft)
Table 8. Pipe materials, maximum velocities and friction loss coefficients (Taylor et al., 1995).

<table>
<thead>
<tr>
<th>Pipe material</th>
<th>Mainline</th>
<th>Sub-mains</th>
<th>Laterals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center pivot</td>
<td>PVC</td>
<td>PVC</td>
<td>Steel</td>
</tr>
<tr>
<td>Traveling gun</td>
<td>PVC</td>
<td>PVC</td>
<td>PE</td>
</tr>
<tr>
<td>Portable pipe</td>
<td>PVC</td>
<td>Aluminium</td>
<td>Aluminium</td>
</tr>
</tbody>
</table>

PVC: poly-vinyl-chloride
PE: polyethylene

Maximum allowable pipe velocity, m/s

<table>
<thead>
<tr>
<th>Irrigation system</th>
<th>Mainline</th>
<th>Sub-mains</th>
<th>Laterals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center pivot</td>
<td>2.0</td>
<td>2.0</td>
<td>N/A</td>
</tr>
<tr>
<td>Traveling gun</td>
<td>2.0</td>
<td>2.0</td>
<td>N/A</td>
</tr>
<tr>
<td>Portable pipe</td>
<td>2.0</td>
<td>2.0</td>
<td>2.5</td>
</tr>
</tbody>
</table>

N/A: Not applicable, laterals sized directly from discharge.

Hazen-Williams friction coefficient

<table>
<thead>
<tr>
<th>Irrigation system</th>
<th>Mainline</th>
<th>Sub-mains</th>
<th>Laterals</th>
</tr>
</thead>
<tbody>
<tr>
<td>Center pivot</td>
<td>150</td>
<td>150</td>
<td>120</td>
</tr>
<tr>
<td>Traveling gun</td>
<td>150</td>
<td>150</td>
<td>180</td>
</tr>
<tr>
<td>Portable pipe</td>
<td>150</td>
<td>120</td>
<td>120</td>
</tr>
</tbody>
</table>
\[ Q_s = \text{system capacity, l/s (gpm)} \]
\[ E_p = \text{pumping system efficiency, decimal notation (0.8 for diesel units)} \]
\[ K = \text{a constant for consistent units, 10 (3960)} \]

The total pumping head, \( H_t \), is determined from:

\[ H_t = V + H_{TF} + P_s \]  \hspace{1cm} (13)

where:

\[ V = \text{vertical distance, or lift, from water source to highest point in the field, m (ft)} \]
\[ H_{TF} = \text{cumulative friction loss in mainlines, sub-mains and laterals, m (ft)} \]
\[ P_s = \text{sprinkler operating pressure, m (ft)} \]

A diesel pumping unit is assumed for all systems. Although electrical units are an option, and often preferred for large-scale systems, diesel power units are usually a more practical selection because of the limited availability of three phase power (Taylor et al., 1985).

**Economic Considerations**

The economic feasibility of an irrigation system is determined by calculating the break-even yield, which is the crop yield required to offset irrigation costs. Break-even yield can be expressed as:

\[ \text{BEY} = \frac{(C_{dry} + C_{irr})}{P_{cr}} \]  \hspace{1cm} (14)

where:

\[ \text{BEY} = \text{break even yield, in appropriate yield units' per hectare (acre)} \]
\[ C_{dry} = \text{cost of non-irrigated production, $ per hectare (acre)} \]

\[ \text{1 The yield units depend on the crop} \]
\[ C_{irr} = \text{cost of irrigation, \$ per hectare (acre)} \]

\[ p_{cr} = \text{crop price, \$ per yield unit used} \]

If the break-even yield exceeds the expected irrigated yield, the irrigation system is not economically feasible. The total profit expected from an economically feasible system can be calculated as:

\[ \text{PROF} = (Y_{irr} - BEY) \times p_{cr} \times A \quad (15) \]

where:

\[ \text{PROF} = \text{total annual profit, \$} \]

\[ Y_{irr} = \text{irrigated yield, appropriate yield units per hectare (acre)} \]

\[ A = \text{total area under irrigation, hectares (acres)} \]

Annual irrigation costs must include all costs associated with owning, operating and maintaining the irrigation system (Thompson et al., 1980). Fixed costs include the initial investment cost, taxes and insurance. Variable costs include energy, labor, repair and maintenance costs.

**Fixed Costs**

The cost of irrigation system components are determined using the cost parameters reported by Taylor et al. (1985). These parameters are defined in the COST.INP file listed in Appendix D. The initial investment costs that have to be considered are:

- Cost of pumping unit
- Cost of pipe network/irrigation system
- Water source development, drainage and clearing costs

The cost of the pumping unit is assumed to be a linear function of the brake power requirements of the pumping unit, therefore:
\[ C_p = P_o \times f_{dp} \]  

(16)

where:

- \( C_p \) = cost of diesel pumping unit, $  
- \( P_o \) = brake power of pumping unit, KW (HP)  
- \( f_{dp} \) = cost parameter for diesel pumping unit, $/KW ($/HP)

The cost of the pipe network/irrigation system will be unique for each irrigation system and is discussed under the cost model for each system. Water source development, drainage and clearing costs are determined within the rule-base during the interactive session and passed on as input parameters to the irrigation cost models.

Once the total initial investment cost has been determined, it is necessary to amortize this cost over the life of the irrigation system to express initial investment cost on an annual basis (Taylor et al., 1985). Amortization is done using the capital recovery relationship:

\[ CRF = \frac{i}{(1 - (1 + i)^{-n})} \]  

(17)

where:

- \( CRF \) = capital recovery factor  
- \( i \) = annual interest rate, decimal notation  
- \( n \) = life of capital asset (assumed to be 15 for all irrigation systems)

The amortization value, assuming zero salvage value, is then given by:

\[ A_r = TI \times CRF \]  

(18)

where:

- \( A_r \) = annual capital recovery charge, $  
- \( TI \) = total initial investment, $

The annual cost of insurance and taxes is assumed to be 2% of the total initial investment.
Variable Costs

The method of determining variable costs is similar for all irrigation systems. Variable costs are highly dependent upon the number of hours an irrigation system is operated during the growing season. The energy requirements of an irrigation system, expressed as the total KW-hr (HP-hr) used during the season is calculated as follows:

\[ T_o = P_b \times T_i \times CPS \]  

(19)

where:

- \[ T_o \] = total number of KW-hr (HP-hr) used by the irrigation system
- \[ P_b \] = brake power of pumping unit, KW (HP)
- \[ T_i \] = time per irrigation cycle, hr
- \[ CPS \] = number of irrigation cycles in the season

For center-pivot systems, the brake power of the diesel engine running the generator motor to power the electric motors on the towers (assumed to be a linear function of the lateral length) was included in \[ P_b \].

The total diesel consumption was calculated by dividing \[ T_o \] by 3.3 (16.5), which represents the KW-hr (HP-hr) of energy supplied by the pumping unit per liter (gallon) of diesel used. Similarly, to obtain the oil consumption, \[ T_o \] was divided by 180 (900). Annual maintenance costs were obtained by multiplying \[ T_o \] by 0.0027 (0.002). The total number of labor hours required to operate the irrigation system in a season was calculated from Equation (9).

The value of crop lost due to irrigation equipment movement and the cost of additional inputs for irrigated production are also included in variable costs. The percentage of area lost due to equipment operation and movement is given in Table 6. The expected non-irrigated yield multiplied by the crop price and weighted by the percentage of land lost to the irrigation system represents the opportunity cost of lost production (Taylor et al., 1985). The cost of additional (non-irrigation) inputs for irrigated production, such as seed and fertilizer were also included in variable costs. These inputs must be included if a high level of management is
desired under irrigation. The cost of additional inputs was assumed constant across all soil types.

**Cost Models**

The cost models determine annual fixed and operating costs of irrigation for different irrigation systems. They also determine the break-even yield and annual profit under irrigation. A flowchart of the procedure used in determining irrigation costs is given in Figure 14. All the cost models require the following input data:

- **Engineering/agronomic parameters:** net depth of irrigation, number of drought days in both normal and dry years, crop consumptive use, horizontal and vertical distance of field from water source, area to be irrigated
- **Economic/cost parameters:** interest rate, maximum and minimum crop prices expected in normal and dry years, non-irrigated yields in normal and dry years, irrigated yield, cost of additional (non-irrigation) inputs, cost of labor, cost of diesel and oil, cost of diesel unit per KW (HP), cost of PVC piping per unit length for a range of diameters, water source development costs, drainage costs, clearing costs

Additional specific input parameters required by each model are as follows:

- **Center-pivot:** number of pivot points, cost per unit length of steel lateral for a range of total lateral lengths, cost of pivot point assembly, cost of generator pad per unit length of lateral
- **Traveling gun:** cost of traveling gun unit per unit flow rate, cost of traveling gun hydrant
- **Portable pipe:** system type (medium or high pressure), cost of riser assemblies for medium and high pressure sprinklers, cost of T-valve connection between field sub-main and laterals, cost of aluminum piping per unit length for a range of diameters
Figure 14. Flowchart of general irrigation cost model.
**Center-pivot cost model**: The center-pivot model first initializes the parameters for system efficiency, sprinkler operating pressure, operating time per day, labor requirements per unit area per irrigation cycle and the area lost to irrigation equipment operation and movement. The value assigned to the last three parameters depends on the number of pivot points. Only low pressure center pivot systems are considered by the model.

Parameters that determine the basis of the irrigation design, that is, the time required per irrigation, the number of irrigation cycles in normal and dry years, and the system capacity are determined from equations (3), (4), (5), (6) and (7). With the system capacity known, the mainline is sized subject to a velocity constraint using equation (10), friction loss in the mainline determined from equation (11), and a cost per unit length assigned depending on the pipe diameter. The center-pivot lateral is sized according to the system capacity and a cost per unit length assigned according to the total length of the lateral. Friction loss in the lateral is determined from equation (11). The pumping unit is sized using equations (12) and (13), and the total cost of the pumping unit obtained from equation (16).

The total cost of the mainline is determined as follows:

\[
TCM = (CM) \times (HD + ((2 \times (NP) - 1) \times (RAD)))
\]  

(20)

where:

- **TCM** = total cost of main line, $
- **CM** = cost of main line, $/m ($/ft)
- **HD** = horizontal distance of field from water source, m (ft)
- **NP** = number of pivot points
- **RAD** = radius of center pivot, m (ft)

The total initial investment cost is then obtained from:

\[
TI_{cp} = (TCM) + (CL \times RAD) + (PUMP) + (f_{cpa} \times NP) + (f_{gp} \times RAD) + DC
\]

(21)

where:

- **TI_{cp}** = total initial investment for center-pivot, $
$$CL = \text{cost of lateral} \ $/m ($/ft)$$

$$PUMPC = \text{total cost of pumping unit,} \ $$$$

$$f_{ps} = \text{cost factor for pivot point assembly,} \ $$$$

$$f_g = \text{cost factor for generator pad,} \ $/m ($/ft)$$

$$DC = \text{total cost of water source development, drainage and clearing,} \ $$$$

Annual fixed costs are calculated using equations (17) and (18).

The procedure discussed previously is used to obtain variable costs. Once annual fixed and variable costs have been determined, the break-even yield and annual profit based on irrigated yield can be calculated from equations (14) and (15).

**Traveling gun cost model:** The traveling gun model first initializes parameters for system efficiency, operating time per day, labor requirements per unit area per irrigation cycle and the area lost due to equipment operation and movement. The design basis is determined as described in the center-pivot model as is the mainline size and cost. The model then determines if more than one traveling gun unit will be needed, based on the assumption that the maximum area that can be covered by one gun is 44 ha (110 ac) and that the maximum discharge possible from a single gun is 76 l/s (1200 gpm).

The length and flow rate in the hose (lateral), field sub-main, and sub-main are determined from the following:

$$HCSL = \frac{\sqrt{A}}{2N_g}$$

(22)

$$FSML = \sqrt{A}$$

(23)

$$SUBL = \frac{\sqrt{A}}{N_g} (N_g - 1)$$

(24)

$$Q_H = Q_{fsm} = \frac{Q_g}{N_g}$$

(25)
\[ Q_{sm} = 0 \quad \text{(for } N_g = 1) \] (26.1)

\[ Q_{sm} = \frac{Q_s}{2} \quad \text{(for } N_g \text{ even}) \] (26.2)

\[ Q_{sm} = \frac{Q_s - Q_{H}}{2} \quad \text{(for } N_g \text{ odd}) \] (26.3)

where:

- HOSL = length of hose, m (ft)
- \( N_g \) = number of traveling guns
- A = area to be irrigated, m² (ft²)
- FSML = length of field sub-main, m (ft)
- SUBL = length of sub-main, m (ft)
- \( Q_s \) = flow in hose, l/s (gpm)
- \( Q_{hm} \) = flow in field sub-main, l/s (gpm)
- \( Q_{sm} \) = flow in sub-main, l/s (gpm)
- \( Q_s \) = system capacity, l/s (gpm)

The field sub-mains and the sub-main are sized subject to a velocity constraint using equation (10), friction losses determined using equation (11), and a cost per unit length assigned to each of them depending on the diameter obtained. The hose diameter and traveling gun operating pressure are determined according to the flow rate in the hose and friction loss in the hose obtained from equation (11). The cost of the hose is included in the cost of the traveling gun unit which is assumed to be a linear function of the flow rate in the hose.

The lane spacing is determined from:

\[ S_{lane} = 2(1 - D_o) \left( \frac{KQ_s}{\pi l_s} \right)^{0.5} \] (27)

where:

- \( S_{lane} \) = traveling gun lane spacing, m (ft)

KNOWLEDGE BASE
\[ D_o = \text{degree of overlap, decimal notation (assumed to be 0.3)} \]

\[ Q_n = \text{flow rate in hose, l/s (gpm)} \]

\[ i_n = \text{maximum soil intake rate, cm/hr (in/hr)} \]

\[ K = \text{constant for consistent units, 3600 (96.3)} \]

The number of travel lanes, NTL, which will be equal to the number of hydrants required per gun, is then given by:

\[ \text{NTL} = \frac{\sqrt{A}}{S_{\text{lane}}} \]  

(28)

The cost of a single hydrant is assumed to be a linear function of the field sub-main diameter. The cost of the pumping unit is obtained as before in the center-pivot model.

The total initial investment cost is then obtained from:

\[ T_{Ig} = (HD \times CM) + (\text{PUMPC}) + (\text{SUBL} \times \text{CSM}) + (\text{FSML} \times \text{CFSM}) + (f_{\text{gun}} \times Q_n \times N_g) + (f_{\text{hy}} \times D_{\text{fsm}} \times N_{\text{c}} \times N_g) + (\text{DC}) \]  

(29)

where:

\[ T_{Ig} = \text{total initial investment for traveling gun, } \$ \]

\[ HD = \text{horizontal distance of field from water source, m (ft)} \]

\[ CM = \text{cost of mainline, } \$/m (\$/ft) \]

\[ \text{PUMPC} = \text{total cost of pumping unit, } \$ \]

\[ \text{CSM} = \text{cost of sub-main, } \$/m (\$/ft) \]

\[ \text{CFSM} = \text{cost of field sub-main, } \$/m (\$/ft) \]

\[ f_{\text{gun}} = \text{cost factor for traveling gun unit, } \$/l/s (\$/gpm) \]

\[ f_{\text{hy}} = \text{cost factor for traveling gun hydrants, } \$/mm (\$/in) \]

\[ D_{\text{fsm}} = \text{diameter of field sub-main, mm (in)} \]

\[ \text{DC} = \text{total cost of water source development, drainage and clearing, } \$ \]

Annual fixed costs, annual variable costs, break-even yield and annual profit are obtained as before in the center-pivot model.
**Portable pipe cost model:** For the portable pipe systems, design parameters include sprinkler spacing and the number of sets per day in addition to system efficiency, sprinkler operating pressure, operating time per day, labor requirements, and area lost to equipment operation and movement. All parameters except the system efficiency and area lost to equipment operation and movement depend on whether a high-pressure or medium pressure system is being evaluated. A 18 by 18 m (60 by 60 ft) spacing is assumed for medium pressure systems and a 54 by 54 m (180 by 180 ft) spacing assumed for high pressure systems.

The design basis, mainline size and cost are determined as in the other cost models. The model then determines the number of field sub-mains that will be needed, assuming that each field sub-main covers 32 ha (80 ac).

The number of laterals and riser assemblies, length and flow in the laterals, field sub-mains and sub-main are determined as follows:

\[
L_{\text{lat}} = \frac{\sqrt{A}}{2N_{\text{fsm}}} \quad (30)
\]

\[
FSM = \sqrt{A} \quad (31)
\]

\[
SUBL = \frac{\sqrt{A}}{N_{\text{fsm}}(N_{\text{fsm}} - 1)} \quad (32)
\]

\[
NOL = \frac{A}{S_{11}(NOSD)D_{L_{\text{lat}}}} \quad (33)
\]

\[
Q_{\text{lat}} = \frac{Q_s}{NOL} \quad (34)
\]

\[
Q_{\text{fsm}} = \frac{Q_s}{N_{\text{fsm}}} \quad (35)
\]

\[
Q_{\text{sm}} = 0 \quad \text{(for } N_{\text{fsm}} = 1) \quad (36.1)
\]

\[
Q_{\text{sm}} = \frac{Q_s}{2} \quad \text{(for } N_{\text{fsm}} \text{ even)} \quad (36.2)
\]
\[ Q_{\text{sm}} = \frac{Q_s - Q_{\text{lsm}}}{2} \quad \text{(for } N_{\text{lsm}} \text{ odd)} \]  
(36.3)

\[ \text{NRS} = \frac{L_{\text{lat}}}{S_{\text{lat}}} \quad \text{(NOL)} \]  
(37)

where:

- \( L_{\text{lat}} \) = length of lateral, m (ft)
- \( N_{\text{lsm}} \) = number of field sub-mains
- \( A \) = area to be irrigated, \( m^2 \) (ft\(^2\))
- \( \text{FSML} \) = length of field sub-main, m (ft)
- \( \text{SUBL} \) = length of sub-main, m (ft)
- \( \text{NOL} \) = number of laterals
- \( S_{\text{lat}} \) = lateral spacing, m (ft)
- \( \text{NOSD} \) = number of sets per day
- \( D_i \) = days in irrigation cycle
- \( Q_{\text{lat}} \) = flow in lateral, l/s (gpm)
- \( Q_{\text{lsm}} \) = flow in field sub-main, l/s (gpm)
- \( Q_{\text{sm}} \) = flow in sub-main, l/s (gpm)
- \( Q_s \) = system capacity, l/s (gpm)
- \( \text{NRS} \) = number of riser assemblies
- \( S_{\text{lat}} \) = riser spacing, m (ft)

The laterals, field sub-mains, and sub-main are sized subject to a velocity constraint using equation (10), friction loss determined from equation (11), and a cost per unit length assigned to each depending on the diameter obtained. It should be noted from Table 7 that a higher maximum velocity is used for sizing laterals than sub-mains.

Cost of the T-value connections for the laterals is based on the field sub-main diameter. The total initial investment cost is then obtained from:
\[ T_{lp} = (HD \times CM) + (PUMPC) + (SUBL \times CSM) + (FSML \times CFSM) + \\
(LL \times CL \times NOL) + (CTV \times NOL) + (CRIS \times NRS) + (DC) \]  

(38)

where:

- \( T_{lp} \) = total initial investment for portable pipe, $
- \text{HD} = \text{horizontal distance of field from water source, m (ft)}$
- \text{CM} = \text{cost of mainline, } \$/$m (\$/ft)$
- \text{PUMPC} = \text{total cost of pumping unit, }$
- \text{CSM} = \text{cost of sub-main, } \$/$m (\$/ft)$
- \text{CFSM} = \text{cost of field sub-main, } \$/$m (\$/ft)$
- \text{CL} = \text{cost of lateral, } \$/$m (\$/ft)$
- \text{CTV} = \text{cost of T-valve, }$
- \text{CRIS} = \text{cost of riser assembly, }$
- \text{DC} = \text{total cost of water source development, drainage and clearing, }$

Annual fixed costs, annual variable costs, break-even yield and annual profit are obtained as in the other cost models.
A description of a typical interactive session, the knowledge base evaluation, and a sensitivity analysis of the irrigation cost models are presented here. The interactive session description will serve to demonstrate to the reader how the KBS operates. The knowledge base evaluation provides an overall assessment of the KBS’s performance, and the sensitivity analysis identifies input parameters that have the greatest impact on irrigation cost model predictions.

**Interactive Session**

During an interactive session with the knowledge base, the user responds to a number of queries from the KBS. The queries may be one of four types:

- **Simple fact queries**, where a statement is displayed and the user selects a Yes or No response by positioning the cursor arrow (moved by the up/down arrow keys, spacebar or tab key) to the desired response and pressing RETURN.

- **Attribute value (AV) queries** present the user with a list of choices for a question and ask the user to select the value that best describes the user’s response. The user may select values from an AV display by positioning the cursor arrow to the item of choice and pressing RETURN.
• String queries ask the user to provide string, or character information. The user is required to check the entry for possible spelling/typing errors before the session proceeds.

• Numeric queries ask the user to input a numeric value in response to a question. A non-numeric response to a numeric query is not accepted.

A series of simple-fact, attribute value, string and numeric queries allow the user to interactively enter the site-specific information required by the KBS to determine suitable irrigation systems and evaluate their economic feasibility.

An example interactive session with the KBS is shown in Figure 15. The session begins with the title screen which provides introductory information about the system. Information on keyboard operations may be obtained if the user is not familiar with the program. In the example shown, the user presses the function key F2 to start the program. The program then informs the user that the input information required during the interactive session will be displayed and asks whether this information should be printed. In the example session, the user selects ‘No’ and the program continues by displaying the input requirements. After viewing this, the user may request additional information on any of the input requirements. Additional information on the input requirements describe exactly what is required and provide the user with hints on how to obtain the input if it is not readily available. At this point, the user would stop the session if all the data needed were not available and return to the session after obtaining the required data. In the example session, the user does not request any additional information on the input requirements and the session continues by asking the user to enter the county where the proposed irrigation development is to be located (Figure 15b). The KBS displays the entry and asks the user to check for possible spelling/typing errors before proceeding. The county name is used by the KBS to determine the user’s geographical area which is used for obtaining agricultural drought information.

The KBS then queries the user if the name of the major soil type in the area to be irrigated is known (Figure 15c). In the example, the user responds ‘Yes’ and the KBS prompts
IRRIG-8 Version 1.0

IRRIG-8

IRRIG-8 is an interactive program which uses site-specific information you provide to determine suitable irrigation systems and provide estimates on irrigation costs and water and labor requirements for each system.

You may press F2 to start the program if you are familiar with keyboard operations for the LEVEL5 Expert System Development Tool. If you need information on keyboard operations, press F1.

The next four screens summarize the input information that will be required. Would you like this information to be printed as well?

Yes

===> No

You will need to provide the following information:

- Area to be irrigated (acres).
- Crop to be irrigated.
- Average slope (percent).
- Geographic location in Virginia.
- Soil name.
- Expected labor availability.
- Whether clearing costs are to be included.
- Maximum and minimum prices expected during a dry/normal year.
- Horizontal and vertical distance of water source (or proposed water source) from the field.

FIELD SHAPE

If the center pivot systems are determined to be suitable, you will be asked about the field shape.
If the field shape is RECTANGULAR, you will need to enter the length and width of the field.
If the field shape is IRREGULAR, you will need to enter the diameter of the biggest single circle, biggest two, and biggest three circles that can fit in the field.
This information can be easily obtained from a map of the area to be irrigated.

Figure 15a. Example interactive session - solid lines indicate the start of a new screen.
For field corn, soybeans and peanuts, you may provide values for the following, otherwise default values will be used. For other crops, you MUST provide this information:

- Non-irrigated yields (normal and dry years).
- Irrigated yield.
- Cost of non-irrigated production.
- Cost of additional (non-irrigation) inputs for irrigated production.

If you plan to use an existing water source, you will also be asked for the following:

- Type of water source (Pond, Stream or Well).
- Total storage if source is a pond.
- Maximum extraction rate if source is a stream or well.

However, if you do not have any information on the water source, the total storage or extraction rate will be assumed sufficient for all suitable systems. It is recommended that you try and obtain an estimate of the storage or maximum extraction rate as water source development costs may be a significant factor in the economic evaluation of an irrigation system.

Would you like additional information on any of the input requirements?

Yes

--> No

In which county of Virginia are you located? Please enter county name ONLY (e.g. Orange). Letters may be entered lower or upper case. If you are located in the Virginia Beach area enter 'Beach area':

ALBEMARLE

Please make sure the spelling of ALBEMARLE is correct. Is it correct?

--> Yes

No

Figure 15b. Example interactive session (continued).
Do you know the name of the major soil type in the area to be irrigated?

==> Yes
No

Enter the soil name. Please check your spelling with the list in the User's Guide. Include all blanks.

DYKE SILTY CLAY LOAM

The soil database access can take considerable time and if you have misspelled the soil name, it will be necessary to search through it again after you re-enter the name.
Please check the spelling of DYKE SILTY CLAY LOAM.
Is it correct?

==> Yes
No

Please enter the area to be irrigated in acres.
The maximum single block that can be irrigated by one mainline is assumed to be 400 acres. If you want to irrigate an area larger than 400 acres, it would be advisable to divide the area into two or more smaller blocks and input information for these blocks separately.

15

Please enter the average slope of the area to be irrigated (in percent):

5

Please select the crop you want to irrigate:

==> Corn for grain
Soybeans
Peanuts
Not listed

Figure 15c. Example interactive session (continued).
Are land clearing costs to be included in the economic analysis:

    Yes
    ===> No

What is the maximum crop price you expect during a DRY year?
(A dry year may be regarded as a 1 in 10 year drought.)
Enter value in $/bu for corn or soybeans and $/lb for peanuts.
For other crops, enter value in $ per unit measure in which the
crop is commonly sold.

    4.00

What is the minimum price you expect during a DRY year?
($/bu for corn/soybeans, $/lb for peanuts)

    3.00

What is the maximum price you expect during a NORMAL year?
($/bu for corn/soybeans, $/lb for peanuts)

    3.50

What is the minimum price you expect during a NORMAL year?
($/bu for corn/soybeans, $/lb for peanuts)

    2.75

What is the annual percentage interest rate at which you expect to
borrow money?

    12

Do you wish to provide any information on dryland/irrigated costs of
production and/or dryland/irrigated yields? Select No to use the
default values.

    Yes
    ===> No

Figure 15d. Example interactive session (continued).
What best describes the field shape?

- Square
- Rectangular
- Irregular

Do you wish to input the cost of labor? If you select No, the default value of 4.00 $/hour will be used.

- Yes
- No

Are labor requirements for a system a critical factor for you? That is, are you limited to only having a certain maximum labor supply? If you respond Yes, irrigation systems for which you do not expect to have adequate labor during a normal year will be eliminated. However, irrigation systems for which you do not have adequate labor only during a dry year will still be considered, but a warning will be displayed in the output for this system.

- Yes
- No

Do you have an existing water source?

- Yes
- No

What kind of water source do you have?

- Stream
- Well
- Pond

Do you know or have any estimate of the maximum water storage of the pond?

- Yes
- No

Figure 15e. Example interactive session (continued).
As you do not have any estimate of the total storage available in the pond, it will be assumed that the storage is sufficient to meet the water requirements of all suitable irrigation systems and no water source development costs will be included for any of the systems when determining irrigation costs.

However it must be realised that water source development, if necessary, can be a substantial part of the total capital cost of irrigation. It is therefore recommended that you try and obtain an estimate of the maximum available storage and run this program again.

Press RETURN to continue.

Would you like information on how to obtain an estimate of the maximum storage available in a pond?

Yes

--- No

Please enter the horizontal distance (in feet) of the field from the pond:

1000

Please enter the vertical distance (in feet) of the field from the pond:

40

In the economic evaluation of suitable systems, it will be assumed that the pumping unit is driven by a diesel engine. Do you wish to input the cost of diesel? Select No to use the default value of 1.25 $/gallon.

Yes

--- No

Figure 15f. Example interactive session (continued).
Do you wish to input the cost of lubricating oil? Select No to use the default value of 6.00 $/gallon.

Yes

===> No

Suitable irrigation systems including water and labor requirements for each system have now been written to the INITIAL.OUT file. Do you wish to see this file?

===> Yes

No

How do you wish to see the file?

Display only

===> Print only

Display and print

Please make sure the printer is connected to the computer and switched on.

Hit RETURN to continue.

The current INITIAL.OUT file will be erased when a new session is started. Do you wish to have it written to another file?

Yes

===> No

Irrigation systems which have been determined to be suitable will now be evaluated for economic feasibility. You will be prompted for the name of the file to which you want results of the economic evaluation written. Do you wish to:

Not view or print the file at present.
Display file only.

===> Print file only.

Display and print file.

Figure 15g. Example interactive session (continued).
Please make sure the printer is connected to the computer and switched on.

Hit RETURN to continue

Enter the name of the file you want the results of the economic evaluation written to. If you do not specify the drive, the current drive will be used: SCENARI0.OUT

The output from the economic evaluation program has been written to SCENARI0.OUT.

Press RETURN to continue.

Do you wish to change any input parameter values and re-run the economic analysis?

Yes

===> No

Do you wish to re-start the session?

Yes

===> No

END OF SESSION

Figure 15h. Example interactive session (continued).
the user for the soil name. The KBS then accesses the soils databases to obtain the available water capacity, intake rate of the soil, and whether artificial drainage is necessary for the soil to be suitable for irrigation. If the user had responded 'No', a generic description of all the irrigation soil groups would have been presented and the user asked to select the description that best matches the field soil. In this case, the soils databases are not accessed since the required soil information is contained within the KBS rules.

The area to be irrigated and the average slope of the area are then entered and the session continues with the KBS requesting the user to select the crop to be irrigated. In the example session, the user selects 'Corn for grain' and the KBS accesses the crop databases to obtain information on growing season, peak consumptive use, root zone depth, and dryland/irrigated yields and cost of production. If the user selects the 'Crop not listed' option, the crop databases are not accessed and the user is prompted to enter all the required crop information.

The KBS then checks if land clearing costs are to be included in the economic analysis (Figure 15d). If the user responds 'Yes', he/she may input the cost of clearing per acre, otherwise a default value is used. In the example session, the user responds 'No' and the KBS continues by asking the user to input the maximum/minimum crop price expected in a dry and a normal year and the annual interest rate. The user then has the opportunity to enter specific data on costs and yields for irrigated and non-irrigated production. The default option uses cost and yield values from the crop databases.

At this point, the KBS accesses the drought days database, and depending on the net irrigation depth computed for the crop, geographical location in Virginia, and growing season of the crop, obtains the long-term, average number of drought days expected in a dry and a normal year. Suitable irrigation systems are then determined, based on the area to be irrigated, soil intake rate, and field slope and shape. The KBS assumes a minimum limit of 10 acres for area covered by a single center pivot circle, thus the minimum area covered by two point and three point towable center pivot systems are 20 and 30 acres respectively. In the example session, as the area to be irrigated is 15 acres, the towable systems are eliminated.

RESULTS AND DISCUSSION
When the user responds 'Square' to the field shape query, the KBS assumes the diameter of the fixed center pivot is equal to the length of one side of the field (Figure 15e). If the response for field shape is 'Rectangular', the KBS queries the user about the field dimensions to determine the length to width (L/W) ratio. If the L/W ratio is less than 1.6, the KBS assumes the diameter of the fixed center pivot is equal to the dimension of the smaller side of the field, otherwise the fixed center pivot system is eliminated. If the response is 'Irregular', the KBS queries the user about the diameter of the biggest single circle that can fit in the field and this is assumed to be the diameter of the fixed center pivot.

The session continues with the KBS giving the user the option of entering the cost of labor or using a default value. The KBS then queries the user if labor requirements for irrigation are a critical factor (that is, whether the user is limited to a maximum labor supply). In the example session, the user responds 'No', and no irrigation systems are eliminated on the basis of labor availability. If the response is 'Yes', the KBS asks the user to input the maximum labor for irrigation expected to be available per week over the growing season. The maximum labor available for irrigation is compared to the labor requirements for each system and irrigation systems having a higher labor requirement in a normal season than that available are eliminated.

The KBS then checks if a water source exists at the site. If the user responds 'No', the cost of developing the water source is included in the capital cost of all suitable systems. The user is given the option of providing a value for the cost of developing the water source (per acre-foot) or using a default value. In the example session, the user responds 'Yes' to the query, and the KBS then prompts for the type of water source, to which the user responds 'Pond'. The KBS then asks the user if any estimate of the maximum storage is available (if the user responds 'Well' or 'Stream' to the type of water source query, the KBS would ask if any estimate of the maximum extraction rate is available). The user responds 'No' to this query, and the KBS informs the user the maximum storage is assumed sufficient to meet the water requirements of all suitable systems and no water source development costs will be included for any of the systems when determining irrigation costs (Figure 15f). However, the user is
advised that since water source development costs may represent a significant part of the total capital costs of irrigation, the user should try and obtain an estimate of the maximum available storage and re-run the program. The user may request information on how to obtain an estimate of the maximum available storage from the KBS. If an estimate of the maximum storage is available, the KBS checks if the total storage is sufficient for all suitable irrigation systems (in a dry year). If the total water requirements for one or more systems is not being met, the KBS asks the user if he/she was willing to consider the cost of providing additional storage. If so, the cost of water source development is added to the capital cost for these systems, otherwise, the area to be irrigated by these systems are reduced according to the available total storage.

The horizontal and vertical distance of the water source from the field are entered next. The KBS then provides the user with the option of entering values for the cost of diesel and lubricating oil for the pumping unit or using default values (Figure 15g). Output on all suitable systems is then written to a temporary file. The user is given the option of viewing or printing this file or saving it permanently. The KBS then evaluates all suitable systems for economic feasibility. The output on economic feasibility is written to a file and may be viewed and/or printed. The user may then change selected input parameters and re-run the irrigation cost models, start another session, or exit to the operating system (Figure 15h).

The complete output for the example interactive session is included in Appendix E. Part of the output on suitable irrigation systems is shown in Figure 16, and a part of the economic evaluation is shown in Figure 17. The output on suitable systems includes a summary of user input and a short description of suitable systems along with the labor and water requirements of each system during a normal and dry year. Parameters for which default values have been used by the KBS are also given and indicated as such in the input summary. The economic evaluation output provides an economic analysis of production under dryland conditions and under all suitable irrigation systems. The output shows returns in a dry and normal year for the maximum and minimum crop price expected and also includes the total initial investment.
SUMMARY OF INPUT INFORMATION

<table>
<thead>
<tr>
<th>Data type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographic location in Virginia</td>
<td>Area C</td>
</tr>
<tr>
<td>County</td>
<td>ALBEMARLE</td>
</tr>
<tr>
<td>Soil name</td>
<td>DYEKE SILTY CLAY LOAM</td>
</tr>
<tr>
<td>Irrigation soil group</td>
<td>Group 13</td>
</tr>
<tr>
<td>Crop</td>
<td>Corn for Grain</td>
</tr>
<tr>
<td>Field shape</td>
<td>Square</td>
</tr>
<tr>
<td>Total area</td>
<td>15.00 acres</td>
</tr>
<tr>
<td>Average field slope</td>
<td>5.00 %</td>
</tr>
<tr>
<td>Maximum crop price expected (dry year)</td>
<td>4.00 $/bu</td>
</tr>
<tr>
<td>Maximum crop price expected (normal year)</td>
<td>3.30 $/bu</td>
</tr>
<tr>
<td>Minimum crop price expected (dry year)</td>
<td>3.00 $/bu</td>
</tr>
<tr>
<td>Minimum crop price expected (normal year)</td>
<td>2.75 $/bu</td>
</tr>
<tr>
<td>Irrigated yield</td>
<td>190.00 bu/acre (D)</td>
</tr>
<tr>
<td>Non-irrigated yield (dry year)</td>
<td>80.00 bu/acre (D)</td>
</tr>
<tr>
<td>Non-irrigated yield (normal year)</td>
<td>110.00 bu/acre (D)</td>
</tr>
<tr>
<td>Cost of non-irrigated production</td>
<td>230.00 $/acre (D)</td>
</tr>
<tr>
<td>Cost of irrigated production excluding</td>
<td></td>
</tr>
<tr>
<td>Irrigation costs</td>
<td>360.00 $/acre. (D)</td>
</tr>
<tr>
<td>Clearing costs</td>
<td>0.00 $/acre</td>
</tr>
<tr>
<td>Drainage costs</td>
<td>0.00 $/acre</td>
</tr>
<tr>
<td>Cost of Diesel</td>
<td>1.25 $/gal. (D)</td>
</tr>
<tr>
<td>Cost of Oil</td>
<td>6.00 $/gal. (D)</td>
</tr>
<tr>
<td>Interest rate</td>
<td>12.00 %</td>
</tr>
</tbody>
</table>

Note: (D) indicates a default value was used for the data type. Crop prices and yields for peanuts are in $/lb and $/bu/acre respectively. For other crops, assume appropriate units.

WATER SOURCE:

Water is available from a Pond.

No information available on maximum total available storage.

Storage assumed sufficient to meet the water requirements of all feasible systems.

Horizontal distance of water source from field 100.00 feet.

Vertical distance of water source from field 40.00 feet.

The following systems have been determined to be suitable:

FIXED CENTER PIVOT

The center pivot system consists of sprinklers mounted on a single lateral arm which moves in a circular motion. The lateral is supported off the ground 8 to 16 feet) by self propelled towers (100 to 200 feet apart), driven by an electric motor on each tower.

The resulting irrigation pattern is a circle, or part circle, and water is fed to the system at the pivot point in the center of the irrigated land.

<table>
<thead>
<tr>
<th>Area irrigated</th>
<th>11.79 Acres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of fixed center pivot</td>
<td>898.33 ft.</td>
</tr>
<tr>
<td>Pumping demand</td>
<td>72.54 GPM</td>
</tr>
<tr>
<td>Total water requirements (dry year)</td>
<td>14.12 Acre-ft</td>
</tr>
<tr>
<td>Total water requirements (normal year)</td>
<td>4.45 Acre-ft</td>
</tr>
<tr>
<td>Total labor requirements (dry year)</td>
<td>7.00 hrs</td>
</tr>
<tr>
<td>Total labor requirements (normal year)</td>
<td>2.00 hrs</td>
</tr>
</tbody>
</table>

Figure 16. Part of output on suitable systems for example interactive session.

RESULTS AND DISCUSSION
*** THE ECONOMIC ANALYSIS IS BASED ON COSTS IN 1984 ***

*** ECONOMIC ANALYSIS FOR DRYLAND PRODUCTION ***

Total area under production = 15.00 Acres
Total cost of Dryland production = $ 4200.00

**RETURNS IN A DRY YEAR (1 IN 10 YEAR DROUGHT)**

With crop price = 4.00 $/BU
Break-even Yield = 70.00 bu/acre
Total profit with a 80.00 bu/acre yield = $ 600.00
Profit per acre = $ 40.00

With crop price = 3.00 $/BU
Break-even Yield = 93.33 bu/acre
The break even yield exceeds the expected yield

**RETURNS IN A NORMAL YEAR (5 IN 10 YEAR DROUGHT)**

With crop price = 3.50 $/BU
Break-even Yield = 80.00 bu/acre
Total profit with a 110.00 bu/acre yield = $ 1575.00
Profit per acre = $ 105.00

With crop price = 2.75 $/BU
Break-even Yield = 101.62 bu/acre
Total profit with a 110.00 bu/acre yield = $ 337.50
Profit per acre = $ 22.50

*** ECONOMIC ANALYSIS FOR FIXED CENTER PIVOT ***

Total area irrigated = 11.79 Acres
Total initial investment = $ 17996.84
Annual fixed cost of Irrigation system = $ 3002.31
Total annual cost of additional inputs for irrigation = $ 942.86

**RETURNS IN A DRY YEAR (1 IN 10 YEAR DROUGHT)**

Annual operating cost of system = $ 1107.94

With crop price = 4.00 $/BU
Value of crop lost due to movement of irrigation equipment = $ 75.43
Break-even Yield = 178.79 bu/acre
Total profit with a 190.00 bu/acre yield = $ 528.60
Profit per acre = $ 44.85

With crop price = 3.00 $/BU
Value of crop lost due to movement of irrigation equipment = $ 56.57
Break-even Yield = 237.85 bu/acre
The break even yield exceeds the expected yield

**RETURNS IN A NORMAL YEAR (5 IN 10 YEAR DROUGHT)**

Annual operating cost of system = $ 348.88

With crop price = 3.50 $/BU
Value of crop lost due to movement of irrigation equipment = $ 90.75
Break-even Yield = 166.29 bu/acre
Total profit with a 190.00 bu/acre yield = $ 152.51
Profit per acre = $ 12.97

With crop price = 2.75 $/BU
Value of crop lost due to movement of irrigation equipment = $ 71.30
Break-even Yield = 236.50 bu/acre
The break even yield exceeds the expected yield

Figure 17. Part of economic evaluation output for example interactive session.

RESULTS AND DISCUSSION
annual fixed cost, annual cost of additional (non-irrigation) inputs, and annual operating costs for all suitable irrigation systems.

The summary of user input in the KBS output on suitable systems is useful if it is desired to re-evaluate a scenario using different input parameters. The output on labor and water requirements for suitable systems provide an indication of the average (normal year) and maximum (dry year) labor and water requirements the user needs to plan for. The economic evaluation output allows the user to compare non-irrigated and irrigated production. An irrigation system which gives lower returns than non-irrigated production in a normal year would be considered economically infeasible. Long term decisions for irrigation are best made on the basis of returns in a normal year, since these are the conditions expected to be encountered most of the time (a normal or average year was defined as a 5 in 10 year drought). However, the returns in a dry year (defined as a 1 in 10 year drought), will be of interest to the user as an indication of the maximum returns that can be expected, since irrigation is generally more profitable in a dry year.

The KBS output on suitable systems for the example session has been summarized in Table 8. The towable center pivot systems were determined not to be suitable as the area proposed to be irrigated is only 15 acres. Water requirements for the portable pipe systems are slightly higher than for the traveling gun, due to their lower overall irrigation efficiency. The labor requirements of the portable pipe systems, particularly the medium pressure system are considerably higher than the traveling gun. Although the fixed center pivot irrigates a smaller acreage than the other systems, on a per acre basis, the water requirements are less because of its higher irrigation efficiency and labor requirements are also extremely low.

The economic evaluation output for the example session has been summarized in Table 10. Although it is likely that users would be inclined to use total profit from the irrigated area to compare irrigation systems, it should be noted that the area irrigated by center pivot systems is always less than the total area proposed to be irrigated as center pivot systems are constrained to irrigating in a circular pattern. This may distort initial, first-cut comparisons of center pivot systems and other irrigation systems on the basis of total profit. When the total
Table 9. Summary of output on suitable irrigation systems for interactive session.

<table>
<thead>
<tr>
<th>Irrigation system (acreage)</th>
<th>Total water requirements, normal year (ac-ft)</th>
<th>Total water requirements, dry year (ac-ft)</th>
<th>Total labor requirements, normal year (hr)</th>
<th>Total labor requirements dry year (hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fixed center pivot (11.79)</td>
<td>4.45</td>
<td>14.12</td>
<td>2</td>
<td>7</td>
</tr>
<tr>
<td>Traveling gun (15.00)</td>
<td>6.04</td>
<td>19.17</td>
<td>8</td>
<td>23</td>
</tr>
<tr>
<td>Portable pipe, medium pressure (15.00)</td>
<td>6.47</td>
<td>20.54</td>
<td>37</td>
<td>115</td>
</tr>
<tr>
<td>Portable pipe, high pressure (15.00)</td>
<td>6.47</td>
<td>20.54</td>
<td>19</td>
<td>58</td>
</tr>
</tbody>
</table>
Table 10. Summary of economic evaluation output for interactive session.

<table>
<thead>
<tr>
<th>Irrigation system (acreage)</th>
<th>Initial investment ($)</th>
<th>Operating costs, normal year ($)</th>
<th>Operating costs, dry year ($)</th>
<th>Profit per acre¹ ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-irrigated (15.00)</td>
<td></td>
<td></td>
<td></td>
<td>N1² N2 D1 D2</td>
</tr>
<tr>
<td>Fixed center pivot (11.79)</td>
<td>17,997</td>
<td>349</td>
<td>1,108</td>
<td>105.00 23.50 40.00 -40.00</td>
</tr>
<tr>
<td>Traveling gun (15.00)</td>
<td>10,716</td>
<td>267</td>
<td>847</td>
<td>12.97 -127.9 44.85 -143.5</td>
</tr>
<tr>
<td>Portable pipe, medium pressure (15.00)</td>
<td>8,042</td>
<td>364</td>
<td>1,154</td>
<td>152.63 13.43 211.59 24.79</td>
</tr>
<tr>
<td>Portable pipe, high pressure (15.00)</td>
<td>7,908</td>
<td>356</td>
<td>1,128</td>
<td>189.48 47.81 233.62 44.42</td>
</tr>
</tbody>
</table>

¹Calculated from total profit for acreage irrigated by system.
²N1 = Normal year with crop price $3.50
N2 = Normal year with crop price $2.75
D1 = Dry year with crop price $4.00
D2 = Dry year with crop price $3.00
area irrigated by the center pivot systems is fairly small compared to the area originally proposed to be irrigated, the total profit for center pivot systems will always be much less than for other systems even though the profit per acre may be comparable or higher. Since the KBS was developed to provide first-cut information only, it is possible that a user, seeing a fairly high profit per acre for a center pivot system (but a low total profit), may decide to clear additional area and re-evaluate a scenario with a larger irrigated area possible under center pivot systems. Hence, to provide an useful basis for an initial, first-cut, comparison of the relative profitability of irrigation systems, profit per acre was used. The economic evaluation output provides both total profit and profit per acre, however only profit per acre has been given in Table 10. To obtain the total profit, the profit per acre should be multiplied by the acreage irrigated by the system.

As can be seen from Table 10, the portable pipe, high pressure system, is the most economically feasible as profits are considerably higher than non-irrigated production in both normal and dry years. The portable pipe, medium pressure system is the next most profitable system. However, the considerably higher labor requirements also have to be considered. Irrigators (or potential irrigators) generally tend to prefer less labor intensive systems. The traveling gun is also a viable alternative and has the advantage of much lower labor requirement than the portable pipe, high pressure system. However, the traveling gun is not as profitable as the portable pipe systems, and in fact has a lower profit in a normal year with a low crop price than non-irrigated production. The fixed center pivot system is not economically feasible as the profit in a normal year with a high crop price is much lower than non-irrigated production, and the system would actually lose money in a normal year with a low crop price.
Knowledge-base Evaluation

The evaluation of a KBS requires assessment of the system's overall value in terms of useability, efficiency, and cost effectiveness (O'Keefe et al., 1988). The KBS evaluation process must consider a number of issues, including testing of the user interface, verification of the knowledge-base, and validation of system performance. O'Keefe et al. (1988) state that separating performance validation from other aspects of evaluation can be difficult and they suggest that particularly in ground-breaking applications, an overall evaluation policy may seem more relevant.

Case data or sample problems are critical to the evaluation of a KBS and must serve a number of functions while other cases are required that will test specific situations (Walters and Nielsen, 1988). Sample cases are required that will evaluate typical or common situations. Still other cases might be generated somewhat randomly to represent the breadth of situations that might at some future time be presented to the application for solution. Taken together, the case data must exercise or test the characteristics of the most critical parts of the application's behavior (Walters and Nielsen, 1988).

The KBS developed in this study provides a basic framework which can be used to build a more comprehensive system which would consider additional irrigation systems and crops. Because of the KBS's limited domain, it was felt that extensive evaluation at this stage would not be meaningful, and it was decided to employ an overall, qualitative procedure in its evaluation. The evaluation procedure used can be summarized as follows:

- The expert, who was the state irrigation specialist, identified sample problems (scenarios representing potential irrigation sites in Virginia) for testing the KBS.
- Solutions to the sample problems were obtained by having users not familiar with the development tool use the KBS to work through the sample problems.
The expert assessed the results obtained from the KBS as being acceptable or unacceptable for each of the scenarios.

The input data for the four scenarios identified by the expert are given in Table 11. Default values were used wherever provided by the KBS and the following was assumed for all the scenarios:

- No clearing costs were included.
- Labor availability was not a critical factor (that is, labor supply was not a factor limiting system selection).
- The maximum/minimum price of corn in a dry and normal year was $4.00/$3.00 per bushel and $3.50/$2.75 per bushel respectively.
- Possible water source development costs were not assessed.
- The annual interest rate was 12 percent.

Scenario 1 was used in the example interactive session and the KBS output for it has already been discussed. The KBS economic evaluation output for Scenario 2 is summarized in Table 12. As explained previously, profit per acre is used to provide a basis for comparing the relative profitability of irrigation systems. For Scenario 2, all irrigation systems were found to be suitable and in a normal year with high crop prices, all irrigation systems showed a greater profit than non-irrigated production. However, in a normal year with low crop prices, only the three point, toteable center pivot system showed a greater profit than non-irrigated production. In addition, the three point, toteable center pivot system showed the greatest profit in a dry year at both low and high crop prices.

The KBS economic evaluation output for Scenario 3 is summarized in Table 13. Although all irrigation systems were found to be suitable for Scenario 3, the fixed center pivot system was economically infeasible. The portable pipe, high pressure system showed the greatest profit in a normal year at both high and low crop prices, and in a dry year at a high crop price.
Table 11. Input data for scenarios.

<table>
<thead>
<tr>
<th></th>
<th>Scenario 1</th>
<th>Scenario 2</th>
<th>Scenario 3</th>
<th>Scenario 4</th>
</tr>
</thead>
<tbody>
<tr>
<td>Area (ac)</td>
<td>15</td>
<td>200</td>
<td>85</td>
<td>80</td>
</tr>
<tr>
<td>Crop</td>
<td>Corn for grain</td>
<td>Corn for grain</td>
<td>Corn for grain</td>
<td>Corn for grain</td>
</tr>
<tr>
<td>Field shape</td>
<td>Square</td>
<td>Irregular</td>
<td>Irregular</td>
<td>Rectangular</td>
</tr>
<tr>
<td>Dimensions (ft)</td>
<td>N/A</td>
<td>N/A</td>
<td>N/A</td>
<td>3485 X 1000</td>
</tr>
<tr>
<td>Diameter of largest</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>circles that can fit</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>in the field (ft):</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Largest single circle</td>
<td>N/A</td>
<td>1430</td>
<td>915</td>
<td>N/A</td>
</tr>
<tr>
<td>Largest two circles</td>
<td>N/A</td>
<td>1170</td>
<td>915</td>
<td>N/A</td>
</tr>
<tr>
<td>Largest three circles</td>
<td>N/A</td>
<td>1080</td>
<td>890</td>
<td>N/A</td>
</tr>
<tr>
<td>Average slope (%)</td>
<td>5</td>
<td>6</td>
<td>2</td>
<td>6</td>
</tr>
<tr>
<td>Location</td>
<td>Albemarle</td>
<td>Brunswick</td>
<td>Southampton</td>
<td>Montgomery</td>
</tr>
<tr>
<td>Soil¹</td>
<td>Dyke scl</td>
<td>Madison fsl</td>
<td>Kempsville</td>
<td>Hayler loam</td>
</tr>
<tr>
<td>Type of water source</td>
<td>Pond</td>
<td>Pond</td>
<td>Pond</td>
<td>Stream</td>
</tr>
<tr>
<td>Distance from water source (R):</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Horizontal</td>
<td>1000</td>
<td>1300</td>
<td>1500</td>
<td>500</td>
</tr>
<tr>
<td>Vertical</td>
<td>40</td>
<td>30</td>
<td>15</td>
<td>50</td>
</tr>
</tbody>
</table>

¹Abbreviations: scl = silty clay loam, fsl = fine sandy loam
N/A: Not applicable
Table 12. Summary of economic evaluation output for Scenario 2.

<table>
<thead>
<tr>
<th>Irrigation system (acreage)</th>
<th>Initial investment ($)</th>
<th>Operating costs, normal year ($)</th>
<th>Operating costs, dry year ($)</th>
<th>Profit per acre¹ ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-irrigated (200.00)</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Fixed center pivot (36.88)</td>
<td>32,906</td>
<td>801</td>
<td>2,552</td>
<td>126.75 -14.10 175.57 -12.83</td>
</tr>
<tr>
<td>Towable, 2 point (49.38)</td>
<td>34,431</td>
<td>887</td>
<td>2,826</td>
<td>161.19 20.56 218.46 30.46</td>
</tr>
<tr>
<td>Towable, 3 point (63.12)</td>
<td>37,227</td>
<td>1,135</td>
<td>3,316</td>
<td>178.99 38.55 238.31 48.31</td>
</tr>
<tr>
<td>Traveling gun (200.00)</td>
<td>134,188</td>
<td>6,297</td>
<td>20.052</td>
<td>146.19 6.99 175.01 -11.79</td>
</tr>
<tr>
<td>Portable pipe, medium pressure (200.00)</td>
<td>146,323</td>
<td>9,857</td>
<td>31.341</td>
<td>129.81 -11.86 117.80 -71.40</td>
</tr>
<tr>
<td>Portable pipe, high pressure (200.00)</td>
<td>128,835</td>
<td>7,833</td>
<td>24.965</td>
<td>156.18 14.48 166.16 -23.02</td>
</tr>
</tbody>
</table>

¹Calculated from total profit for acreage irrigated by system.
²N1 = Normal year with crop price $3.50
N2 = Normal year with crop price $2.75
D1 = Dry year with crop price $4.00
D2 = Dry year with crop price $3.00
Table 13. Summary of economic evaluation output for Scenario 3.

<table>
<thead>
<tr>
<th>Irrigation system (acreage)</th>
<th>Initial investment ($)</th>
<th>Operating costs, normal year ($)</th>
<th>Operating costs, dry year ($)</th>
<th>Profit per acre¹ ($)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-irrigated (95.00)</td>
<td>21,081</td>
<td>332</td>
<td>1,296</td>
<td>105.00 23.50 40.00 -40.00</td>
</tr>
<tr>
<td>Fixed center pivot (15.10)</td>
<td></td>
<td></td>
<td></td>
<td>42.46 -96.39 74.89 -113.5</td>
</tr>
<tr>
<td>Towable, 2 point (30.20)</td>
<td>26,997</td>
<td>456</td>
<td>1,781</td>
<td>131.15 -9.29 183.93 -4.09</td>
</tr>
<tr>
<td>Towable, 3 point (42.86)</td>
<td>31,235</td>
<td>428</td>
<td>1,944</td>
<td>162.17 21.73 225.08 37.06</td>
</tr>
<tr>
<td>Traveling gun (95.00)</td>
<td>55,901</td>
<td>1,711</td>
<td>6,674</td>
<td>173.42 34.22 218.79 31.99</td>
</tr>
<tr>
<td>Portable pipe, medium pressure (95.00)</td>
<td>55,374</td>
<td>2,340</td>
<td>9,359</td>
<td>178.65 36.98 201.05 11.85</td>
</tr>
<tr>
<td>Portable pipe, high pressure (95.00)</td>
<td>49,359</td>
<td>2,066</td>
<td>8,056</td>
<td>192.73 51.06 225.33 36.13</td>
</tr>
</tbody>
</table>

¹Calculated from total profit for acreage irrigated by system.
²N1 = Normal year with crop price $3.50
N2 = Normal year with crop price $2.75
D1 = Dry year with crop price $4.00
D2 = Dry year with crop price $3.00
However, the three point, towable center pivot system showed the greatest profit in a dry year with a low crop price.

The KBS economic evaluation output for Scenario 4 is summarized in Table 14. The fixed and two point towable center pivot systems were determined not to be suitable as the length to width ratio of the field exceeded 2.5. All suitable systems showed a greater profit than non-irrigated production in both dry and normal years. However, the profit for the portable pipe systems was considerably higher than the traveling gun or three point towable center pivot system, particularly during a normal year.

For the KBS evaluation, suitable irrigation systems for a given scenario were ranked on the basis of the KBS output for profit per acre in a normal year with a crop price of $3.5 per bushel. This was taken as representing long-term ‘average’ conditions. A system which gave a lower profit per acre than dryland production in a normal year was considered to be economically infeasible. The expert was asked to rate the KBS performance as acceptable or not acceptable for each scenario based on an objective assessment of the KBS’s results, keeping in mind the system’s limitations. Results of the KBS evaluation are presented in Table 15. The KBS performance was found to be acceptable for all scenarios.

The user-interface was evaluated by user comments on system prompts and whether any ambiguities were encountered. All users had some general familiarity with irrigation and were provided with the data required to evaluate each scenario. Results of the user-interface are presented in Table 16. The user-interface was found to be satisfactory with users giving the interface an average rating of 8.2 on a scale of 1 to 10 (with 10 representing excellent), based on system prompts and the ease with which they were able to input data. The time for obtaining a solution was considerably reduced after the users had run through the system once.

Although the KBS performance was acceptable for the domain targeted, the expert noted a number of areas where the knowledge base could be enhanced:

- Center-pivot systems need to be evaluated with the option of having large end guns or corner systems for irrigating additional area.
Table 14. Summary of economic evaluation output for Scenario 4.

<table>
<thead>
<tr>
<th>Irrigation system (acreage)</th>
<th>Initial investment ($)</th>
<th>Operating costs, normal year ($)</th>
<th>Operating costs, dry year ($)</th>
<th>Profit per acre ($)¹</th>
</tr>
</thead>
<tbody>
<tr>
<td>Non-irrigated (80.00)</td>
<td></td>
<td></td>
<td></td>
<td>105.00 23.50 40.00 -40.00</td>
</tr>
<tr>
<td>Towable, 3 point (54.11)</td>
<td>32,265</td>
<td>397</td>
<td>1,965</td>
<td>188.57 48.13 258.21 68.21</td>
</tr>
<tr>
<td>Traveling gun (80.00)</td>
<td>44,675</td>
<td>842</td>
<td>4,161</td>
<td>185.92 46.72 242.02 55.22</td>
</tr>
<tr>
<td>Portable pipe, medium pressure (80.00)</td>
<td>35,742</td>
<td>987</td>
<td>4,877</td>
<td>214.28 72.61 261.30 72.10</td>
</tr>
<tr>
<td>Portable pipe, high pressure (80.00)</td>
<td>31,850</td>
<td>936</td>
<td>4,625</td>
<td>223.04 81.36 272.57 83.37</td>
</tr>
</tbody>
</table>

¹Calculated from total profit for acreage irrigated by system.
²N1 = Normal year with crop price $3.50
N2 = Normal year with crop price $2.75
D1 = Dry year with crop price $4.00
D2 = Dry year with crop price $3.00
<table>
<thead>
<tr>
<th>Scenario 1</th>
<th>Suitable systems and ranking based on KBS output</th>
<th>Expert’s assessment</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>PPH(^1), PPM(^2), TG(^3) CP(^-)</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Scenario 2</td>
<td>CP(^3), CP(^2), PPH(^3) TG(^4), PPM(^5), CP(^6)</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Scenario 3</td>
<td>PPH(^1), PPM(^2), TG(^3) CP(^3), CP(^2), CP(^-)</td>
<td>Acceptable</td>
</tr>
<tr>
<td>Scenario 4</td>
<td>PPH(^1), PPM(^2), CP(^3) TG(^4)</td>
<td>Acceptable</td>
</tr>
</tbody>
</table>

CP: Fixed center pivot  
CP2: Towable center pivot, two point  
CP3: Towable center pivot, three point  
TG: Traveling gun  
PPH: Portable pipe (High pressure)  
PPM: Portable pipe (Low pressure)  

Superscripts show the economic ranking of the irrigation system. A minus superscript indicates that the irrigation system had lower profit per acre than without irrigation.
Table 16. User-interface evaluation.

<table>
<thead>
<tr>
<th>User</th>
<th>Experience with KBSs</th>
<th>Knowledge of irrigation</th>
<th>Number of ambiguous statements</th>
<th>Rating of user-interface</th>
<th>Time taken for first run (min)</th>
<th>Average time for subsequent runs (min)</th>
</tr>
</thead>
<tbody>
<tr>
<td>User 1</td>
<td>S</td>
<td>C</td>
<td>1</td>
<td>8</td>
<td>19</td>
<td>9</td>
</tr>
<tr>
<td>User 2</td>
<td>S</td>
<td>S</td>
<td>0</td>
<td>8</td>
<td>22</td>
<td>12</td>
</tr>
<tr>
<td>User 3</td>
<td>N</td>
<td>S</td>
<td>0</td>
<td>9</td>
<td>40</td>
<td>8</td>
</tr>
<tr>
<td>User 4</td>
<td>S</td>
<td>S</td>
<td>0</td>
<td>8</td>
<td>20</td>
<td>13</td>
</tr>
<tr>
<td>User 5</td>
<td>N</td>
<td>S</td>
<td>0</td>
<td>8</td>
<td>30</td>
<td>9</td>
</tr>
</tbody>
</table>

1 N = No experience, S = Some experience, C = Considerable experience
2 N = No knowledge, S = Some knowledge, C = Considerable knowledge
3 On a scale of 1 to 10, based on system prompts and the ease with which the user was able to input data (1 = Poor,...5 = Fair,...10 = Excellent)
• The fixed center-pivot evaluation is severely limited if it only considers the largest (whole) circular area that can be irrigated in the field because of the generally irregular field shapes in Virginia. A routine which would consider a part-circle, fixed center pivot for irregularly shaped fields should be included in the KBS. The part-circle, center-pivot system only irrigates in one direction of travel. The pivot is located at a suitable point at the edge of the field so as to allow the lateral to sweep out the maximum area possible. Although fixed costs are high for a part-circle center pivot system, it may be a viable choice for irregular fields because it maximizes the area (for a center pivot system) that can be brought under irrigation.

• The KBS should be able to consider crop rotations e.g. a corn/soybean system. This could be done by including routines in the irrigation cost models which determine fixed costs with respect to the crop with the higher water requirements, while variable costs and returns are determined for each crop.

• The KBS should have some facility for handling personal preferences of the user. For example, a user growing a large acreage of corn may not want to consider portable-pipe systems at all, even if sufficient labor is available, because of the difficulty in moving pipes in a field near crop maturity.

The following comments were made by persons evaluating the user-interface:

• Checks should be provided for warning the user when illogical crop prices/yields are entered e.g. a higher non-irrigated yield in a dry year than a normal year.

• For the case where the ‘crop not listed’ option is selected, the user should also be required to input the units for yield and crop price so that these are displayed in the appropriate units in the KBS output.

• A summary table ranking suitable irrigation systems should be included in the economic evaluation output.
**Sensitivity Analysis**

The results of the economic evaluation for Scenario 2 were used as the base scenario for a sensitivity analysis of profit per acre to key engineering and economic input parameters. Scenario 2 was chosen because all six irrigation systems were found to be feasible under it. To provide a uniform basis for comparison, the irrigated area for the base scenario was taken to be 200 acres for all six systems. Relative sensitivity for input parameters was calculated as follows:

\[
S_R = \frac{R - R_b}{R_b - P_b} \frac{R_b}{P_b}
\]

where:
- \(S_R\) = relative sensitivity
- \(P_b\) = parameter value for base scenario
- \(R_b\) = model result using base scenario
- \(P\) = new parameter value
- \(R\) = model result using \(P\) with all other input variables held constant

This method of calculating sensitivity provides a consistent measure for comparison between parameters. Higher absolute values of \(S_R\) indicate increased sensitivity of the model output to the parameter in question. Negative \(S_R\) values indicate an inverse relationship between parameter and output (Heatwole et al., 1987).

The results of the sensitivity analysis for the center-pivot systems are shown in Table 17. Results of the sensitivity analysis for the traveling gun and portable pipe systems are shown in Table 18.

All the irrigation cost models were very sensitive to crop price, with \(S_R\) values ranging from 3.31 for the three point towable center pivot model to 5.09 for the portable pipe, high
Table 17. Sensitivity analysis for center-pivot cost models.

<table>
<thead>
<tr>
<th>Param. base value</th>
<th>Param. base</th>
<th>Percent- age of Value</th>
<th>CP  Value</th>
<th>( S_n )</th>
<th>Value</th>
<th>( S_n )</th>
<th>Value</th>
<th>( S_n )</th>
</tr>
</thead>
<tbody>
<tr>
<td>BASE SCENARIO</td>
<td>300</td>
<td>+50</td>
<td>207.03</td>
<td>0.103</td>
<td>212.93</td>
<td>0.115</td>
<td>209.06</td>
<td>0.120</td>
</tr>
<tr>
<td>AREA (200)</td>
<td>260</td>
<td>+30</td>
<td>206.60</td>
<td>0.167</td>
<td>209.98</td>
<td>0.142</td>
<td>206.36</td>
<td>0.141</td>
</tr>
<tr>
<td></td>
<td>140</td>
<td>-30</td>
<td>194.61</td>
<td>0.039</td>
<td>194.84</td>
<td>0.108</td>
<td>194.57</td>
<td>0.057</td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>-30</td>
<td>186.14</td>
<td>0.109</td>
<td>190.64</td>
<td>0.107</td>
<td>192.26</td>
<td>0.058</td>
</tr>
<tr>
<td>HD (1300)</td>
<td>1950</td>
<td>+50</td>
<td>192.13</td>
<td>-0.045</td>
<td>196.61</td>
<td>-0.048</td>
<td>193.17</td>
<td>-0.049</td>
</tr>
<tr>
<td></td>
<td>1560</td>
<td>+20</td>
<td>195.01</td>
<td>-0.048</td>
<td>199.49</td>
<td>-0.047</td>
<td>196.07</td>
<td>-0.048</td>
</tr>
<tr>
<td></td>
<td>1040</td>
<td>+20</td>
<td>198.85</td>
<td>-0.049</td>
<td>203.35</td>
<td>-0.049</td>
<td>199.95</td>
<td>-0.050</td>
</tr>
<tr>
<td></td>
<td>650</td>
<td>-50</td>
<td>201.73</td>
<td>-0.049</td>
<td>206.24</td>
<td>-0.048</td>
<td>202.85</td>
<td>-0.049</td>
</tr>
<tr>
<td>VD (30)</td>
<td>45</td>
<td>+50</td>
<td>195.25</td>
<td>-0.017</td>
<td>199.71</td>
<td>-0.017</td>
<td>196.27</td>
<td>-0.017</td>
</tr>
<tr>
<td></td>
<td>35</td>
<td>+20</td>
<td>196.26</td>
<td>-0.016</td>
<td>200.74</td>
<td>-0.016</td>
<td>197.31</td>
<td>-0.017</td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>-20</td>
<td>197.60</td>
<td>-0.016</td>
<td>202.11</td>
<td>-0.018</td>
<td>198.71</td>
<td>-0.018</td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>-50</td>
<td>198.66</td>
<td>-0.017</td>
<td>203.13</td>
<td>-0.017</td>
<td>199.76</td>
<td>-0.018</td>
</tr>
<tr>
<td>INT (12.0)</td>
<td>15.96</td>
<td>+33</td>
<td>180.49</td>
<td>-0.252</td>
<td>186.07</td>
<td>-0.231</td>
<td>182.05</td>
<td>-0.244</td>
</tr>
<tr>
<td></td>
<td>13.98</td>
<td>+16.5</td>
<td>188.85</td>
<td>-0.248</td>
<td>193.88</td>
<td>-0.226</td>
<td>169.66</td>
<td>-0.233</td>
</tr>
<tr>
<td></td>
<td>10.02</td>
<td>-16.5</td>
<td>204.69</td>
<td>-0.240</td>
<td>208.67</td>
<td>-0.219</td>
<td>205.55</td>
<td>-0.232</td>
</tr>
<tr>
<td></td>
<td>8.04</td>
<td>-33</td>
<td>210.78</td>
<td>-0.213</td>
<td>214.36</td>
<td>-0.195</td>
<td>211.46</td>
<td>-0.209</td>
</tr>
<tr>
<td>CRPR (3.50)</td>
<td>4.20</td>
<td>+20</td>
<td>328.39</td>
<td>3.346</td>
<td>332.49</td>
<td>3.258</td>
<td>329.09</td>
<td>3.310</td>
</tr>
<tr>
<td></td>
<td>3.85</td>
<td>+10</td>
<td>262.66</td>
<td>3.339</td>
<td>266.96</td>
<td>3.256</td>
<td>263.55</td>
<td>3.311</td>
</tr>
<tr>
<td></td>
<td>3.15</td>
<td>-10</td>
<td>131.20</td>
<td>3.337</td>
<td>135.89</td>
<td>3.253</td>
<td>132.47</td>
<td>3.309</td>
</tr>
<tr>
<td></td>
<td>2.80</td>
<td>-20</td>
<td>65.47</td>
<td>3.338</td>
<td>70.35</td>
<td>3.253</td>
<td>65.94</td>
<td>3.309</td>
</tr>
<tr>
<td>CLAB (4.00)</td>
<td>5.5</td>
<td>+37.5</td>
<td>196.60</td>
<td>-0.004</td>
<td>200.76</td>
<td>-0.008</td>
<td>197.02</td>
<td>-0.013</td>
</tr>
<tr>
<td></td>
<td>4.5</td>
<td>+12.5</td>
<td>196.81</td>
<td>-0.004</td>
<td>201.20</td>
<td>-0.008</td>
<td>197.68</td>
<td>-0.012</td>
</tr>
<tr>
<td></td>
<td>3.5</td>
<td>-12.5</td>
<td>197.04</td>
<td>-0.005</td>
<td>201.64</td>
<td>-0.010</td>
<td>198.34</td>
<td>-0.015</td>
</tr>
<tr>
<td></td>
<td>3.0</td>
<td>-25.0</td>
<td>197.15</td>
<td>-0.007</td>
<td>201.86</td>
<td>-0.009</td>
<td>198.67</td>
<td>-0.014</td>
</tr>
</tbody>
</table>

Abbreviations and symbols:
- Param. = Parameter
- HD = horizontal distance (feet)
- VD = vertical distance (feet)
- INT = Annual percentage interest rate
- CRPR = Crop price in a normal year ($/bu)
- CLAB = Cost of labor ($/hour)
- CP = Fixed center pivot
- CP2 = Two-point towable center pivot
- CP3 = Three-point towable center pivot
- \( S_n \) = Relative sensitivity
Table 18. Sensitivity analysis for traveling gun and portable pipe cost models.

<table>
<thead>
<tr>
<th>Param. (base value)</th>
<th>Param. value</th>
<th>Percent-age of</th>
<th>Param. base</th>
<th>TG Value</th>
<th>S_R</th>
<th>Profit per acre</th>
<th>PPM Value</th>
<th>S_R</th>
<th>PPH Value</th>
<th>S_R</th>
</tr>
</thead>
<tbody>
<tr>
<td>AREA (200)</td>
<td>300</td>
<td>+50</td>
<td>134.92</td>
<td>-0.154</td>
<td>103.74</td>
<td>-0.402</td>
<td>125.44</td>
<td>-0.393</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>260</td>
<td>+30</td>
<td>139.64</td>
<td>-0.149</td>
<td>105.44</td>
<td>-0.626</td>
<td>127.53</td>
<td>-0.611</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>140</td>
<td>-30</td>
<td>150.65</td>
<td>-0.102</td>
<td>146.77</td>
<td>-0.436</td>
<td>170.45</td>
<td>-0.305</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>100</td>
<td>-50</td>
<td>155.23</td>
<td>-0.260</td>
<td>152.06</td>
<td>-0.497</td>
<td>179.04</td>
<td>-0.293</td>
<td></td>
<td></td>
</tr>
<tr>
<td>HD (1300)</td>
<td>1950</td>
<td>+50</td>
<td>141.24</td>
<td>-0.068</td>
<td>124.45</td>
<td>-0.082</td>
<td>150.98</td>
<td>-0.066</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1560</td>
<td>+20</td>
<td>144.21</td>
<td>-0.068</td>
<td>127.66</td>
<td>-0.082</td>
<td>154.08</td>
<td>-0.066</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>1040</td>
<td>-20</td>
<td>148.17</td>
<td>-0.068</td>
<td>131.95</td>
<td>-0.083</td>
<td>158.23</td>
<td>-0.066</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>650</td>
<td>-50</td>
<td>151.13</td>
<td>-0.068</td>
<td>135.17</td>
<td>-0.083</td>
<td>161.33</td>
<td>-0.066</td>
<td></td>
<td></td>
</tr>
<tr>
<td>VD (30)</td>
<td>45</td>
<td>+50</td>
<td>144.16</td>
<td>-0.028</td>
<td>127.20</td>
<td>-0.040</td>
<td>153.70</td>
<td>-0.031</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>36</td>
<td>+20</td>
<td>145.38</td>
<td>-0.028</td>
<td>128.77</td>
<td>-0.040</td>
<td>155.17</td>
<td>-0.032</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>24</td>
<td>-20</td>
<td>146.99</td>
<td>-0.028</td>
<td>130.85</td>
<td>-0.040</td>
<td>157.14</td>
<td>-0.031</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>15</td>
<td>-50</td>
<td>148.22</td>
<td>-0.028</td>
<td>132.41</td>
<td>-0.040</td>
<td>158.61</td>
<td>-0.031</td>
<td></td>
<td></td>
</tr>
<tr>
<td>INT (12.0)</td>
<td>15.96</td>
<td>+33</td>
<td>124.58</td>
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Abbreviations and symbols:
- Param. = Parameter
- TD = Total distance (feet)
- VD = Vertical distance (feet)
- CRPR = Crop price in a normal year ($/bu)
- TG = Traveling gun
- CLAB = Cost of labor ($/hour)
- PPM = Portaible pipe (medium-pressure)
- PPH = Portable pipe (high pressure)
- HD = Horizontal distance (feet)
- INT = Annual percentage interest rate
- S_R = Relative sensitivity

RESULTS AND DISCUSSION
pressure model. A $S_R$ value of 5 means that a 10% change in parameter value would produce a 50% change in model output. However, the $S_R$ values obtained for the center pivot models were lower than for the other models, indicating that risks associated with irrigation by center pivot systems were lower than with other irrigation systems.

The models were also fairly sensitive to interest rate and area irrigated. The portable pipe models, particularly the medium pressure model showed the greatest sensitivity to both area and interest rate. The $S_R$ values for area for the center pivot systems were positive, showing that profit per acre for center pivot systems always increases with increasing area. However, the $S_R$ values for area for the traveling gun and portable pipe models were negative, showing that profit per acre for these systems decreases after the acreage irrigated reaches a certain point.

The models showed a moderate degree of sensitivity to horizontal and vertical distance. The portable pipe, medium pressure model was the most sensitive to both horizontal and vertical distance. The center pivot and traveling gun models were generally insensitive to the cost of labor. The portable pipe, medium pressure model was fairly sensitive to the cost of labor, while the portable pipe, high pressure model showed slight sensitivity.

Based on the results of the sensitivity analysis, potential users of the KBS should focus on obtaining accurate input values for crop price and interest rate. The total area that can be brought under irrigation is also an important factor affecting model output.
SUMMARY AND CONCLUSIONS

Summary

A prototype knowledge based system (KBS) has been developed to determine the economic feasibility of several irrigation systems site-specific conditions in Virginia. Irrigation systems considered by the KBS are center pivot, traveling gun and portable pipe. Crops considered are field corn, soybeans, and peanuts.

The KBS has three major components: a rule-base for controlling information flow, databases for providing soils, crops and drought information, and irrigation cost models for determining average annual irrigation costs for different systems. The KBS uses information input by the user to determine possible irrigation alternatives and provides an economic evaluation of suitable systems based on domain-specific knowledge about soils, crops, irrigation costs and agricultural drought in Virginia. The KBS output on suitable systems provides a summary of user input and a short description of suitable systems along with labor and water requirements of each system during a normal and dry year. The economic evaluation output provides an analysis of production under dryland conditions and under all suitable systems. The output shows returns in a dry and normal year for the maximum and minimum crop price expected and includes the total initial investment, annual fixed cost, annual cost of additional (non-irrigation) inputs, and annual operating costs for all suitable irrigation systems.
The KBS was evaluated by using it to assess scenarios representing potential irrigation sites in Virginia and having an expert critically examine the results. The KBS performance was found to be satisfactory for the domain targeted. The KBSs evaluation of fixed center pivot systems needs to be improved so that part-circle systems are considered. Other areas where the KBS needs improvement are handling situations where more than one crop is to be irrigated and being more responsive to personal preferences of users. A sensitivity analysis of the irrigation cost models to key engineering and economic parameters showed that potential KBS users should focus on obtaining accurate input values for crop price and interest rate. The total area that can be brought under irrigation is also an important factor affecting model output.

**Conclusions**

A knowledge based system to provide first-cut information on suitable irrigation systems and an economic evaluation of these systems for site-specific situations in Virginia was successfully developed. The KBS consists of a rule-base for controlling information flow, databases for providing soils, crops and drought information, and irrigation cost models for determining average annual irrigation costs for different systems. The KBS has a limited domain and can be regarded as a prototype of a more comprehensive system.

Preliminary evaluation of the KBS indicated that its performance was satisfactory in addressing the domain targeted. However, some areas of the knowledge base need to be improved and a larger domain addressed to produce solutions of better quality so that it may be deployed for use by farmers and/or extension agents exploring irrigation development in Virginia.

The following recommendations are given for future expansion of the KBS:
1. Develop routines for part-circle irrigation center pivot systems in the current center-pivot cost model.
2. Include large end guns for irrigating additional area in center pivot cost models.
3. Develop routines for handling crop rotations, for example a corn/soybean system.
4. Make the KBS more responsive to personal preferences of users.
5. Include checks for warning the user when illogical values are entered.
6. Include a summary table ranking suitable irrigation systems in the economic evaluation output.
7. Develop irrigation cost models for other sprinkler systems and trickle systems.
8. Include additional crops in the databases and draw up production budgets for these crops. Incorporate the methodology used in developing the budget into a rule base that could be used for easy updating of the crops databases.
9. Include crop dryland yields in the crop databases to reflect differences across soil types and/or geographical location.
10. Include crop irrigated yields in the crop databases to reflect differences in uniformity of water application and timing of irrigation for different irrigation systems.
11. Consider the soil type when drainage costs are to be included and develop a rule base for updating drainage costs.
12. Develop a rule base for updating of the cost parameters used in the KBS.
13. Carry out extensive on-site evaluation of the KBS.
REFERENCES


APPENDIX A: Variable Glossary

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<td>TCSM</td>
<td>R</td>
<td>Total cost of sub-main, $</td>
</tr>
<tr>
<td>TH</td>
<td>R</td>
<td>Total pumping head, ft</td>
</tr>
<tr>
<td>TLL</td>
<td>R</td>
<td>Total length of laterals for portable pipe systems, ft</td>
</tr>
<tr>
<td>TPI</td>
<td>R</td>
<td>Time per irrigation cycle, hr</td>
</tr>
<tr>
<td>TVC</td>
<td>RV</td>
<td>Total variable costs, $</td>
</tr>
<tr>
<td>TVCA</td>
<td>RV</td>
<td>Total variable costs per acre</td>
</tr>
<tr>
<td>TWR</td>
<td>RV</td>
<td>Total water requirements, ac-in</td>
</tr>
<tr>
<td>VD</td>
<td>R</td>
<td>Vertical distance from water source to field, m</td>
</tr>
<tr>
<td>VHOS</td>
<td>R</td>
<td>Velocity of water in traveling gun hose, ft/s</td>
</tr>
<tr>
<td>VL</td>
<td>R</td>
<td>Velocity of water in lateral, ft/s</td>
</tr>
<tr>
<td>VM</td>
<td>R</td>
<td>Velocity of water in mainline, ft/s</td>
</tr>
<tr>
<td>WAI</td>
<td>R</td>
<td>Gross irrigation depth, in</td>
</tr>
<tr>
<td>WATDC</td>
<td>RV</td>
<td>Water source development costs, $</td>
</tr>
<tr>
<td>X</td>
<td>R</td>
<td>Length of square field being irrigated by a single field sub-main along the X-axis, ft</td>
</tr>
<tr>
<td>Y</td>
<td>R</td>
<td>Linear dimension of square field along the Y-axis, ft</td>
</tr>
<tr>
<td>YEAR</td>
<td>I</td>
<td>Year in which irrigation system cost parameters have been determined</td>
</tr>
<tr>
<td>------</td>
<td>---</td>
<td>---------------------------------------------------------------------</td>
</tr>
<tr>
<td>Yi</td>
<td>R</td>
<td>Irrigated yield, appropriate units</td>
</tr>
</tbody>
</table>

1 Real
2 Real Vector
3 Character
4 Integer
5 Character array
APPENDIX B: Program Listing of Irrigation Cost Models

IRRIGATION COST MODELS FOR IRRIG-8
5/18/90

Author: Dipmani Kumar

This program is part of the knowledge base of IRRIG-8, a microcomputer based program developed to determine suitable irrigation systems subject to engineering/agronomic constraints and determine the economic feasibility of these systems for a given user situation in Virginia. The program evaluates the economic feasibility of the irrigation systems considered by IRRIG-8: center-pivot, (fixed, two point and three point), traveling gun, and portable pipe (medium and high pressure).

Input data is read from two files: COST.INP and ECONEV.INP. The COST.INP file contains updateable cost parameters used in the irrigation cost model algorithms. The ECONEV.INP file contains engineering, agronomic, and economic parameters used in the irrigation cost models, generated during an interactive IRRIG-8 session. The interactive session and subsequent activation of this program is under the control of the rule-base component of IRRIG-8, which was developed using the LEVEL5 Expert System Development Tool (PC Version) from Information Builders Inc., New York. However, this program may be run by itself if the ECONEV.INP file is created in the appropriate format. The parameter definitions for ECONEV.INP are given in Appendix C. A listing of the COST.INP file is given in Appendix D.

This program relies heavily on algorithms and heuristics used in irrigation cost models developed by B.B. Ross and G. Vellidis, Department of Agricultural Engineering, Virginia Tech and D. B. Taylor and A. B. Lanier, Department of Agricultural Economics, Virginia Tech. These cost models developed to assess the feasibility and potential expansion of large scale riparian irrigation in Virginia, were originally coded in interpreter BASIC.

This program was written in the FORTRAN language standard for Microsoft's Optimizing Compiler (Version 4.0, 1987) and may need to be modified if other compilers are used. All variables are defined in Appendix A. The program may be easily modified to evaluate additional systems by expanding the main program and including appropriate subroutines.

DIMENSION GPARM(15),NOD25(3),NOD50(3),SPARM(11),CPVC(7),COSG(4), XCAL(7),CPLAT(5),SCP(2),CTG(2),CPP(3),TVC(2),BEY(4), XPORF(4),COLP(4),DYP(2),ALC(2),CRPR(4),WATDC(6),AREA(3)
CHARACTER*12 FNAME
REAL NOD25,NOD50, NP
INTEGER YEAR
EQUIVALENCE (GPARM(2),CRPR(1)),(GPARM(3),CRPR(2)),(GPARM(4),CRPR
X(3)),(GPARM(5),CRPR(4)),(GPARM(6),DRY(1)),(GPARM(7),DRY(2)),
X(GPARM(8),AIC(1)),(GPARM(9),AIC(2)),(SPARM(10),YI)
COMMON /GP/GPARM
COMMON /ND50/ NOD50
COMMON /CG/COSG
OPEN(6,FILE='NAME.OUT')
CLOSE(6,STATUS='DELETE')
OPEN(7,FILE='TRANSFER.OUT')
CLOSE(7,STATUS='DELETE')
OPEN(1,FILE='ECONEV.INP')
OPEN(2,FILE='COST.INP')
OPEN(4,FILE='PRN.OUT')
OPEN(5,FILE='NAME.OUT')
DO 373, I=1,20
373 WRITE(*,*)
   WRITE(*,*)'X
   WRITE(*,*)' Enter the name of the file you want the 
   WRITE(*,*)' the results of the economic evaluation 
   WRITE(*,*)' written to. If you do not specify the 
   WRITE(*,'(A)')' drive, the present drive will be used:'
117 READ(*,'(A)',ERR=118,END=118)FNAME
DO 213, I=1,10
213 WRITE(*,*)
   WRITE(5,*)' 1'
   WRITE(5,177)FNAME
177 FORMAT('C',1X,A12)
GOTO 119
118 WRITE(*,*)' COULD NOT UNDERSTAND RESPONSE 
   WRITE(*,*)' Please enter filename again. 
   GOTO 117
119 CONTINUE
   OPEN(3,FILE=FNAME)
   C
   C Read input parameters from ECONEV.INP
   C
   READ(1,*)INPARM
   IF (INPARM .NE. 45) THEN
      WRITE(*,*)'ERROR IN READING INPUT PARAMETERS'
   GOTO 1000
ENDIF
   READ (1,200)PR
   DO 2,I=1,15
      READ (1,200)GPARM(I)
2 CONTINUE
   READ (1,200)(COSG(I),I=1,3)
   READ (1,200)(AREA(I),I=1,3)
   READ (1,200)(NOD25(I),I=1,3)
   READ (1,200)(NOD50(I),I=1,3)
READ (1,200)(SPARM(I),I=1,11)
READ (1,200)(WATDC(I),I=1,6)

C Read input parameters from COST.INP
C
DO 5, I=1,5
READ(2,*)
5 CONTINUE
READ(2,*)YEAR
WRITE(3,201)YEAR
IF (PR .EQ.1EO) THEN
WRITE (4,201)YEAR
ENDIF
READ(2,*)
READ(2,*)COSG(4)

6 CONTINUE
DO 7,I=1,7
READ(2,*)
READ(2,*)CPVC(I)
7 CONTINUE
DO 8,I=1,7
READ(2,*)
READ(2,*)CAL(I)
8 CONTINUE
DO 9,I=1,5
READ(2,*)
READ(2,*)CPLAT(I)
9 CONTINUE
DO 10,I=1,2
READ(2,*)
READ(2,*)CCP(I)
10 CONTINUE
DO 11,I=1,2
READ(2,*)
READ(2,*)CTG(I)
11 CONTINUE
DO 12,I=1,3
READ(2,*)
READ(2,*)CPP(I)
12 CONTINUE
READ(2,*)
READ(2,*)CBG
CONTINUE
IJ=1
CALL FLASH(IJ)

C Evaluate dryland production
C
CALL DRYAN(CRPR,DRY,AIC(1),GPARM(15),BEY,PROF)
WRITE(3,*)
WRITE(3,*)
WRITE(3,1999)
IF (PR .EQ. 1E0) THEN
WRITE(4,*)
WRITE(4,*)
WRITE(4,1999)
ENDIF
DO 1, I=1,4
COLP(I)=0.
1 CONTINUE
TVC(1)=0.
TVC(2)=0.
TCOST=0.
AFC=0.
CALL OUTPUT(GPARM(15),TCOST,AFC,TVC,CO LP,PR,C RPR,
XAI C,BEY,PROF,D RY,YI)
ICHECK=0
C
C Check which systems have been found to be feasible from an
C engineering/agronomic standpoint
C
IF (SPARM(1) .EQ. 1E0)GOTO 220
20 CONTINUE
IF (SPARM(3) .EQ. 1E0)GOTO 330
30 CONTINUE
IF (SPARM(5) .EQ. 1E0)GOTO 440
40 CONTINUE
IF (SPARM(7) .EQ. 1E0)GOTO 550
50 CONTINUE
IF (SPARM(8) .EQ. 1E0)GOTO 660
60 CONTINUE
IF (SPARM(9) .EQ. 1E0)GOTO 770
70 CONTINUE
IF (ICHECK .EQ. 0)GOTO 999
GOTO 880
C
C Make appropriate subroutine calls to determine economic
C feasibility of suitable systems
C
220 NP=1.
IJ=2
CALL FLASH(IJ)
CALL CPIV(GPARM,NOD50,SPARM(10),SPARM(2),WATDC(1),NP,COSG,CCP
X,CPVC,CPLAT,AAREA,TVC,TCOST,AFC,PROF,BEY,CO LP)
WRITE(3,*)
WRITE(3,*)
WRITE(3,2000)
IF (PR .EQ. 1E0) THEN
WRITE(4,*)
WRITE(4,*)
APPENDICES 105
WRITE(4,2000)
ENDIF
CALL OUTPUT(AAREA, TCOST, AFC, TVC, COLP, PR, CRPR, AIC, BEY, PROF, DRY, YI)
ICHECK = ICHECK + 1
GOTO 20
330 NP=2.
  IJ=3
  CALL FLASH(IJ)
  CALL CPIV(GPAM, NOD50, SPARM(10), SPARM(4), WATDC(2), NP, COSG, CCP
X, CPVC, CPLAT, AAREA, TVC, TCOST, AFC, PROF, BEY, COLP)
  WRITE(3,*)
  WRITE(3,*)
  WRITE(3,3000)
  IF (PR .EQ. 1E0) THEN
  WRITE(4,*)
  WRITE(4,*)
  WRITE(4,3000)
  ENDIF
  CALL OUTPUT(AAREA, TCOST, AFC, TVC, COLP, PR, CRPR, AIC, BEY, PROF, DRY, YI)
  ICHECK = ICHECK + 1
GOTO 30
440 NP=3.
  IJ=4
  CALL FLASH(IJ)
  CALL CPIV(GPAM, NOD50, SPARM(10), SPARM(6), WATDC(3), NP, COSG, CCP
X, CPVC, CPLAT, AAREA, TVC, TCOST, AFC, PROF, BEY, COLP)
  WRITE(3,*)
  WRITE(3,*)
  WRITE(3,4000)
  IF (PR .EQ. 1E0) THEN
  WRITE(4,*)
  WRITE(4,*)
  WRITE(4,4000)
  ENDIF
  CALL OUTPUT(AAREA, TCOST, AFC, TVC, COLP, PR, CRPR, AIC, BEY, PROF, DRY, YI)
  ICHECK = ICHECK + 1
GOTO 40
550 CONTINUE
  IJ=5
  CALL FLASH(IJ)
  CALL TGUN(GPAM, AREA, NOD50, SPARM(10), SPARM(11), WATDC(4), COSG, CPVC
X, CTG(1), CTG(2), AAREA, TVC, TCOST, AFC, PROF, BEY, COLP)
  WRITE(3,*)
  WRITE(3,*)
  WRITE(3,5000)
  IF (PR .EQ. 1E0) THEN
  WRITE(4,5000)
  WRITE(4,*)
  WRITE(4,*)
  ENDIF
CALL OUTPUT(AAREA, TCOST, AFC, TVC, COLP, PR, CRPR, AIC, BEY, PROF, DRY, YI)
ICHECK = ICHECK + 1
GOTO 50

660 ISY = 1
IJ = 6
CALL FLASH(IJ)
CALL PPPIP(ISY, GPARM, AREA, NOD50, SPARM(10), WATDC(6), COSG, CPVC, CAL,
XCOP, CBG, AAREA, TVC, TCOST, AFC, PROF, BEY, COLP)
WRITE(3,*)
WRITE(3,*)
WRITE(3,6000)
IF (PR .EQ. 1E0) THEN
WRITE(4,6000)
ENDIF
CALL OUTPUT(AAREA, TCOST, AFC, TVC, COLP, PR, CRPR, AIC, BEY, PROF, DRY, YI)
ICHECK = ICHECK + 1
GOTO 60

770 ISY = 2
IJ = 7
CALL FLASH(IJ)
CALL PPPIP(ISY, GPARM, AREA, NOD50, SPARM(10), WATDC(5), COSG, CPVC, CAL,
XCOP, CBG, AAREA, TVC, TCOST, AFC, PROF, BEY, COLP)
WRITE(3,*)
WRITE(3,*)
WRITE(3,7000)
IF (PR .EQ. 1E0) THEN
WRITE(4,*)
WRITE(4,*)
WRITE(4,7000)
ENDIF
CALL OUTPUT(AAREA, TCOST, AFC, TVC, COLP, PR, CRPR, AIC, BEY, PROF, DRY, YI)
ICHECK = ICHECK + 1
GOTO 70

880 CONTINUE

888 WRITE (3,*)'
WRITE (3,*)' END OF ECONOMIC EVALUATION'
WRITE (3,*)'
WRITE (3,*)' Note: All yields have been expressed in bu/acre'
WRITE (3,*)' and crop prices in $/bu. However, the appro-
WRITE (3,*)' priate units should be assumed for crops'
WRITE (3,*)' not sold in bushels.'
IF (PR .EQ. 1E0) THEN
WRITE (4,*)'
WRITE (4, *)' END OF ECONOMIC EVALUATION'
WRITE (4,*)'
WRITE (4,*)' Note: All yields have been expressed in bu/acre'
WRITE (4,*)' and crop prices in $/bu. However, the appro-
WRITE (4,*)' priate units should be assumed for crops'
WRITE (4,*)' not sold in bushels.
ENDIF
GOTO 1111
999 WRITE (3,*)
    WRITE (3,*)'NO SYSTEMS EVALUATED'
    IF (PR .EQ. 1E0) THEN
      WRITE(4,*)
      WRITE(4,*)'NO SYSTEMS EVALUATED'
    ENDIF
1111 CONTINUE
200 FORMAT(1X,E13.7)
201 FORMAT('1***** THE ECONOMIC ANALYSIS IS BASED ON COSTS IN',I5,1X,'* x*** ')
1999 FORMAT(' *** ECONOMIC ANALYSIS FOR DRYLAND PRODUCTION ***')
2000 FORMAT('1*** ECONOMIC ANALYSIS FOR FIXED CENTER PIVOT ***')
3000 FORMAT('1*** ECONOMIC ANALYSIS FOR TOWABLE TWO POINT CENTER PIVOT X****')
4000 FORMAT('1*** ECONOMIC ANALYSIS FOR TOWABLE THREE POINT CENTER PIVOT XT ****')
5000 FORMAT('1*** ECONOMIC ANALYSIS FOR TRAVELING GUN ***')
6000 FORMAT('1*** ECONOMIC ANALYSIS FOR PORTABLE PIPE ***')
7000 FORMAT('1*** ECONOMIC ANALYSIS FOR BIG GUN ***')
1000 STOP
END
C

Subroutine for evaluating non-irrigated production

SUBROUTINE DRYAN(CRPR,DRY,CPROD,AAREA,BEY,PROF)
DIMENSION CRPR(4),DRY(2),BEY(4),PROF(4)
DO 10,I=1,2
    BEY(I)=CPROD/CRPR(I)
    PROF(I)=(DRY(1)*CRPR(I)-CPROD)*AAREA
10 CONTINUE
IF (BEY(1) .EQ. BEY(2)) THEN
    BEY(2)=0.
ENDIF
DO 20,I=3,4
    BEY(I)=CPROD/CRPR(I)
    PROF(I)=(DRY(2)*CRPR(I)-CPROD)*AAREA
20 CONTINUE
IF (BEY(3) .EQ. BEY(4)) THEN
    BEY(4)=0.
ENDIF
RETURN
END
C

Subroutine for evaluating center-pivot systems. The evaluation
C
C
C
C
C
C
SUBROUTINE CPIV(GPARAM,NOD50,YI,DIA,WATDC,NP,COSG,CCP,CPVC,CPLAT,
XAREA,TVC,TCOST,AFC,PROF,BEY,COLP)


```
DIMENSION GPARM(15),NOD50(3),COSG(4),CCP(2),NOD(2),CPLAT(5)
X,CPVC(7),CP(2),TVCA(2),PROF(4),BEY(4),TVC(2),CRPR(4),DRY(2),
XAIJC(2),COLP(4)
REAL NH,NP,NOD50,NOD,LABHRS
COMMON /GP/ DINTR,CRPR,DRY,AIC,CU,DRAIN,CLRC,HD,VD,AREAD
COMMON /ND50/ BASIS,NOD
COMMON /CG/ CLAB,COIL,CDIES,CHPDU
DATA E /0.8/
PI = 22./7.
RAD=DIA/2.
IF (NP .EQ. 1.)THEN
   NH=23.
   LABHRS=0.1
   ALOST=0.02
ENDIF
IF (NP .EQ. 2.)THEN
   NH=22.
   LABHRS=0.2
   ALOST=0.025
ENDIF
IF (NP .EQ. 3.)THEN
   NH=21.
   LABHRS=0.3
   ALOST=0.025
ENDIF
AAREA =((((PI)*RAD**2)/43560.)*FLOAT(NP)
IF (AAREA .GT. 400.) THEN
   AAREA=400.
   RAD= SQRT(((400./FLOAT(NP))*43560.)/PI)
ENDIF

C C Determine the design basis of the system

C CALL DESBA(AAREA,BASIS,CU,E,NH,NOD,QS,TPI,CPS)

C Obtain diameter and friction loss in main line

C CALL MPVC(QS,DM,HFM)

C Obtain cost/ft of main line

C CALL CMPVC(DM,CPVC,CM)

C Obtain center-pivot lateral diameter

C CALL LAT(QS,DL)

C Obtain cost of lateral
```

APPENDICES 110
CALL CLAT(NP,RAD,CPLAT,CL)

Determine friction loss in lateral

CALL CPIVL(QS,DL,HFL)

Determine variable costs of system

CALL VARC1(AAREA, QS, E, VD, HFL, RAD, HFM, HD, NP, CPS, TPI, LABRHS, XCLA$$, CDIES, COIL, HP, TVC, TVCA)

Determine fixed costs of system

CALL FIXC1(CM, CL, NP, HD, RAD, AAREA, DRAIN, CLEARC, WATDC, CHPDU, CCP(1), XCCP(2), HP, TCOST)

Obtain final economic analysis

CALL FINEC(DINTR, TVCA, TCOST, ALOST, YI, CRPR, DRY, AIC, AAREA, AFC, X, BEY, PROF, COLP)
RETURN
END

Subroutine for evaluating traveling gun

SUBROUTINE TGUN(GPARAM, AREA, NOD50, YI, SINT, WATDC, COSG, CPVC, XCTGX1, CTGX2, AAREA, TVC, TCOST, AFC, PROF, BEY, COLP)
DIMENSION GPARAM(15), NOD50(3), COSG(4), NOD(2), CPVC(7), XPROF(4), BEY(4), CPS(2), TVC(2), TVCA(2), DRY(2), CRPR(4), AIC(2), COLP(4), X, AREA(3)
REAL NH, NOD50, NOD, LABRHS
COMMON /GP/ DINTR, CRPR, DRY, AIC, CU, DRAIN, CLEARC, HD, VD, AREAD
COMMON /ND50/ BASIS, NOD
COMMON /GC/ CLAB, COIL, CDIES, CHPDU
DATA E, NH, LABRHS, ALOST /0.75, 20., 0.3, 0.04/
PI=22./7.
AAREA=AREA(1)
 IF (AAREA .GT. 400.) AAREA=400.

Determine design basis, diameter, friction loss and cost of main line

CALL DESBA(AAREA, BASIS, CU, E, NH, NOD, QS, TPI, CPS)
CALL MPVC(QS, DM, HFM)
CALL CMPVC(DM, CPVC, CM)

Determine number of traveling gun units

NGUN=1
 IF (QS .GT. 1200. .OR. AAREA .GT. 110.) THEN
NGUN1 =IFIX(QS/1200.)+1
NGUN2 =IFIX(AAREA/110.)+1
    IF (NGUN1 .GT. NGUN2) THEN
        NGUN=NGUN1
    ELSE
        NGUN=NGUN2
    ENDIF
ENDIF

If more than one traveling gun unit is needed, determine sub-
main diameter(s), friction loss in sub-mains, and cost of sub-
main lines

SQFT=SQR(AREA*43560.)
Y=SQFT
X=SQFT/(FLOAT(NGUN))
HOSL=X/2.
SUBL=X*(FLOAT(NGUN)-1.)
QSLG=QS/(FLOAT(NGUN))
    IF (MOD(NGUN,2) .EQ. 1 .AND. NGUN .EQ. 1)THEN
        QSSUB=0
    ELSEIF (MOD(NGUN,2) .EQ. 0) THEN
        QSSUB=QS/2.
    ELSE
        QSSUB=(QS-QSLG)/2.
    ENDIF
    CALL MPVC(QSSUB,DSM,HFSM)
    CALL CMPVC(DSM,CFVC,CSM)
    CALL MPVC(QSLG,DL,HFFSM)
    CALL CMPVC(DL,CPVC,CFSM)

Determine the number of travel lanes

ALS= 1.4*(SQR((95.3*QSLG)/PI*SINT))
NTL=IFIX((Y/ALS)+0.5)

Select hose diameter and operating pressure

    IF (QSLG .LE. 200.) THEN
        DHOS=3.
        PHOS=173.
    ELSEIF (QSLG .GT. 200. .AND. QSLG .LE. 300.) THEN
        DHOS=3.5
        PHOS=185.
    ELSEIF (QSLG .GT. 300. .AND. QSLG .LE. 400.) THEN
        DHOS=4.0
        PHOS=196.4
    ELSEIF (QSLG .GT. 400. .AND. QSLG .LE. 500.) THEN
        DHOS=4.5
        PHOS=208.
    ENDIF
ELSEIF (QSL. GE. 500. AND. QSL. LE. 1200.) THEN
  DHOS=5.0
  PHOS=219.
  ENDIF

C Determine friction loss in hose

  VHOS=(0.408*QSL)/(DHOS**2)
  HFH=(((2.3*VHOS)/((1.318*(180))*((DHOS/12.)*0.63)))*1.852)

C Determine total pumping head

  TH=(VD+10)+(HFH*HOSL*FLOAT(NGUN))+(HFSTMY*FLOAT(NGUN)) +
  X(HFSTM*SUBL)+(HFMY*HD)+PHOS

C Obtain variable costs

  CALL VERC2(AAREA, QSL, TH, CP5, TPI, LABHRS, CLA3,
  XCDIES, COIL, HP, TVC, TVCA)

C Determine fixed costs

  PUMP=(HP*CHPDU)
  TCM=HD*CM
  TCSM=SUBL*CM
  TCFSM=Y*CFSM*FLOAT(NGUN)
  TCHCR=CTGX1*QSL*FLOAT(NGUN)
  CHYD=CTGX2*DL*FLOAT(NTL)
  TCOST=PUMP+TCM+TCSM+TCFSM+TCHCR+CHYD+((DRAINC+CLEARC)*AAREA)
  X+WATDC

C Obtain final economic analysis

  CALL FINEC(DINTR, TVCA, TCOST, ALOST, YI, CRPR, DRY, AIC, AAREA
  X, AFC, BEY, PROF, COLP)
  RETURN
  END

C Subroutine for evaluating portable pipe system

  SUBROUTINE PPIP(ISY, GPARM, AREA, NOD50, YI, WATDC, COSG, CPVC, CAL, CPP,
  XCBG, AAREA, TVC, TCOST, AFC, PROF, BEY, COLP)
  DIMENSION GPARM(15), NOD50(3), COSG(4), CPVC(7), CAL(7), CPP(3),
  XPROF(4), BEY(4), CPS(2), TVCA(4), NOD(2), TVC(2), CRPR(4), DRY(2), AIC(2
  X), COLP(4), AREA(3)
  REAL NH, NOD50, NOD, LABHRS, LL
  COMMON /GP/DINTR, CRPR, DRY, AIC, CU, DRAINC, CLEARC, HD, VT, AREAD
  COMMON /ND50/BASIS, NOD
  COMMON /CG/CLAB, COIL, CDIES, CHPDU

APPENDICES
DATA E,ALOST /0.7,0.01/

Set design and cost parameters for system being evaluated (medium or high pressure)

IF (ISY .EQ. 1) THEN
NH=16.
LABHRS=1.5
CRISER=CPP(3)
SPACE=60.
PHEAD=115.5
NOSD=2
AAREA=AREA(3)
ELSE
NH=18.
LABHRS=0.75
CRISER=CBG
SPACE=180.
PHEAD=173.25
NOSD=3
AAREA=AREA(2)
ENDIF
IF (AAREA .GT. 400.)AAREA=400.

Determine design basis, diameter, friction loss and cost of mainline

CALL DESBA(AAREA,BASIS,CU,E,NH,NOD,QS,TPI,CPS)
CALL MPVC(QS,DM,HTM)
CALL CMPVC(DM,CPVC,CM)

Determine if sub-mains will be necessary and the area covered by each sub-main

NFSM=1
IF (AAREA .GT. 80.) THEN
NFSM=IFIX(AAREA/80.)+1
ENDIF
SQFT=SQRAT(AAREA*43560.)
Y=SQFT
X=SQFT/FLOAT(NFSM)
AREAN=(Y*X)/43560.

Determine the days allowed per irrigation cycle, the total number of sets and the area covered per set

IDPI=IFIX(TPI/NH)
NOS=IDPI*NOSD
APS=AREAN/FLOAT(NOS)
LL=X/2.
SUBL=X*(FLOAT(NFSM)-1.)
TLL=(APS*43560.)/SPACE

C Determine the total number of laterals needed
NOL=IFIX((TLL/LL)*FLOAT(NFSM))+1

C Determine flow in lateral, field sub-main, and sub-main
QSL=QS/FLOAT(NCL)
QSFSM=QS/FLOAT(NFSM)
IF (MOD(NFSM,2) .EQ. 1 .AND. NFSM .EQ. 1) THEN
QSSUB=0
ELSEIF (MOD(NFSM,2) .EQ. 0) THEN
QSSUB=QS/2.
ELSE
QSSUB=(QS-QSFSM)/2.
ENDIF

C Obtain diameter, friction loss and cost of sub-main
CALL MPVC(QSSUB,DSM,HFSM)
CALL CMPVC(DSM,CPVC,CSM)

C Obtain diameter, friction loss and cost of field sub-main
LINT=2
CALL ALUM(ISY,QSFSM,LINT,DFSM,HFFSM)
CALL CALU(DFSM,CAL,CFSM)
LINT=3

C Obtain diameter, friction loss and cost of lateral
CALL ALUM(ISY,QSL,LINT,DL,HFL)
CALL CALU(DL,CAL,CL)

C Set cost of T-valve at lateral hydrants
IF(DFSM .LE. 4.) THEN
CTV=CPP(1)
ELSE
CTV=CPP(2)
ENDIF

C Determine the number of riser assemblies needed
NRS=IFIX(((TLL/SPACE)*FLOAT(NFSM))+0.5)
IF(NRS .EQ. 0)NRS=1
Determine total pumping head

\[ \text{TH} = (\text{VD} + 10.) + (\text{HFL} \times \text{LL} \times \text{FLOAT(NOL)}) + (\text{HFFSM} \times \text{Y} \times \text{FLOAT(NFSM)}) + (\text{HFSM} \times \text{SUBL}) \times (\text{HFM} \times \text{HD}) + \text{PHEAD} \]

Obtain variable costs

CALL VARC2(AAREA, QS, E, TH, CPS, TPI, LABHRS, CLAB, CDIES, COIL, HP, TVC, XTVCA)

Determine fixed costs

\[ \text{PUMPC} = \text{HP} \times \text{CHPDU} \]
\[ \text{TCM} = \text{HD} \times \text{CM} \]
\[ \text{TCSM} = \text{SUBL} \times \text{CSM} \]
\[ \text{TCFSM} = \text{Y} \times \text{CFSM} \times \text{FLOAT(NFSM)} \]
\[ \text{TCLAT} = \text{LL} \times \text{CL} \times \text{FLOAT(NOL)} \]
\[ \text{TCTV} = \text{CTV} \times \text{FLOAT(NOL)} \]
\[ \text{TCRS} = \text{CRISER} \times \text{FLOAT(NRS)} \]
\[ \text{TCOSt} = \text{PUMPC} + \text{TCM} + \text{TCSM} + \text{TCFSM} + \text{TCLAT} + \text{TCTV} + \text{TCRS} + ((\text{DRAINC} + \text{CLEARC}) \times \text{AAREA}) \]
\[ \times \text{WATDC} \]

Obtain final economic analysis

CALL FINEC(DINTR, TVCA, TCOST, ALOST, YI, CRPR, DRY, AIC, AAREA, AFC, BEY, XPROF, COLP)
RETURN
END

Determines the design basis - system capacity, time per irrigation cycle, and cycles per season in normal and dry years

SUBROUTINE DESBA(AAREA, BASIS, CU, E, NH, NOD, QS, TPI, CPS)
REAL NH, NOD
DIMENSION NOD(2), CPS(2), TWR(2)
DPI = BASIS / CU
WAI = BASIS / E
TPI = DPI / NH
QS = (WAI * AAREA * 453.) / TPI
DO 10, I = 1, 2
CPS(I) = NOD(I) / DPI
TWR(I) = WAI * AAREA * CPS(I)
10 CONTINUE
RETURN
END

Determines diameter and friction loss in a PVC pipe

SUBROUTINE MPVC(QS, DM, HFM)
DM=1.
10 DM=DM+1.
IF (DM .EQ. 5.0 .OR. DM .EQ. 7.0) DM=DM+1.
IF (DM .EQ. 9.0 .OR. DM .EQ. 11.0) DM=DM+1.
VM=(0.408*QS)/(DM**2)
IF (VM .GT. 5.0 .AND. DM .LT. 12.) GOTO 10
HFM=((2.3*VM)/(1.318*150.*((DM/12.)**0.63)))**1.852
RETURN
END

C
Determine the diameter and friction loss in an aluminium pipe.
The values of the friction factor and maximum velocity depend
on whether the pipe is a sub-main or a lateral, and if the pipe
is a lateral, the friction factor depends on the number of
the number of sprinklers in the pipe.

SUBROUTINE ALUM(ISY,QSX,LINT,DM,HFX)
DM=1.
10 DM=DM+1.
VM=(0.408*QS)/(DM**2)
FRFAC=1.0
VCRIT=6.0
IF (LINT .EQ. 3 .AND. ISY .EQ. 1) THEN
VCRIT=7.5
FRFAC=0.33
ELSEIF (LINT .EQ. 3 .AND. ISY .EQ. 2) THEN
VCRIT=7.5
FRFAC=0.5
ENDIF
IF (VM .GT. VCRIT .AND. DM .LT. 8.0) GOTO 10
HFX = (((2.3*VM)/(1.318*120.*((DM/12.)**0.63)))**1.852)*FRFAC
RETURN
END

C
Determine the center pivot lateral diameter and friction loss
in it.

SUBROUTINE CPIVL(QS,DL,HFL)
VL=(0.408*QS)/(DL**2)
HFL = (((2.3*VL)/(1.318*120*((DL/12.)**0.63)))**1.852)*0.33
RETURN
END

C
Selects the cost/ft of aluminium pipe based on diameter

SUBROUTINE CALU(DX,CAL,CX)
DIMENSION CAL(7)
IF (DX .EQ. 2.) CX=CAL(1)
IF (DX .EQ. 3.) CX=CAL(2)
IF (DX .EQ. 4.) CX=CAL(3)
IF (DX .EQ. 5.) CX = CAL(4)
IF (DX .EQ. 6.) CX = CAL(5)
IF (DX .EQ. 7.) CX = CAL(6)
IF (DX .EQ. 8.) CX = CAL(7)
RETURN
END

C                      Determines the variable costs for center-pivot systems
C
SUBROUTINE VARC1(AAREA, QS, E, VD, HFL, RAD, HFM, HD, NP, CPS, TPI, LABHRS
X, CLAB, CDIES, COIL, HP, TVC, TVCA)
DIMENSION CPS(2), TVCA(2), HPHRG(2), Gald(2), GALO(2),
XMAINT(2), LCOST(2), TVC(2)
REAL NP, LABHRS, MAINT
TH = (VD+10)+(HFL*RAD)+(HFM*(HD+((2.*NP)-1.)*RAD))+(2.31*30.)
HP = ((TH*QS)/(3960*E)+0.5)
HG = ((0.02*RAD)+0.5)
DO 30, I = 1, 2
HPHR(I) = CPS(I)*HP*TPI
HPHRG(I) = CPS(I)*HG*TPI
Gald(I) = (HPHR(I)+HPHRG(I))/16.6
GALO(I) = (HPHR(I)+HPHRG(I))/300.
MAINT(I) = (HPHR(I)+HPHRG(I))*0.002
LCOST(I) = CPS(I)*AAREA*LABHRS*CLAB
TVC(I) = (Gald(I)*CDIES)+(GALO(I)*COIL) + MAINT(I) + LCOST(I)
TVC(A) = TVC(I)/AAREA
30 CONTINUE
RETURN
END

C                      Determines the fixed costs for center-pivot systems
C
SUBROUTINE FIXC1(CM, CL, NP, HD, RAD, AAREA, DRAINC, CLEARC, WATDC, CHPDU,
XCLXL1, CXL2, HP, TCOST)
REAL NP
TCM = (CM*(HD+(((2.*NP)-1.)*RAD)))
TCL = CL*(RAD)
PUMPC = HP*CHPDU
CGEN = (CXL1*RAD) + (CXL2*NP)
TCOST = TCM + TCL + PUMPC + CGEN + ((DRAINC+CLEARC)*AAREA) + WATDC
RETURN
END

C                      Determines the break-even yield and profit
C
SUBROUTINE FINEC(DINTR, TVCA, TCOST, ALOST, YI, CRPR, DRY, AIC, AAREA
X, AFC, BEY, PROF, COLP)
DIMENSION ATCA(4), TVCA(2), DRY(2), AIC(2), BEY(4), PROF(4),
XCOLP(4), COLPA(4), CRFR(4)
REAL IRS
IRS=TCOST*0.02
CRF=DINT/(1-((1.+DINT)*)((-15)))
ACR=TCOST*CRF
AFC=ACR+IRS
AFCPA=AFC/AAREA
DO 10,I=1,2
COLPA(I)=DRY(I)*CRPR(I)*AOST
CCLP(I)=COLPA(I)*AAREA
10 CONTINUE
DO 20,I=3,4
COLPA(I)=DRY(2)*CRPR(I)*AOST
CCLP(I)=COLPA(I)*AAREA
20 CONTINUE
ADDIN=AIC(2)-AIC(1)
DO 30,I=1,2
ATCA(I)=TVCA(I)+AFCPA+C3LPA(I)+ADDIN
BEY(I)=(ATCA(I)/CRPR(I))+(AIC(I)/CRPR(I))
PROF(I)=(YI-BEY(I))*CRPR(I)*AAREA
30 CONTINUE
IF(BEY(1).EQ.BEY(2))THEN
BEY(2)=0.
ENDIF
DO 40,I=3,4
ATCA(I)=TVCA(2)+AFCPA+COLPA(I)+ADDIN
BEY(I)=(ATCA(I)/CRPR(I))+(AIC(I)/CRPR(I))
PROF(I)=(YI-BEY(I))*CRPR(I)*AAREA
40 CONTINUE
IF(BEY(3).EQ.BEY(4))THEN
BEY(4)=0.
ENDIF
RETURN
END

C
Determines variable costs for traveling gun and portable pipe
C
SUBROUTINE VARC2(AAREA,QS,E,TH,CPS,TPI,LABHRS,CLAB,
XCDIES,COIL,HP,TVCA)
DIMENSION CPS(2),TVCA(2),HPHR(2),GALD(2),GALO(2),MAINT(2),
XLKOST(2),TVC(2)
REAL LABHRS,LCOST,MAINT
HP=(((TH*QS)/(3960*E))+0.5)
DO 30,I=1,2
HPHR(I)=CPS(I)*HP*TPI
GALD(I)=(HPHR(I))/16.6
GALO(I)=(HPHR(I))/900.
MAINT(I)=(HPHR(I))*0.002
LCOST(I)=CPS(I)*AAREA*LABHRS*CLAB
TVC(I)=(GALD(I)*XCDIES)+(GALO(I)*COIL) +MAINT(I)+LCOST(I)
TVCA(I)=TVC(I)/AAREA
30 CONTINUE
RETURN
END

C Selects the cost/ft of PVC pipe based on diameter

SUBROUTINE CMPVC(DM, CPVC, CM)
DIMENSION CPVC(7)
IF (DM .EQ. 2.) CM=CPVC(1)
IF (DM .EQ. 3.) CM=CPVC(2)
IF (DM .EQ. 4.) CM=CPVC(3)
IF (DM .EQ. 6.) CM=CPVC(4)
IF (DM .EQ. 8.) CM=CPVC(5)
IF (DM .EQ. 10.) CM=CPVC(6)
IF (DM .EQ. 12.) CM=CPVC(7)
RETURN
END

C Selects the cost/ft of steel pipe for the center-pivot lateral
based on lateral length

SUBROUTINE CLAT(NP, RAD, CPLAT, CL)
DIMENSION CPLAT(5)
REAL NP
IF (RAD .LE. 1.445.) CL=CPLAT(1)
IF (RAD .GT. 1.445. .AND. RAD .LE. 1.560.) CL=CPLAT(2)
IF (RAD .GT. 1.560. .AND. RAD .LE. 1.900.) CL=CPLAT(3)
IF (RAD .GT. 1.900.) CL=CPLAT(4)
IF (NP .EQ. 2. .OR. NP .EQ. 3.) CL=CPLAT(5)
RETURN
END

C Selects the center-pivot lateral diameter based on total flow

SUBROUTINE LAT(QS, DL)
IF (QS .LT. 930.) DL=6.
IF (QS .GT. 930. .AND. QS .LT. 1080.) DL=6.5
IF (QS .GT. 1080. .AND. QS .LT. 1600.) DL=7.5
IF (QS .GT. 1600.) DL=8.0
RETURN
END

C Flashes a message on screen about system being evaluated

SUBROUTINE FLASH(II)
REAL IK, IK1
CHARACTER*62 STRING(7)
CHARACTER*62 BLANK
DATA STRING(1) /'Input parameters read. Economic evaluation progra
Xm running.'/
DATA STRING(2) /' Evaluating Fixed center pivot '/

APPENDICES 120
DATA STRING(3) /* Evaluating Two-point towable center pivot */
DATA STRING(4) /* Evaluating Three-point towable center pivot */
DATA STRING(5) /* Evaluating Traveling gun */
DATA STRING(6) /* Evaluating Big gun */
DATA STRING(7) /* Evaluating Portable pipe */
DATA BLANK /* */
X /* */
DO 999, I=1,5
999 WRITE(*,201)
DO 1000, I=1,2
WRITE(*,100)STRING(I)
DO 500, K=1,60
IK=0.001
300 IF (IK .LT.10) THEN
IK=IK+0.01
GOTO 300
ENDIF
500 CONTINUE
WRITE(*,100)BLANK
DO 600, J=1,50
IK1=0.01
400 IF (IK1 .LT.10) THEN
IK1=IK1+0.01
GOTO 400
ENDIF
600 CONTINUE
1000 CONTINUE
100 FORMAT('+',A70)
201 FORMAT('+'
RETURN
END

C Writes output in appropriate format
C
SUBROUTINE OUTPUT(AAREA,TCOST,AF,TC,V,COLP,PR,CRFR,AIC,
XBEY,PROF,DRY,YI)
DIMENSION TC(2),CRFR(4),AIC(2),BEY(4),PROF(4),COLP(4),DRY(2)
X,PPA(4)
DO 10, I=1,4
PPA(I)=PROF(I)/AAREA
10 CONTINUE
ND=3
C This writes the total area under production/to be irrigated
C
15 WRITE(ND,*)
WRITE(ND,*)
IF(COLP(1) .NE. 0.) THEN
WRITE(ND,100)AAREA
ELSE

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WRITE(ND,110)AAREA
ENDIF

This writes the total initial cost, annual fixed cost and total costs of additional inputs for irrigation

IF (COLP(1) .EQ. 0.) THEN
AAIC=AAREA*AIC(1)
WRITE(ND,200)AAIC
WRITE(ND,*)
ELSEIF(COLP(1) .NE. 0.) THEN
ADDPIN=(AIC(2)-AIC(1))*AAREA
WRITE(ND,250)TCOST
WRITE(ND,300)AFC
WRITE(ND,400)ADDPIN
WRITE(ND,*)
ENDIF

This writes returns in a dry year

WRITE(ND,500)
WRITE(ND,*)
IF (TVC(1) .NE. 0.)THEN
WRITE(ND,550)TVC(1)
WRITE(ND,*)
ENDIF
WRITE(ND,600)CRPR(1)
IF (COLP(1) .NE. 0.) THEN
WRITE(ND,650)COLP(1)
ENDIF
WRITE(ND,700)BEY(1)
IF (PROF(1) .GE. 0. AND. COLP(1) .EQ. 0.) THEN
WRITE(ND,800)DRY(1),PROF(1)
WRITE(ND,850)PPA(1)
ELSEIF (PROF(1) .GE. 0. .AND. COLP(1) .NE. 0.) THEN
WRITE(ND,800)YI,PROF(1)
WRITE(ND,850)PPA(1)
ELSEIF (PROF(1) .LT. 0. .AND. COLP(1) .EQ. 0.) THEN
WRITE(ND,900)
WRITE(ND,800)DRY(1),PROF(1)
WRITE(ND,850)PPA(1)
ELSEIF (PROF(1) .LT. 0. .AND. COLP(1) .NE. 0.) THEN
WRITE(ND,900)
WRITE(ND,800)YI,PROF(1)
WRITE(ND,850)PPA(1)
ENDIF
IF (BEY(2) .NE. 0.) THEN
WRITE(ND,*)
WRITE(ND,600)CRPR(2)
IF (COLP(2) .NE. 0.) THEN
WRITE(ND,650)COLP(2)
ENDIF
WRITE(ND,700)BEY(2)
IF(PROF(2) .GE. 0. .AND. COLP(2) .NE. 0.) THEN
WRITE(ND,800)YI,PROF(2)
WRITE(ND,850)PPA(2)
ELSEIF (PROF(2) .GE. 0. .AND. COLP(2) .EQ. 0.) THEN
WRITE(ND,800)DRLY(1),PROF(2)
WRITE(ND,850)PPA(2)
ELSEIF (PROF(2) .LT. 0. .AND. COLP(2) .EQ. 0.) THEN
WRITE(ND,900)
WRITE(ND,800)DRLY(1),PROF(2)
WRITE(ND,850)PPA(2)
ELSEIF (PROF(2) .LT. 0. .AND. COLP(2) .NE. 0.) THEN
WRITE(ND,900)
WRITE(ND,800)YI,PROF(2)
WRITE(ND,850)PPA(2)
ENDIF
ENDIF

This writes returns in a normal year

WRITE(ND,*)
WRITE(ND,1000)
WRITE(ND,*)
IF (TVC(2) .NE. 0.) THEN
WRITE(ND,550)TVC(2)
WRITE(ND,*)
ENDIF
WRITE(ND,600) CPR(3)
IF (COLP(3) .NE. 0.) THEN
WRITE(ND,650)COLP(3)
ENDIF
WRITE(ND,700)BEY(3)
IF (PROF(3) .GE. 0. .AND. COLP(3) .EQ. 0.) THEN
WRITE(ND,800)DRLY(2),PROF(3)
WRITE(ND,850)PPA(3)
ELSEIF (PROF(3) .GE. 0. .AND. COLP(3) .NE. 0.) THEN
WRITE(ND,800)YI,PROF(3)
WRITE(ND,850)PPA(3)
ELSEIF (PROF(3) .LT. 0. .AND. COLP(3) .EQ. 0.) THEN
WRITE(ND,900)
WRITE(ND,800)DRLY(2),PROF(3)
WRITE(ND,850)PPA(3)
ELSEIF (PROF(3) .LT. 0. .AND. COLP(3) .NE. 0.) THEN
WRITE(ND,900)
WRITE(ND,800)YI,PROF(3)
WRITE(ND,850)PPA(3)
ENDIF
IF (BEY(4) .NE. 0.) THEN
WRITE(ND,*
WRITE(ND,600)CRPR(4)
     IF (COLP(2) .NE. 0.) THEN
WRITE(ND,650)COLP(4)
ENDIF
WRITE(ND,700)BEY(4)
     IF(PROF(4) .GE. 0. .AND. COLP(4) .NE. 0.) THEN
WRITE(ND,800)YI,PROF(4)
WRITE(ND,850)PPA(4)
ELSEIF (PROF(4) .GE. 0. .AND. COLP(4) .EQ. 0.) THEN
WRITE(ND,800)DRY(2),PROF(4)
WRITE(ND,850)PPA(4)
ELSEIF (PROF(4) .LT. 0. .AND. COLP(4) .EQ. 0.) THEN
WRITE(ND,900)
WRITE(ND,800)DRY(2),PROF(4)
WRITE(ND,850)PPA(4)
ELSEIF (PROF(4) .LT. 0. .AND. COLP(4) .NE. 0.) THEN
WRITE(ND,900)
WRITE(ND,800)YI,PROF(4)
WRITE(ND,850)PPA(4)
ENDIF
IF (ND .EQ. 4) GOTO 20
IF (PR .EQ. 1E0) THEN
ND=4
GOTO 15
ENDIF
ENDIF
CONTINUE
200 FORMAT(' Total area irrigated = ',F7.2,1X,'Acre's')
110 FORMAT(' Total area under production = ',F7.2,1X,'Acre's')
200 FORMAT(' Total cost of Dryland production = $',1X,F8.2)
250 FORMAT(' Total initial investment = $',1X,F12.2)
300 FORMAT(' Annual fixed cost of Irrigation system = $',1X,F8.2)
400 FORMAT(' Total annual cost of additional inputs for irrigation = $ X',1X,F8.2)
500 FORMAT(' **RETURNS IN A DRY YEAR (1 IN 10 YEAR DROUGHT)** ')
550 FORMAT(' Annual operating cost of system = $',1X,F8.2)
600 FORMAT(' With crop price = ',F8.2,1X,'$',/BU')
650 FORMAT(' Value of crop lost due to movement of irrigation equ
Xpiment = $',1X,F8.2)
700 FORMAT(' Break-even Yield = ',F8.2,1X,'bu/acre')
800 FORMAT(' Total profit with a ',F8.2,' bu/acre yield = $',1X, XF8.2)
850 FORMAT(' Profit per acre = $',1X,F7.2)
900 FORMAT(' The break even yield exceeds the expected yield')
1000 FORMAT(' **RETURNS IN A NORMAL YEAR(5 IN 10 YEAR DROUGHT)** ')
RETURN
END

APPENDICES
APPENDIX C: Example ECONEV.INP file with Parameter Definitions

45
N1.00000000E+00 Economic evaluation results to be printed? (1=Yes, 0=No)
N0.12000000E+00 Interest rate (decimal)
N4.00000000E+00 Maximum crop price, dry year (appropriate units)
N3.50000000E+00 Minimum crop price, dry year (appropriate units)
N3.70000000E+00 Maximum crop price, normal year (appropriate units)
N3.30000000E+00 Minimum crop price, normal year (appropriate units)
N8.00000000E+01 Non-irrigated yield, dry year (appropriate units)
N1.10000000E+02 Non-irrigated yield, normal year (appropriate units)
N2.80000000E+02 Cost of non-irrigated production ($/ac)
N3.60000000E+02 Cost of irrigated production, excluding irrigation ($/ac)
N0.25000000E+00 Crop consumptive use (in/day)
N0.00000000E+00 Drainage costs ($/ac)
N1.00000000E+02 Clearing costs ($/ac)
N3.00000000E+03 Horizontal distance from water source (ft)
N2.00000000E+01 Vertical distance from water source (ft)
N2.50000000E+02 Area proposed to be irrigated (ac)
N4.00000000E+00 Labor cost per hour
N1.25000000E+00 Cost of Diesel per gallon
N6.00000000E+00 Cost of Oil per gallon
N2.50000000E+02 Actual area that may be irrigated by Traveling gun (ac)
N2.50000000E+02 Actual area that may be irrigated by Big gun (ac)
N2.50000000E+02 Actual area that may be irrigated by Portable pipe (ac)
N0.60000000E+00 Basis (Trigger point = 0.25)
N6.90000000E+01 Drought days, dry year (Trigger point = 0.25)
N3.20000000E+01 Drought days, normal year (Trigger point = 0.25)
N1.20000000E+00 Basis (Trigger point = 0.50)
N6.50000000E+01 Drought days, dry year (Trigger point = 0.50)
N2.86000000E+01 Drought days, normal year (Trigger point = 0.50)
N1.00000000E+00 Fixed center pivot to be evaluated? (1=Yes, 0=No)
N3.30000000E+03 Diameter of fixed center pivot (ft)
N0.00000000E+00 Two-point towable center pivot to be evaluated?
N0.00000000E+00 Diameter of two-point towable center pivot (ft)
N0.00000000E+00 Three-point towable center pivot to be evaluated?
N0.00000000E+00 Diameter of three-point towable center pivot (ft)
N1.00000000E+00 Traveling gun to be evaluated?
N1.00000000E+00 Big gun to be evaluated?
N1.00000000E+00 Portable pipe to be evaluated?
N1.90000000E+02 Irrigated yield (appropriate units)
N0.40000000E+00 Maximum soil intake rate (in/hr)
N0.00000000E+00 Water development costs (Fixed center-pivot)
N0.00000000E+00 Water development costs (Two-point center pivot)
N0.00000000E+00 Water development costs (Three-point center pivot)
N0.00000000E+00 Water development costs (Traveling gun)
N0.0000000E+00  Water development costs (Big gun)
N0.0000000E+00  Water development costs (Portable pipe)
APPENDIX D: Listing of Current COST.INP File

This file contains updateable cost parameters used by the economic evaluation program. Parameter values may be entered anywhere in the line following the parameter definition. All parameters EXCEPT the year must be entered with a decimal point.

YEAR
1984
COST OF DIESEL PUMPING UNIT, $/HP
150.00
COST OF 2" PVC PIPE (INCLUDING THE COST OF BURYING), $/FT
1.50
COST OF 3" PVC PIPE (INCLUDING THE COST OF BURYING), $/FT
2.00
COST OF 4" PVC PIPE (INCLUDING THE COST OF BURYING), $/FT
2.50
COST OF 6" PVC PIPE (INCLUDING THE COST OF BURYING), $/FT
3.00
COST OF 8" PVC PIPE (INCLUDING THE COST OF BURYING), $/FT
4.25
COST OF 10" PVC PIPE (INCLUDING THE COST OF BURYING), $/FT
6.25
COST OF 12" PVC PIPE (INCLUDING THE COST OF BURYING), $/FT
8.50
COST OF 2" ALUMINIUM PIPE, $/FT
1.29
COST OF 3" ALUMINIUM PIPE, $/FT
1.77
COST OF 4" ALUMINIUM PIPE, $/FT
2.27
COST OF 5" ALUMINIUM PIPE, $/FT
2.89
COST OF 6" ALUMINIUM PIPE, $/FT
3.86
COST OF 7" ALUMINIUM PIPE, $/FT
5.73
COST OF 8" ALUMINIUM PIPE, $/FT
7.15
COST OF CENTER PIVOT LATERAL ( < 1445 FT, FIXED), $/FT
28.0
COST OF CENTER PIVOT LATERAL ( 1445-1560 FT, FIXED), $/FT
32.0
COST OF CENTER PIVOT LATERAL ( 1560-1900 FT, FIXED), $/FT
34.0
COST OF CENTER PIVOT LATERAL ( > 19000 FT, FIXED), $/FT
37.0
COST OF CENTER PIVOT LATERAL ( < 1445 FT, TOWABLE), $/FT
31.0
COST OF GENERATOR PAD, $/FT
7.0
COST OF PIVOT POINT ASSEMBLY, $
500.0
COST OF TRAVELING GUN, CART AND HOSE, $/GPM
40.0
COST OF TRAVELING GUN HYDRANT, $
10.0
COST OF PORTABLE PIPE T-VALVE (SUB-MAIN DIA 3'' OR 4''), $
120.0
COST OF PORTABLE PIPE T-VALVE (SUB-MAIN DIA 5'' OR 6''), $
140.0
COST OF PORTABLE PIPE RISER ASSEMBLY, $
35.0
COST OF BIG GUN RISER ASSEMBLY, $
800.0
APPENDIX E: Output for Example Session

SUMMARY OF INPUT INFORMATION
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<table>
<thead>
<tr>
<th>Data type</th>
<th>Value</th>
</tr>
</thead>
<tbody>
<tr>
<td>Geographic location in Virginia</td>
<td>Area C</td>
</tr>
<tr>
<td>County</td>
<td>ALBEMARLE</td>
</tr>
<tr>
<td>Soil name</td>
<td>DYKE SILTY CLAY LOAM</td>
</tr>
<tr>
<td>Irrigation soil group</td>
<td>Group 13</td>
</tr>
<tr>
<td>Crop</td>
<td>Corn for Grain</td>
</tr>
<tr>
<td>Field shape</td>
<td>Square</td>
</tr>
<tr>
<td>Total area</td>
<td>15.00 acres</td>
</tr>
<tr>
<td>Average field slope</td>
<td>5.00 %</td>
</tr>
<tr>
<td>Maximum crop price expected (dry year)</td>
<td>4.00 $/bu</td>
</tr>
<tr>
<td>Maximum crop price expected (normal year)</td>
<td>3.50 $/bu</td>
</tr>
<tr>
<td>Minimum crop price expected (dry year)</td>
<td>3.00 $/bu</td>
</tr>
<tr>
<td>Minimum crop price expected (normal year)</td>
<td>2.75 $/bu</td>
</tr>
<tr>
<td>Irrigated yield</td>
<td>190.00 bu/acre (D)</td>
</tr>
<tr>
<td>Non-irrigated yield (dry year)</td>
<td>80.00 bu/acre (D)</td>
</tr>
<tr>
<td>Non-irrigated yield (normal year)</td>
<td>110.00 bu/acre (D)</td>
</tr>
<tr>
<td>Cost of non-irrigated production</td>
<td>280.00 $/acre (D)</td>
</tr>
<tr>
<td>Cost of irrigated production excluding irrigation costs</td>
<td>360.00 $/acre (D)</td>
</tr>
<tr>
<td>Clearing costs</td>
<td>0.00 $/acre</td>
</tr>
<tr>
<td>Drainage costs</td>
<td>0.00 $/acre</td>
</tr>
<tr>
<td>Cost of Diesel</td>
<td>1.25 $/gal. (D)</td>
</tr>
<tr>
<td>Cost of Oil</td>
<td>6.00 $/gal. (D)</td>
</tr>
<tr>
<td>Interest rate</td>
<td>12.00 %</td>
</tr>
</tbody>
</table>

Note: (D) indicates a default value was used for the data type. Crop prices and yields for peanuts are in $/lb and lb/acre respectively. For other crops, assume appropriate units.

WATER SOURCE:

Water is available from a Pond.
No information available on maximum total available storage.
Storage assumed sufficient to meet the water requirements of all feasible systems.

Horizontal distance of water source from field 1000.00 feet.
Vertical distance of water source from field 40.00 feet.

The following systems have been determined to be suitable:
FIXED CENTER PIVOT

The center pivot system consists of sprinklers mounted on a single lateral arm which moves in a circular motion. The lateral is supported off the ground 8 to 16 feet) by self propelled towers (100 to 200 feet apart), driven by an electric motor on each tower. The resulting irrigation pattern is a circle, or part circle, and water is fed to the system at the pivot point in the center of the irrigated land.

<table>
<thead>
<tr>
<th>Area irrigated</th>
<th>11.79 Acres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Diameter of fixed center pivot</td>
<td>808.33 ft.</td>
</tr>
<tr>
<td>Pumping demand</td>
<td>72.54 GPM</td>
</tr>
<tr>
<td>Total water requirements (dry year)</td>
<td>14.12 Acre-ft</td>
</tr>
<tr>
<td>Total water requirements (normal year)</td>
<td>4.45 Acre-ft</td>
</tr>
<tr>
<td>Total labor requirements (dry year)</td>
<td>7.00 hrs</td>
</tr>
<tr>
<td>Total labor requirements (normal year)</td>
<td>2.00 hrs</td>
</tr>
</tbody>
</table>

TRAVELING GUN

The traveling gun irrigation system consists of a single big sprinkler mounted on a moving cart which irrigates rectangular strips (150-350 feet wide and up to 1400 feet long) across a field. Water is fed to the sprinkler unit, and the cart itself is towed, by a flexible polyethylene pipe, or hose (2 to 5 inches inside diameter). For this reason this system is commonly referred to as a hose tow traveling gun system. This hose is stored on, and unwound for use from, a moveable reel. When preparing to irrigate, the unit is moved into position, and gun cart and hose pulled to the starting point by a farm tractor. During irrigation, the unit automatically pulls the gun cart back to the reel while winding the hose. The unit is then repositioned to irrigate another rectangular strip.

<table>
<thead>
<tr>
<th>Area irrigated</th>
<th>15.00 Acres</th>
</tr>
</thead>
<tbody>
<tr>
<td>Pumping demand</td>
<td>113.25 GPM</td>
</tr>
<tr>
<td>Total water requirements (dry year)</td>
<td>19.17 Acre-ft</td>
</tr>
<tr>
<td>Total water requirements (normal year)</td>
<td>6.04 Acre-ft</td>
</tr>
<tr>
<td>Total labor requirements (dry year)</td>
<td>23.00 hrs</td>
</tr>
<tr>
<td>Total labor requirements (normal year)</td>
<td>8.00 hrs</td>
</tr>
</tbody>
</table>

PORTABLE PIPE (HIGH PRESSURE) SYSTEM OR 'STATIONARY BIG GUN'

The big gun system consists of high pressure sprinkler guns mounted on portable stands, connected by quick coupling lateral piping and sub-mains at fairly wide spacings (of the order of 180 by 180 feet). Based on design characteristics and field conditions, a given arrangement of pipe and sprinklers, or set, must be available to be moved around the field. A portion of the total acreage is irrigated by each set for an established duration, and the entire acreage is
irrigated within the total time allotted for completing the irrigation cycle.

| Area irrigated | 15.00 Acres |
| Pumping demand | 134.82 GPM |
| Total water requirements (dry year) | 20.54 Acre-ft |
| Total water requirements (normal year) | 6.47 Acre-ft |
| Total labor requirements (dry year) | 58.00 hrs |
| Total labor requirements (normal year) | 19.00 hrs |

**PORTABLE PIPE (MEDIUM PRESSURE) SYSTEM**

The portable pipe system consists of pipe risers and sprinklers connected by quick coupling lateral piping and submains at fairly small spacings (of the order of 60 by 60 feet). Based on design characteristics and field conditions, a given arrangement of pipe and sprinklers, or set, must be available to be moved around the field. A portion of the total acreage is irrigated by each set for an established duration, and the entire acreage is irrigated within the total time allotted for completing the irrigation cycle.

| Area irrigated | 15.00 Acres |
| Pumping demand | 151.67 GPM |
| Total water requirements (dry year) | 20.54 Acre-ft |
| Total water requirements (normal year) | 6.47 Acre-ft |
| Total labor requirements (dry year) | 115.00 hrs |
| Total labor requirements (normal year) | 37.00 hrs |

End of input summary and output on suitable systems.

**** THE ECONOMIC ANALYSIS IS BASED ON COSTS IN 1984 ****

*** ECONOMIC ANALYSIS FOR DRYLAND PRODUCTION ***

Total area under production = 15.00 Acres
Total cost of Dryland production = $ 4200.00

**RETURNS IN A DRY YEAR (1 IN 10 YEAR DROUGHT)**

With crop price = 4.00 $/BU
   Break-even Yield = 70.00 bu/acre
   Total profit with a 80.00 bu/acre yield = $ 600.00
   Profit per acre = $ 40.00

With crop price = 3.00 $/BU
   Break-even Yield = 93.33 bu/acre
   The break even yield exceeds the expected yield
   Profit per acre = $ -40.00

APPENDICES
**RETURNS IN A NORMAL YEAR (5 IN 10 YEAR DROUGHT)**

With crop price = 3.50 $/BU  
Break-even Yield = 80.00 bu/acre  
Total profit with a 110.00 bu/acre yield = $ 1575.00  
Profit per acre = $ 105.00

With crop price = 2.75 $/BU  
Break-even Yield = 101.82 bu/acre  
Total profit with a 110.00 bu/acre yield = $ 337.50  
Profit per acre = $ 22.50

*** ECONOMIC ANALYSIS FOR FIXED CENTER PIVOT ***

Total area irrigated = 11.79 Acres  
Total initial investment = $ 17996.84  
Annual fixed cost of Irrigation system = $ 3002.31  
Total annual cost of additional inputs for irrigation = $ 942.86

**RETURNS IN A DRY YEAR (1 IN 10 YEAR DROUGHT)**

Annual operating cost of system = $ 1107.94

With crop price = 4.00 $/BU  
Value of crop lost due to movement of irrigation equipment = $ 75.43  
Break-even Yield = 178.79 bu/acre  
Total profit with a 190.00 bu/acre yield = $ 528.60  
Profit per acre = $ 44.83

With crop price = 3.00 $/BU  
Value of crop lost due to movement of irrigation equipment = $ 56.57  
Break-even Yield = 237.85 bu/acre  
The break even yield exceeds the expected yield  
Profit per acre = $ -127.90

**RETURNS IN A NORMAL YEAR (5 IN 10 YEAR DROUGHT)**

Annual operating cost of system = $ 348.68

With crop price = 3.50 $/BU  
Value of crop lost due to movement of irrigation equipment = $ 90.75  
Break-even Yield = 186.29 bu/acre  
Total profit with a 190.00 bu/acre yield = $ 152.91  
Profit per acre = $ 12.97

With crop price = 2.75 $/BU  
Value of crop lost due to movement of irrigation equipment = $ 71.30  
Break-even Yield = 236.50 bu/acre  
The break even yield exceeds the expected yield  
Profit per acre = $ -143.50
*** ECONOMIC ANALYSIS FOR TRAVELING GUN ***

Total area irrigated = 15.00 Acres
Total initial investment = $ 10715.83
Annual fixed cost of Irrigation system = $ 1787.66
Total annual cost of additional inputs for irrigation = $ 1200.00

**RETURNS IN A DRY YEAR (1 IN 10 YEAR DROUGHT)**

Annual operating cost of system = $ 846.48

With crop price = 4.00 $/BU
Value of crop lost due to movement of irrigation equipment = $192.00
Break-even Yield = 137.10 bu/acre
Total profit with a 190.00 bu/acre yield = $ 3173.86
Profit per acre = $ 211.59

With crop price = 3.00 $/BU
Value of crop lost due to movement of irrigation equipment = $144.00
Break-even Yield = 181.74 bu/acre
Total profit with a 190.00 bu/acre yield = $ 371.86
Profit per acre = $ 24.79

**RETURNS IN A NORMAL YEAR (5 IN 10 YEAR DROUGHT)**

Annual operating cost of system = $ 266.83

With crop price = 3.50 $/BU
Value of crop lost due to movement of irrigation equipment = $231.00
Break-even Yield = 146.39 bu/acre
Total profit with a 190.00 bu/acre yield = $ 2289.51
Profit per acre = $ 152.63

With crop price = 2.75 $/BU
Value of crop lost due to movement of irrigation equipment = $181.50
Break-even Yield = 185.11 bu/acre
Total profit with a 190.00 bu/acre yield = $ 201.51
Profit per acre = $ 13.43

*** ECONOMIC ANALYSIS FOR PORTABLE PIPE ***

Total area irrigated = 15.00 Acres
Total initial investment = $ 8042.50
Annual fixed cost of Irrigation system = $ 1341.68
Total annual cost of additional inputs for irrigation = $ 1200.00

**RETURNS IN A DRY YEAR (1 IN 10 YEAR DROUGHT)**

Annual operating cost of system = $ 1154.98

APPENDICES
With crop price = 4.00 $/BU  
Value of crop lost due to movement of irrigation equipment = $ 48.00  
Break-even Yield = 132.41 bu/acre  
Total profit with a 190.00 bu/acre yield = $ 3455.33  
Profit per acre = $ 230.36

With crop price = 3.00 $/BU  
Value of crop lost due to movement of irrigation equipment = $ 36.00  
Break-even Yield = 176.28 bu/acre  
Total profit with a 190.00 bu/acre yield = $ 617.33  
Profit per acre = $ 41.16

**RETURNS IN A NORMAL YEAR (5 IN 10 YEAR DROUGHT)**

Annual operating cost of system = $ 364.07

With crop price = 3.50 $/BU  
Value of crop lost due to movement of irrigation equipment = $ 57.75  
Break-even Yield = 136.45 bu/acre  
Total profit with a 190.00 bu/acre yield = $ 2811.50  
Profit per acre = $ 187.43

With crop price = 2.75 $/BU  
Value of crop lost due to movement of irrigation equipment = $ 5.37  
Break-even Yield = 173.36 bu/acre  
Total profit with a 190.00 bu/acre yield = $ 686.37  
Profit per acre = $ 45.76

*** ECONOMIC ANALYSIS FOR BIG GUN ***

Total area irrigated = 15.00 Acres  
Total initial investment = $ 7908.47  
Annual fixed cost of Irrigation system = $ 1319.32  
Total annual cost of additional inputs for irrigation = $ 1200.00

**RETURNS IN A DRY YEAR (1 IN 10 YEAR DROUGHT)**

Annual operating cost of system = $ 1128.35

With crop price = 4.00 $/BU  
Value of crop lost due to movement of irrigation equipment = $ 48.00  
Break-even Yield = 131.59 bu/acre  
Total profit with a 190.00 bu/acre yield = $ 3504.32  
Profit per acre = $ 233.62

With crop price = 3.00 $/BU  
Value of crop lost due to movement of irrigation equipment = $ 36.00  
Break-even Yield = 175.19 bu/acre  
Total profit with a 190.00 bu/acre yield = $ 666.32
Profit per acre = $ 44.42

**REturns in a normal year (5 in 10 year drought)**

Annual operating cost of system = $ 355.68

With crop price = 3.50 $/BU
Value of crop lost due to movement of irrigation equipment = $ 57.75
Break-even Yield = 135.86 bu/acre
Total profit with a 190.00 bu/acre yield = $ 2842.25
Profit per acre = $ 189.48

With crop price = 2.75 $/BU
Value of crop lost due to movement of irrigation equipment = $ 45.37
Break-even Yield = 172.62 bu/acre
Total profit with a 190.00 bu/acre yield = $ 717.12
Profit per acre = $ 47.81

END OF ECONOMIC EVALUATION

Note: All yields have been expressed in bu/acre and crop prices in $/bu. However, the appropriate units should be assumed for crops not sold in bushels.
Vita

Dipmani Kumar was born on January 14, 1963 in Ranchi, India. He received a B.Tech degree in Agricultural Engineering from Punjab Agricultural University, Ludhiana, India in June, 1986. He was a lecturer in the Agricultural Engineering section at Gwebi Agricultural College, Harare, Zimbabwe for two years before entering Virginia Tech to pursue an MS in Agricultural Engineering in August, 1988. He plans to begin studies in August, 1990 towards a Ph.D at Virginia Tech.

Dipmani Kumar