Computer Model to Optimize Above–Ground Drip Irrigation Systems for Small Areas

R. Narayanan, D. D. Steele, T. F. Scherer

Abstract. *Drip irrigation systems offer the potential for efficient irrigation of high value crops and have proven feasible from engineering and agronomic standpoints in the northern Great Plains. However, little information is available in this region regarding the optimum design and economics of these systems. The objective of this study was to develop a computerized model for design and economic optimization of above–ground drip irrigation systems for carrots, cabbage, onions, and sweet corn. The method of complete enumeration was used to find the optimum sizes of main line, sub main, and lateral pipelines using hydraulic principles; field, crop, water, and soils information; and characteristics and costs of drip irrigation components. Economic analyses were performed using 0.4–, 0.8–, 1.6–, and 4.0–ha fields with one, two, or four irrigated zones and two possible well locations. Benefit–cost ratios (B/C ratios) were estimated. The cost per area of a drip irrigation system was highest for the 0.4–ha field with four zones and the water source located at the corner of the field and lowest for 4 ha with four zones and the water source located at the center. The B/C ratio was highest for a 4–ha field with four zones and lowest for a 0.4–ha field with four zones. Among the crops, the B/C ratio was highest for carrots followed by cabbage, sweet corn, and onion. The model provides useful information in the design and optimization of drip irrigation systems for small areas.*

Keywords. *Trickle irrigation, Optimization, Economic analysis, Design, Hydraulic.*

Irrigation is often an essential input for production of alternative crops in the northern Great Plains region of the United States. Scherer (2000) indicated that sprinkler and surface irrigation are the most commonly used methods in North Dakota, with 77,500 and 18,700 ha (191,600 and 46,200 acres), respectively, while drip irrigation is not a common method of irrigation in the state at 81 ha (200 acres). However, sprinkler and surface irrigation systems are not always appropriate. Drip irrigation systems will be more suitable in situations where the water supply is minimal or expensive, and the irrigated area is small, irregularly shaped, or of uneven topography.

Steele et al. (1996) designed, installed, and studied a subsurface drip irrigation (SDI) system at Oakes, North Dakota from 1993 to 1995. They concluded that drip irrigation systems are suitable for use in the northern Great Plains region from engineering and agronomic standpoints for production of sweet corn, winter squash, and cabbage. Little information is available regarding optimum design and economics of drip irrigation systems for alternative crops in the northern Great Plains region. The uncertainty about cost is one of the contributing factors for the low use of drip irrigation systems in this region (Steele et al., 1996). The high capital cost on a per–unit–area basis of drip irrigation systems, compared to sprinkler and surface systems, is also a disadvantage. To better understand the economics of investing in drip irrigation, a thorough analysis is essential. The analysis should include: 1) engineering principles, to insure an effective, efficient, economic, and durable system; 2) agronomic principles, to assure viable cropping sequences, pest management, weed, and disease control; and 3) economic principles to assure profitability.

The objectives of this study were to: 1) develop a computerized model, which can be used to design and optimize drip irrigation systems for alternative crops; and 2) analyze the economics of using drip irrigation systems for alternative crop production in the northern Great Plains region. This article outlines the following: 1) the procedure used for design and optimization of drip irrigation system, 2) the procedure used for economic analysis, 3) the computer model developed for design optimization and economic analysis, and 4) the results of economic analysis of using drip irrigation systems for the crop sequence of carrot, cabbage, onion, and sweet corn. The reader is referred to Narayanan (1997) for further literature and details of the study. We do not present model validations based on field studies. The model is for aboveground drip irrigation systems, not SDI systems.

Model Development

The steps involved in the development of a drip irrigation design and economic analysis tool can be broadly classified

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into the following three categories: 1) defining the procedure for design of the drip irrigation system, 2) selecting a method for economic analysis, and 3) building a computerized tool. Detailed flow charts showing the algorithms used in the model are provided by Narayanan (1997) but are not reproduced here because of space constraints.

DESIGN OF DRIP IRRIGATION SYSTEMS

The procedure for the design of drip irrigation system was classified into: (1) irrigation planning, (2) layout of the irrigation system, (3) selection of the irrigation system components, and (4) optimization of the irrigation system design.

Irrigation Planning

Irrigation planning constitutes the determination of the depth of water to be applied and the maximum interval of irrigation based on the available water holding capacity (AWHC) of the soil and the evapotranspiration requirement of the crop (ET_c). The soil moisture holding capacities provided by Lundstrom and Stegman (1988) were used to estimate the depth of water to be applied as represented by the equation:

$$d = AWHC \times P_w \times d_r \tag{1}$$

where d is the depth of water applied available for crop (cm), AWHC is the available water holding capacity of the soil (cm cm^{-1}), P_w is the percentage area of soil wetted (%), and d_r is the depth of root zone (cm).

The percentage of soil wetted depends on the soil characteristics and the discharge and spacing of emitters. The P_w for non–overlapping wetted areas was determined using an equation suggested by Dandy and Hassanli (1996) where:

$$P_w = 100\left[\frac{\pi WD^2}{4 d_l d_e}\right] \tag{2}$$

Here WD represents the wetting diameter of emitter (m), d_l and d_e represent the spacing of laterals (m) and the spacing of emitters (m), respectively.

In case of overlapping wetted area, a more complex equation (Eves, 1976) for P_w has to be used. In such cases, for economical reasons, the wetting diameter of two adjacent emitters should not overlap more than 60% as suggested by Karmeli et al. (1985). The following empirical equations for WD for different soils were used:

$$WD = 3.936 + 74.456 q_e \text{ for fine soil} \tag{3a}$$

$$WD = 2.296 + 81.90 q_e \text{ for medium soil} \tag{3b}$$

$$WD = 0.984 + 89.34 q_e \text{ for coarse soil} \tag{3c}$$

where q_e is the discharge of an emitter (L s^{-1}). The shortest irrigation interval was determined using the equation:

$$F = \frac{d}{ET_p} \tag{4}$$

where F is the irrigation interval (days), d is the depth of water applied available for crop (cm), and ET_P is the maximum ET demand by the crop (cm d^{-1}).

Layout of Irrigation System

A preliminary design of the proposed irrigation system is required to decide the number of zones of irrigation and a layout of the pipelines from the water source. Figure 1 shows some layouts of drip irrigation systems with single and multiple zones of irrigation and water source located at the center and corner of the field. Using multiple zones in an irrigation program allows the application of water in different shifts of operation and it is favorable when the irrigated area is large and the discharge from the pump does not allow the irrigation of the entire area at once. As the number of zone increases, the operating hours for the entire field also increases. When identifying or selecting the location of the water source, the user should consider installation difficulties and additional costs that may be encountered, especially if the center location is chosen.

Selection of Irrigation System Components

Selecting components for an irrigation system requires a thorough hydraulic analysis. Hydraulic analysis will enable the design of a system that will provide uniform amounts of water for all crops with a minimum loss of irrigation water. Hydraulic analysis will also minimize the total cost of the irrigation system, i.e., the initial cost plus the annual operating cost of the system. The selection procedure can be classified into: 1) selection of drip tape, 2) selection of lengths and diameters of PVC pipes for manifold, sub main, and mainline, and 3) selection of pump and accessories such as filters, fertilizing units, valves, pressure regulators, etc.

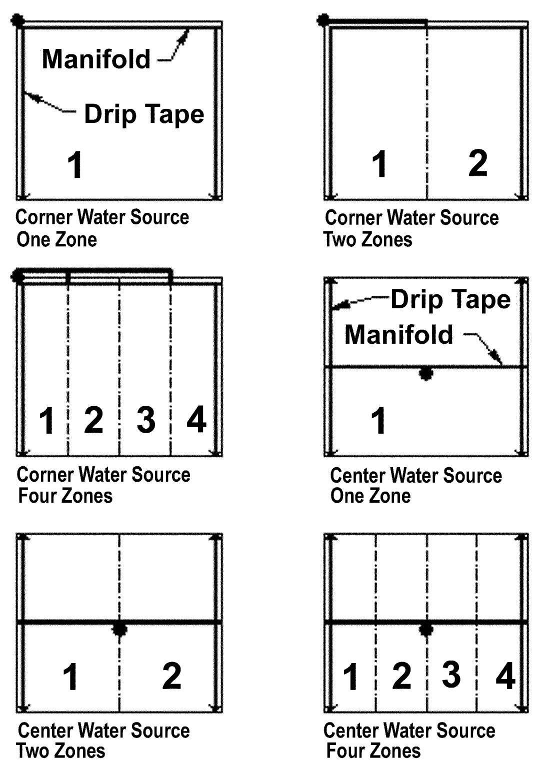

Figure 1. Layout of drip irrigation systems.

Selection of Drip Tape. Drip tapes available in the market are manufactured with emitters at predetermined spacing. Manufacturers specify a drip tape by its discharge (q_e), emitter spacing (d_e), and diameter (d). A suitable drip tape can be selected based on the following conditions: 1) the discharge rate should satisfy the irrigation requirement of the crop, 2) the percentage of area wetted should be within acceptable limits (i.e. 33% < P_w< 100) (von Bernuth and Solomon, 1986), and 3) the rate of discharge should not exceed the infiltration capacity of the soil (Dandy and Hassanli, 1996), i.e.,

$$q_e \le \left[\frac{I_{soil}\, d_l\, d_e\, P_w}{100}\right] = \left[\frac{I_{soil}\, \pi (WD)^2}{4}\right] \tag{5}$$

where I_{soil} is the infiltration capacity of soil (m min^{-1}). The head loss in drip tape can be calculated using the Hazen–Williams equation, discussed below.

Selection of Manifold, Sub main, and Mainline. The Hazen–Williams equation used to determine the head loss through the distribution and lateral lines is given as (Howell et al., 1983):

$$H_l = 1.13 \times 10^{11} \left[\frac{0.060 q_t}{c}\right]^{1.852} d_i^{-4.871} f \tag{6a}$$

where H_l is the head loss expressed as a percentage of pipe length, q_t is the discharge through the pipe (L min^{-1}), c is the friction factor (140 to 160 for plastic pipes), d_i is the inside diameter of pipe (mm), and f is a factor to compensate for the discharge along the pipe. The factor f is calculated using the equation:

$$f = \frac{\sum_{i=1}^{n_e} i^{1.85}}{n_e^{2.85}} \tag{6b}$$

where n_e represents number of outlets. The head loss (in % of pipe length) was converted to head loss (in meters) based on the lengths of distribution and lateral lines.

The acceptable limits of head loss in drip tape, as specified by the manufacturers, were used as a constraint for the selection of manifolds. The combined head losses of the manifold and drip tape were maintained within this limit. The velocity of flow (V) was constrained for the selection of the sub mains and mainline. Pipe sizes limiting V to 1.5 m s^{-1} are acceptable to prevent water hammer effects. The velocity of flow is determined by the equation:

$$V = 21.22 \times \frac{q_t}{d_i^2} \tag{7}$$

where V represents the velocity of flow (m s^{-1}).

Selection of Pump and Accessories. The maximum volume of water to be pumped at any time for any zone is the required discharge of the pump. The power requirement for the pump was computed from the formula:

$$P = \frac{1.633 \times 10^{-4} QH}{E_p E_m} \tag{8}$$

where P is the input power to the pump (kW); Q is the discharge rate (L min^{-1}); H is the total head in (m) and includes operating head, suction head, and the head losses in valves, filters, fertilizing unit, flow meter, pressure regulator, distribution lines, and laterals; E_p and E_m are the pump and motor efficiency represented as decimal fractions, respectively; and the specific weight of water is assumed to be 9.8×10^3 N m^{-3} (Vennard and Street, 1982). Accessories included in the model are discussed later.

Optimization of the Irrigation System Design. Drip irrigation systems are associated with high initial investment and considerable operational costs and maintenance costs. These costs depend upon the design of the system. For a given size of operation, a system that is overdesigned (e.g. pipe diameters larger than needed) will have high initial cost and a low operating cost. On the other hand, for a system that is under designed, although the initial cost will be less, the operating cost will often be very high. Therefore, when analyzing the system it is necessary to consider the total cost of the system to select the most economical system. Proper design and optimization are essential to achieve the minimum cost solution.

The method of complete enumeration provides a simple procedure to optimize the design of drip irrigation system and it is suitable when the size of network analyzed is small and the number of alternatives for pipe sizes is relatively small. Optimization is achieved by minimizing the following cost function, similar to that presented by Dandy and Hassanli (1996):

$$C = C_p + C_{pu} + C_a + C_i + C_o + C_r \tag{9}$$

In this equation, C_p represents the combined costs of lateral, manifold, sub main, and mainline pipes. The total cost of pipes is given by $C_p = \Sigma(L_p \times UC_p)$, where L_p is the length of pipe (m) and UC_p is the unit cost of pipe ($ m^{-1}) for each type of pipe. In equation 9, C_{pu} is the cost of pump. Cost of accessories C_a is given by $C_a = \Sigma(N_a \times UC_a)$ where N_a is the quantity of accessories (number) and UC_a is the unit cost of accessories ($ each) for each type of accessory. Accessories required for drip tapes are PVC pipe–to–drip tape connectors and end plugs. The end plugs provide automatic flushing until system–operating pressure is reached, although a simpler solution is to fold over the ends of the drip tape and hold the folded end in place with a "sleeve" of approximately 5 cm of drip tape. If end plugs are not intended to be part of the physical design, the model user can input zero cost for the end plugs and ignore the resulting computation of the number of end plugs required. The number of connectors and end plugs required was computed using $N_a = [(MLL / d_l) + 1] \times 2$ for the case with the manifold at the center of the field and $N_a = [(MLL / d_l) + 1]$ when the manifold was at the corner of the field, where MLL is the length of manifold in meters and d_l is the spacing between laterals in meters.

The variable C_i represents the cost of installation of drip irrigation system. It includes the labor charge for installation and the cost of excavation of trenches. It is given by the equation $C_i = (I_c \times \text{Area}) + (L_t \times C_t)$, where I_c is the cost of installation per ha ($), Area represents the total irrigated area in ha, L_t is the total length of trench (m), and C_t is the cost of excavation ($ m^{-1}).

The present value of operating cost (C_o)of the drip irrigation system was computed based on the number of hours of operation of the pump through the lifetime of irrigation system. It is given by the equation $C_o = (P \times E_c \times OH) \times [(1 - (1 + i)^{-n} / i)]$, where P is the power of the pump, E_c represents the electricity charge ($ KWH^{-1}), OH is the operating hours per year, n is the useful life of the irrigation system (years), and i is the discount rate in decimal fraction.

For trouble–free performance, drip irrigation systems require periodic repair and maintenance, e.g., tape flushing, replacing a faulty part, chlorine and/or acid treatment of the system to prevent clogging, etc. Dhuyvetter et al. (1994) estimated annual repair and maintenance costs of \$7.73 ha^{-1} (\$3.13 $acre^{-1}$) for SDI systems in Kansas. The cost can also be estimated by consulting with the manufacturer of the irrigation system. The present value of the cost of repair and maintenance (C_r) was represented empirically by the equation $C_r = A_m \times [(1 - (1 + i)^{-n} / i)]$ where A_m is the annual repair and maintenance cost (\$) and n the useful life of system (years).

Economic Analysis

Farming is an enterprise that involves several inputs. Analyzing its cost as a single entity may not provide accurate information on the profitability of the enterprise. The economic influence of each component of this enterprise has to be evaluated to obtain accurate results. In analyzing the economics of using drip irrigation systems a benefit–cost (B/C) ratio is a good indicator of the profitability. A project with a B/C ratio of one or greater is acceptable. A B/C ratio however, does not represent the cash flow for a project.

The cost involved with the production of alternative crops is subdivided into two categories: fixed cost (F) and variable cost (V). Fixed cost represents those costs that vary little over the period of production, i.e., do not depend on the annual usage. It includes the costs of land, building, machinery, irrigation system, tax on real estate, and insurance. It can be represented empirically as:

$$F = D + i + R + T + I \tag{10}$$

where D is the annual depreciation given by (N – S)/ n, where N is the new price of the property, S is salvage value i.e. the expected value of the property after its useful life (n). The interest on capital investment (i) is computed as AV × *ir*, where AV is the average value of the property represented by the equation (N + S) / 2 and the parameter *ir* is the rate of interest charged by the financier. The annual tax on real estate (T) is charged as a fixed rate of tax (tr) per acre. The annual insurance (I) on the property is dependent on the value of the property. It is represented empirically by the equation Va × IR, where Va is the value of the property, and IR the annual rate of insurance. Reff (1985) provides more information estimating fixed cost of machinery.

Variable cost represents those costs that vary over the period of production or that depend on usage. It includes the costs of inputs for growing, harvesting, and marketing the produce. It can be represented as:

$$V = G + H + M + i \tag{11}$$

where V is the annual variable cost; G is the growing cost represented by the sum of the cost of all inputs including seeds, fertilizer, pesticide, fuel, labor, etc.; H is the cost involved with harvesting; M is the cost involved with packaging, transporting, and marketing of the produce.

The total cost (T) is the sum of annual fixed and variable costs. The return (R) from the crop is the monetary value of the produce. It is given by benefit (B) = R. The benefit–cost ratio is the total return divided by the total cost and is given by (B/C) = B/T.

Building a Computerized Tool

A computer model for the design and optimization of drip irrigation system and economic analysis was developed using TK Solver® (UTS, 1996), a mathematical application software. A user friendly front–end for the model was created using Visual Basic® (Microsoft, 1995). The model allows the user to supply or change the following variables to analyze different scenarios: 1) area and dimensions of the field, including the number of irrigation zones; 2) soil type and maximum depth of root zone; 3) water available, water source location, and pumping lift; 4) crop to be irrigated and spacing of crop; 5) cost of the components of drip irrigation system, their useful life and salvage value; 6) cost of general machinery, specialized machinery, land, buildings, interest rate, and tax; and 7) costs of inputs for growing, harvesting, and marketing of the crop. Input and output data sheets or screens of the computer model are shown in the figures (figs. 2–8). (The algorithms and computer programs use English units for input and output. Useful conversion factors include the following: 1 ft = 0.3048 m, 1 acre = 0.4047 ha, 1 gal = 3.7854 L, 1 lb $in.^{-2}$ (psi) = 6.8948 kPa. All costs are in 1997 US\$.) The user is prompted for the number of irrigation zones and can select different values to compare different scenarios. The values shown are for illustration only–estimates have been inserted in place of quotes or bids for some of the input costs. A prompting system to warn the user about non–operable inputs or choices was beyond the scope of this project and therefore not included in the computer model.

The model provides the user with the following outputs: 1) available soil moisture holding capacity; 2) maximum irrigation interval; 3) time to irrigate; 4) required flow; 5) total length required, emitter spacing, discharge, diameter, manufacturer, and cost for the drip tape; 6) percentage area of soil wetted; 7) size and quantity of pipe required and its cost; 8) size and quantity of fittings and accessories; 9) discharge, operating head, and power of pump and its cost; 10) cost of installation, operation, and maintenance; 11) total cost of the system; 12) depreciation, interest, taxes, and insurance on machinery, land, and building; 13) variable cost of production and total cost; and 14) benefit–cost ratio of enterprise. The computer model does not include a procedure for cash flow analysis to serve as a decision support system.

Model Application

Hypothetical study areas of sizes 0.4, 0.8, 1.6, and 4.0 ha (1, 2, 4, and 10 acres) with dimensions of 63 × 63 m, 90 × 90 m, 127 × 127 m, and 201 × 201 m (208 × 208 ft, 295 × 295 ft, 417 × 417 ft, and 660 × 660 ft) having a crop rotation of carrot, cabbage, onion and sweet corn were chosen for design of drip irrigation systems and economic analysis. The soil was assumed to be sandy loam soil, with an allowable maximum root zone depth of 0.91 m (3 ft). The root zone depths for carrot, cabbage, onion, and sweet corn were

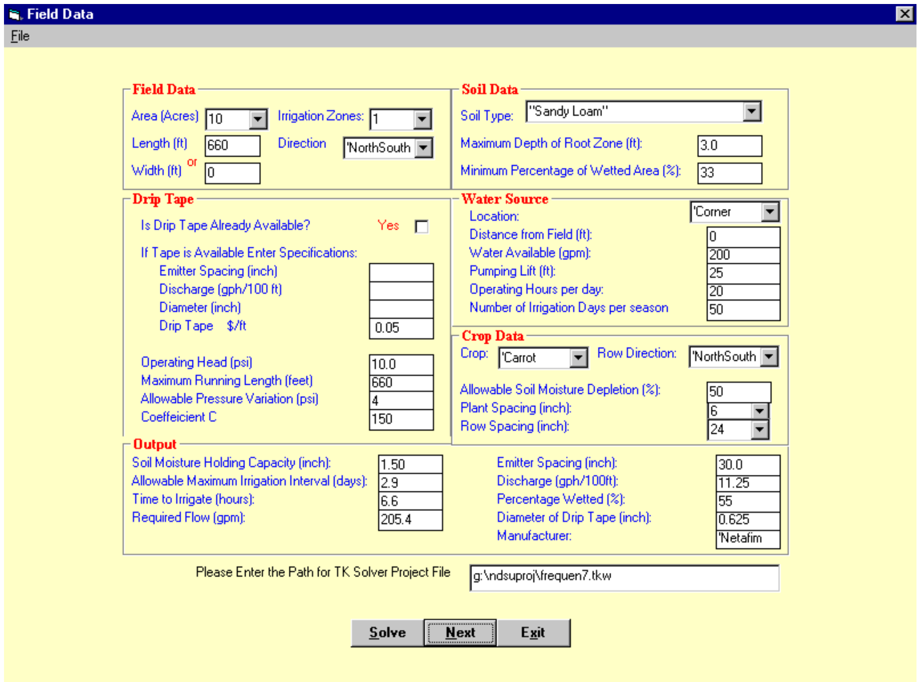

Figure 2. Input screen 1: Field and crop data.

considered to be 0.61, 0.46, 0.30, and 0.91 m (2.0, 1.5, 1.0, and 3.0 ft), respectively. With irrigation scheduled at 50% depletion of available soil moisture, the depletion levels were computed to be 38, 28, 18, and 56 mm (1.5, 1.1, 0.7, and 2.2 in.) for carrot, cabbage, onion, and sweet corn, respectively. These values are based on Lundstrom and Stegman's (1988) approximations of available soil moisture for a sandy loam soil. If the 50% depletion of available soil moisture depletion is not appropriate, the user can enter another value in the model. Average peak summer ET (i.e., when there is maximum crop growth and the weather is hot and dry) determined by Lundstrom and Stegman (1988) from several crops in North Dakota [7.6 mm day^{-1} (0.3 in. day^{-1})] was considered as the design ET_P for the crops. The designed maximum allowable frequency of irrigation varied from 2 to 7 days for this design ET_p and available water holding capacity of the sandy loam soil used in this example.

The water source was considered to be located either at the center or the corner of the field. Design and economic analysis were performed for drip irrigation systems with both

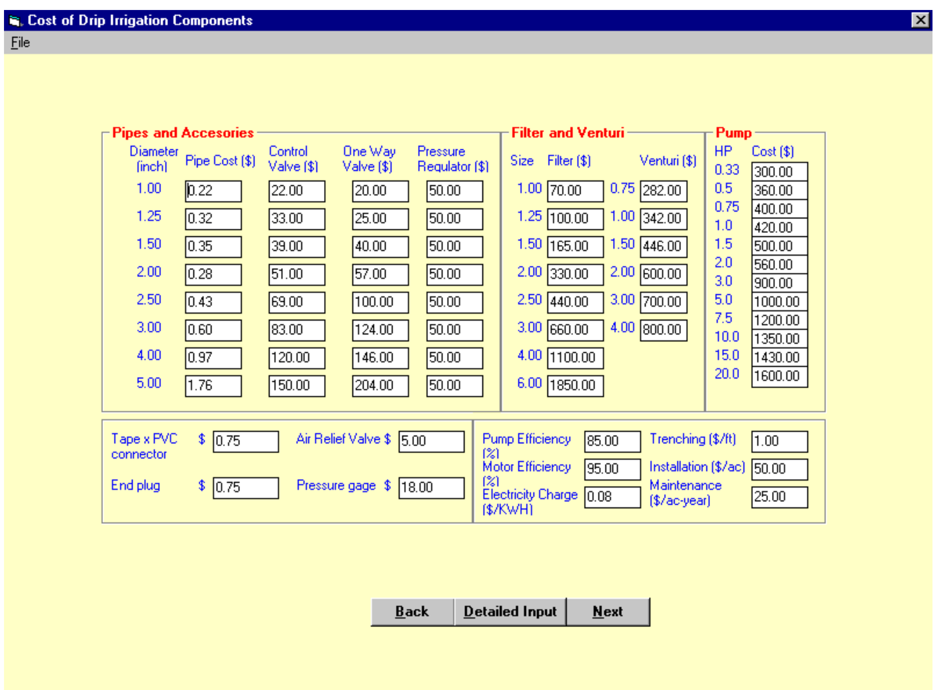

Figure 3. Input screen 2: Cost of drip irrigation components.

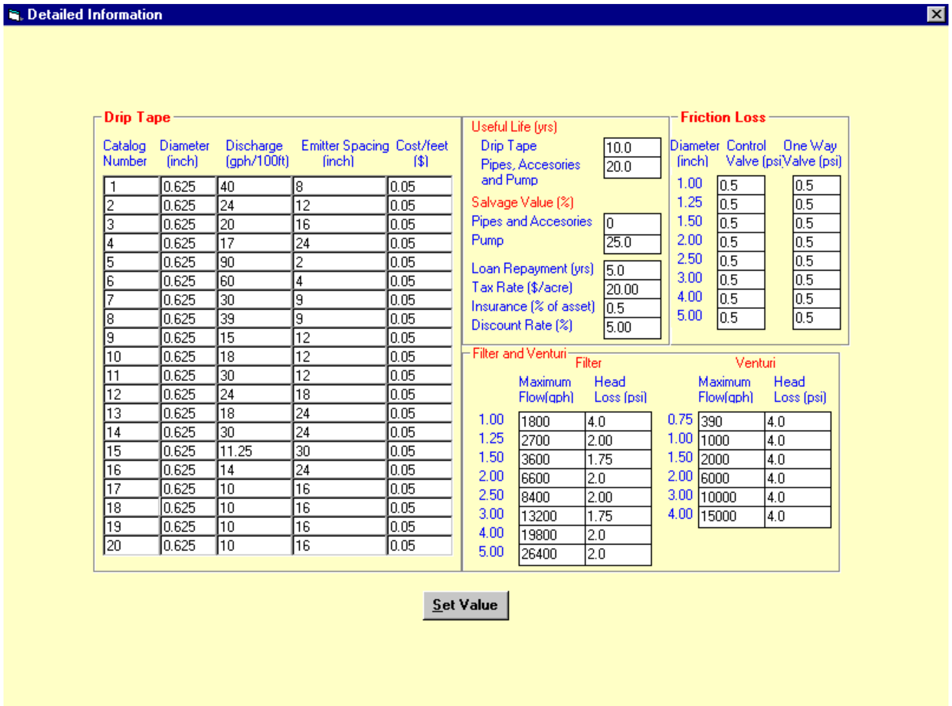

Figure 4. Input screen 3: Detailed information about drip irrigation components.

of these options to understand the change in material requirement and cost of drip irrigation system and B/C ratio with the change in location of water source. The water requirement varied from 0.33 L s^{-1} (5.2 gpm) for an irrigated area of 0.4 ha (1 acre) with four zones to 12.9 L s^{-1} (205 gpm) for an irrigated area of 4 ha (10 acres) as one zone. The pumping lift was assumed to be 7.6 m (25 ft).

Based on assumed crop row spacing of 0.61 m (24 in.) for carrots, onions, and sweet corn and 1.22 m (48 in.) for cabbage, the design drip tape spacing was fixed at 1.22 m (48 in.). Drip tapes were always assumed parallel to the crop rows. Seventeen different drip tapes were analyzed to select a single drip tape suitable for use with the irrigation system. Based on the emitter spacing and flow rate of the drip tape, the wetted diameter and percentage of area wetted were computed. A drip tape with a percentage wetted in the range of 33 to 100% was selected. The total flow along the distribution lines was computed from the flow rate of drip

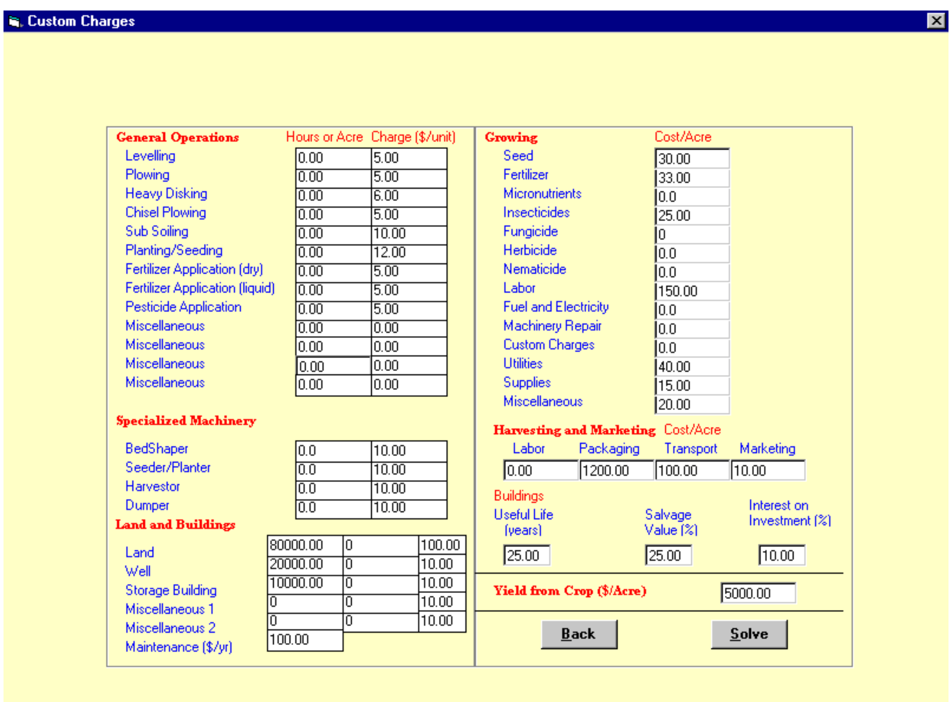

Figure 5. Input screen 4: Custom charges and production cost.

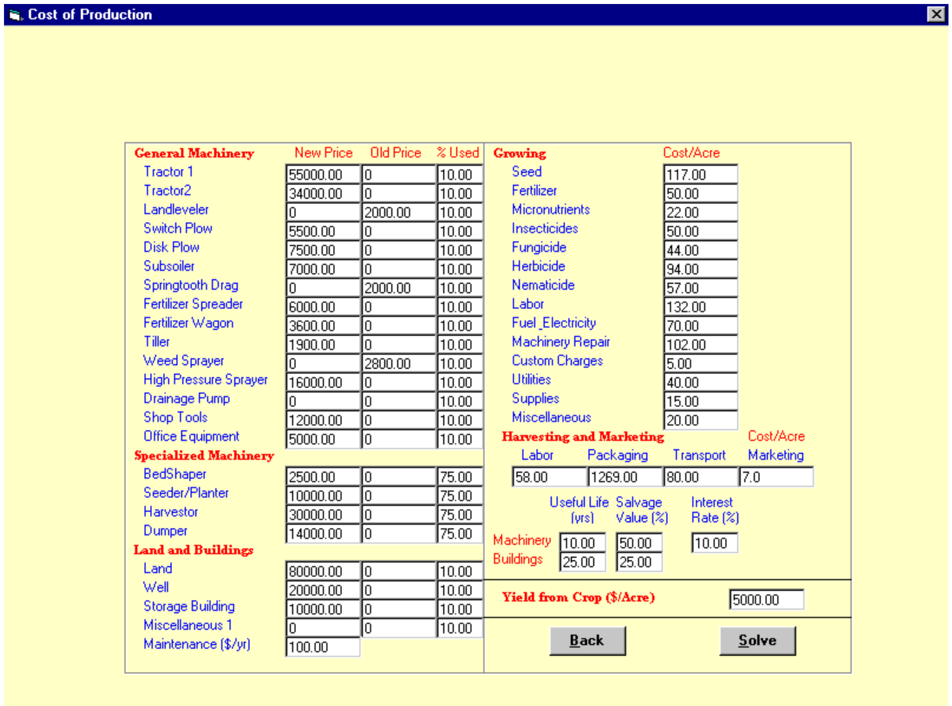

Figure 6. Input screen 5: Cost of machinery and production cost.

tape and the total length of drip tape in the zone. The size of the manifold was selected suitably to maintain the combined head loss in the manifold and drip tape within 27.6 kPa (4 psi). To prevent the effect of water hammer, pipe sizes that limited the velocity of flow to 1.5 m s^{-1} (5 ft s^{-1}) were considered for submains and the main line. The best combination of pipe sizes for the main, submains, and manifold were selected from eight different pipe sizes [25, 32, 38, 51, 64, 76, 102, and 127 mm (1.0, 1.25, 1.5, 2.0, 2.5, 3.0, 4.0, 5.0 in.)], i.e., from a total of 512 network combinations using the complete enumeration optimization procedure.

To prevent damage to the pump and to comply with chemigation regulations, a one–way valve for the size of main line was included in the design. For filtration of water, a mesh filter (screen filter) was included. The size of filter selected was based on the maximum flow in the irrigation system. The capacity of the smallest filter used in the design

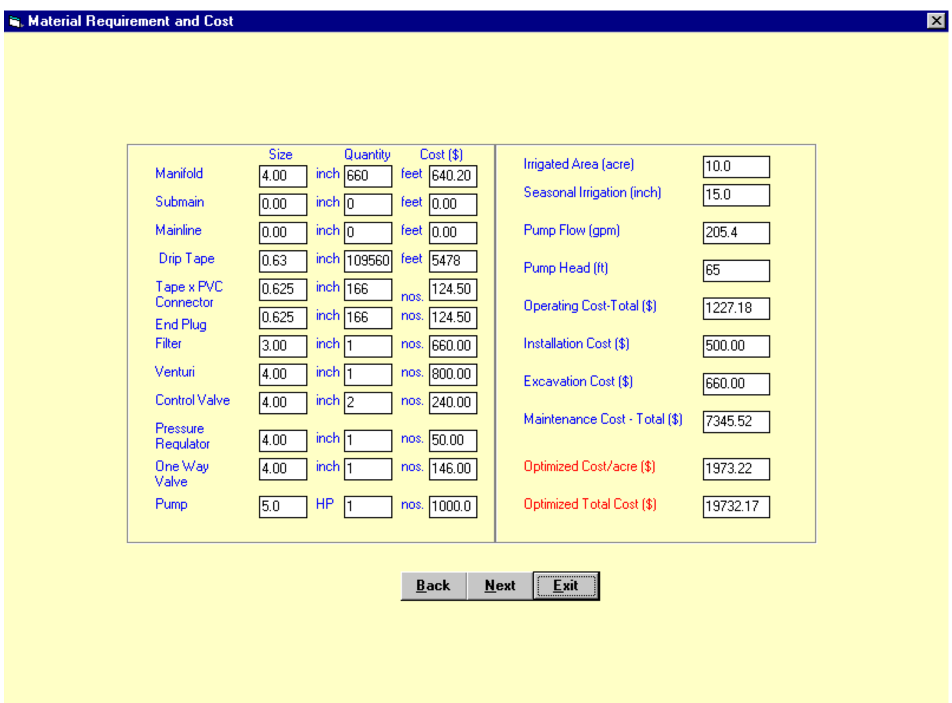

Figure 7. Output screen 1: Material requirement and cost of drip irrigation.

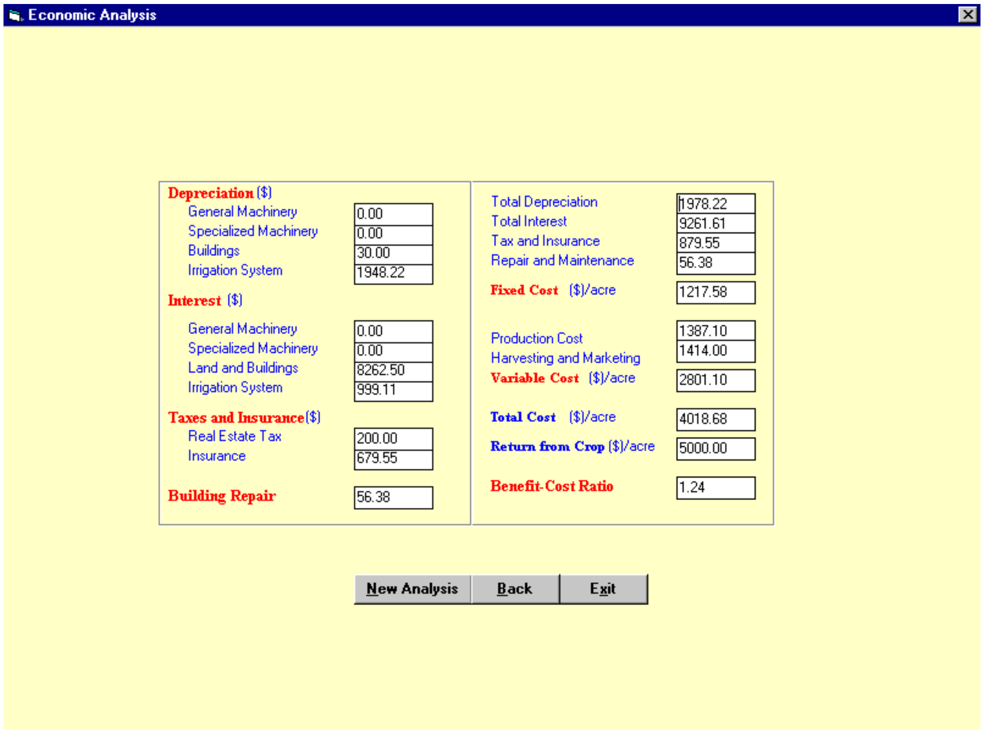

Figure 8. Output screen 2: Economic summary of the drip irrigation system.

was 1.89 L s^{-1} (1800 gal h^{-1}). The provision of sand media filter and/or a hydro cyclone filter is optional, and was not considered in this study.

Drip irrigation systems facilitate effective application of liquid fertilizer through irrigation pipes (fertigation). A venturi assembly enables proper mixing of fertilizer with irrigation water at a predetermined rate. The venturi assembly was selected based on the total flow in the irrigation system. To control the flow rate and monitor the pressure in the system, a control head assembly consisting of a manual control valve and a pressure regulator was considered. The control valve was selected for the size of the main line. Selecting a smaller size valve may cause increased friction loss due to restriction of flow.

The total head loss was computed from the head loss of individual components. The total loss is the sum head loss in distribution lines, drip tape, minor losses in filters, venturi, and other accessories, operating pressure, and pumping lift. A pump was selected to meet the pressure and flow requirements for the system. The operating cost was computed based on the kilowatt hours (KWH) of power required for operation of pump and the cost of electricity per KWH. The costs of components were obtained from the catalogs of Grainger (1997), Chapin Watermatics (1997), and Wade Rain (1993).

The costs and benefits associated with the use of drip irrigation systems for carrot, cabbage, onion, and sweet corn were compared for irrigated areas of 0.4, 0.8, 1.6, and 4.0 ha (1, 2, 4, and 10 acres) with one, two, and four irrigated zones. The benefits and costs of drip irrigation were not compared with the benefits and costs of any other type of irrigation system or non–irrigation. Hence the results of this study can only be used to select the best crop, land size, and number of zones within the alternatives analyzed and cannot be used to make a decision on changing from a sprinkler, surface, or any other type of irrigation to drip irrigation.

The fixed cost was computed from the costs of drip irrigation system, buildings, well, and custom charges for field operations. The variable cost for production was computed from the costs of inputs required to produce the crop based on quantity of materials used by Greenland and Brademeyer (1994; 1995) and Lee et al. (1995) for production of alternative crops at Oakes, North Dakota. The costs of production inputs were obtained from Oslund Chemical (1997) and Sunseeds (1997). The value of produce was computed using Today's Market Prices (1997 values; obtained on 18 January 2002 at http://www.todaymarket.com/). Custom charges provided by Aakre (1996) were used for the cost of machinery and labor. Annual interest rate of 10% of the total cost and an annual tax rate of \$49.40 ha^{-1} (\$20 acre^{-1}) were used. The rate of insurance was assumed to be 0.5% of the total value of the asset. Table 1 summarizes the yield, price, and gross income for each crop; see Narayanan (1997) for detailed information on per–area production costs (seed, fertilizer, chemicals, labor, harvesting, etc.).

The results of the economic analysis are compared with those from Dhuyvetter et al. (1994), who studied the economics of SDI systems for corn in Kansas. It would be desirable to compare our results with the results of studies closer to North Dakota, but there was no current literature on the economics of drip irrigation in the north–central region of the United States at the time Narayanan (1997) performed the analysis. More recent additions to the literature in the region include O'Brien et al. (1998), who compared the economics of SDI and center pivot irrigation of corn in Kansas, and Sharmasarkar et al. (2001), who reported an agroeconomic analysis of surface drip versus furrow irrigation systems for sugar beet production in Wyoming.

Table 1. Yield, price, and gross crop income parameters used in the model.

Crop	Yield Amount	Yield Unit	Market Price Amount	Market Price Unit	Income $ ha^{-1}
Production Coefficients(SI units[a])					
Carrot	90,000	kg ha^{-1}	$0.276	$ kg^{-1}	$24,800
Cabbage	49,000	kg ha^{-1}	$0.250	$ kg^{-1}	$12,300
Onion	28,000	kg ha^{-1}	$0.176	$ kg^{-1}	$4,900
Sweet corn	77,000	ears ha^{-1}	$0.1452	$ ear^{-1}	$11,200
Production Coefficients (Conventional Units)					Income $ acre^{-1}
Carrot	80,000	lb acre^{-1}	$0.125	$ lb^{-1}	$10,000
Cabbage	44,000	lb acre^{-1}	$0.1136	$ lb^{-1}	$5,000
Onion	25,000	lb acre^{-1}	$0.08	$ lb^{-1}	$2,000
Sweet corn	31,000	ears acre^{-1}	$0.1452	$ ear^{-1}	$4,500

[a] The model was developed using conventional units and SI values in this table are rounded.

Results and Discussion

For the selected set of input parameters, a drip tape with a per–emitter flow rate of 0.0177 L min^{-1} (equivalent to a tape with a flow rate of 11.25 gal h^{-1} per 100 ft) and an emitter spacing of 0.76 m (30 in.) was selected by the model for all the design layouts. This drip tape had P_w = 55%, the smallest value among all the drip tapes. If this emitter spacing is unacceptable from the crop production standpoint, the user could eliminate tapes with emitter spacing larger than 0.46 m (18 in.) from the list of drip tapes available for the model to consider (see figs. 2 and 4) and rerun the analysis. Based on a tape spacing of 1.22 m (4 ft), 8197 m ha^{-1} (10,890 ft acre^{-1}) tape is required. The cost of drip tape constituted a significant portion of the total cost of the irrigation system. Considering all the alternatives analyzed, the cost of drip tape was 19, 23, 27, and 30% of the total cost of the drip irrigation system for 0.4–, 0.8–, 1.6–, and 4.0–ha (1–, 2–, 4–, and 10–acre) irrigated areas, respectively, regardless of the number of zones of irrigation. By adopting a wider spacing for drip tapes or using a thinner drip tape, e.g., 0.25– or 0.38–mm (10– or 15–mil) instead of 0.51–mm (20–mil) tapes, the total cost of the system can be reduced.

A 1.5 to 2.0% difference in the total cost was observed by comparing the costs of drip irrigation systems with the water source located at the center and at the corner of the field. The field with the water source located at the center required fewer lengths of distribution pipes than a field with the water source located in the corner. So the costs of distribution pipes and excavation were higher for fields with the water source located at the corner. The cost of installation of $124 ha^{-1} ($50 acre^{-1}) is assumed to include the increased installation cost that may be incurred for installing lateral pipes on either side of the manifold when the water source (and manifold) is located at the center of the field.

The cost per area of drip irrigation systems is presented in table 2. As the irrigated area increases from 0.4 to 4.0 ha (1 to 10 acres), the cost of drip irrigation system is reduced because some of the components (especially filters, venturi, and pump) are under–utilized in the 0.4–ha (1–acre) system with one, two, and four irrigated zones and in the 0.8–ha (2–acre) system with two and four irrigated zones. These components are utilized to capacity at 1.6– and 4.0–ha (4– and 10–acre) irrigated fields. The maximum investment cost per area of drip irrigation was $8612 ha^{-1} ($3485 acre^{-1}) for an irrigated area of 0.4 ha (1 acre) with four zones of irrigation and the well located at the corner. The minimum cost was $4332 ha^{-1} ($1753 acre^{-1}) for an irrigated area of 4 ha (10 acres) with four zones of irrigation and the well located at the center.

Table 2. Irrigation system costs and benefit–cost ratios.

Field Size (ha)	No. of Zones	Well Location	Irrigation System Cost ($ ha^{-1})	Irrigation System Cost ($ acre^{-1})	Benefit–Cost Ratios Carrot	Cabbage	Onion	Sweet Corn
0.4	1	Center	7406	2997	2.36	1.19	0.44	1.05
0.4	1	Corner	7406	2997	2.36	1.19	0.44	1.05
0.4	2	Center	7141	2890	2.37	1.19	0.44	1.05
0.4	2	Corner	7581	3068	2.35	1.18	0.44	1.05
0.4	4	Center	7700	3116	2.35	1.18	0.44	1.04
0.4	4	Corner	8612	3485	2.32	1.17	0.43	1.03
0.8	1	Center	6101	2469	2.55	1.28	0.47	1.13
0.8	1	Corner	6099	2468	2.55	1.28	0.47	1.13
0.8	2	Center	5767	2334	2.57	1.29	0.48	1.14
0.8	2	Corner	6121	2477	2.55	1.19	0.47	1.13
0.8	4	Center	5849	2367	2.56	1.29	0.47	1.13
0.8	4	Corner	6306	2552	2.54	1.28	0.47	1.13
1.6	1	Center	5375	2175	2.73	1.37	0.51	1.21
1.6	1	Corner	5375	2175	2.72	1.37	0.50	1.21
1.6	2	Center	4967	2010	2.75	1.38	0.51	1.22
1.6	2	Corner	5278	2136	2.73	1.37	0.50	1.21
1.6	4	Center	4954	2005	2.75	1.38	0.51	1.22
1.6	4	Corner	5308	2148	2.73	1.37	0.50	1.21
4.0	1	Center	4875	1973	2.91	1.41	0.54	1.29
4.0	1	Corner	4875	1973	2.89	1.45	0.53	1.28
4.0	2	Center	4492	1818	2.93	1.48	0.54	1.30
4.0	2	Corner	4856	1965	2.90	1.46	0.53	1.28
4.0	4	Center	4332	1753	2.94	1.48	0.54	1.30
4.0	4	Corner	4767	1929	2.90	1.46	0.43	1.28

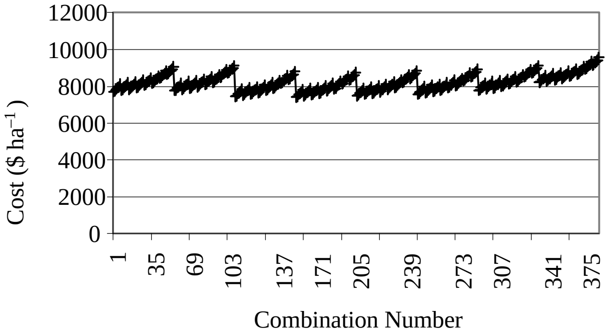

Figure 9. Cost of drip irrigation systems for all possible combinations of distribution pipes for a 0.4–ha (1–acre) system with one zone of irrigation.

Figure 9 shows the total cost of all possible drip irrigation systems for a 0.4–ha (1–acre) irrigated field with one zone of irrigation. Similar results (not shown) were obtained for 0.8–, 1.6–, and 4.0–ha (2–, 4–, and 10–acre) fields with one zone of irrigation. Costs of the drip irrigation systems and B/C ratios for all combinations of field sizes, number of zones, and well locations are summarized in table 2.

The importance of optimization in cost reduction is clearly evident from figure 9. For example, for the 0.4–ha (1–acre) system with one irrigation zone, the optimum cost was $7406 (table 2), while the corresponding maximum (poorest optimization) cost was $9558 ha^{-1} (not shown). Similarly, the optimum and maximum costs were $6099 and $8300 ha^{-1} for the 0.8–ha system, $5375 and $10,626 ha^{-1} for the 1.6–ha system, and $4875 and $5360 ha^{-1} for the 4–ha system. The differences between the optimized cost and maximum cost were 29, 36, 97, and 9% of the optimum costs for areas of 0.4, 0.8, 1.6, and 4 ha (1, 2, 4, and 10 acres) with one zone of irrigation, respectively. The smaller difference in cost for a 4–ha (10–acre) system with one zone is due to the fact that the 4–ha (10–acre) system with one zone has a higher flow rate, thereby eliminating some of the available pipe size combinations. A better estimate of optimization can be achieved by including more pipe diameters in design and analysis. In that case, using the complete enumeration technique may be very computer intensive and a use of a different technique for optimization is recommended.

The highest B/C ratio (table 2) was 2.94 for 4–ha (10–acre) irrigated carrot field with four zones of irrigation and a well located at the center of the field. For the same field, the B/C ratios were 1.48 for cabbage, 0.54 for onion, and 1.30 for sweet corn. The lowest B/C ratios for these crops were for a 0.4–ha (1–acre) system with four zones of irrigation and a water source located at the corner.

The cost of the drip irrigation system per unit area in this study is significantly higher than the cost per area estimated by Dhuyvetter et al. (1994) and the difference can be attributed to several factors. Table 3 summarizes the differences in tape spacing, tape cost, maintenance, installation, and trenching. In this study, the cost of the 4–ha (10–acre) system with four zones and the well located at the center is $4332 ha^{-1} ($1753 acre^{-1}, see table 2), while the 65–ha (160–acre) SDI system of Dhuyvetter et al. (1994) was estimated to cost $1406 ha^{-1} ($569 acre^{-1}), a difference of $2926 ha^{-1} ($1184 acre^{-1}). This difference is slightly over the $2619 ha^{-1} ($1067 acre^{-1}) cost difference shown in table 3.

Table 3. Cost differences between this study and Dhuyvetter et al. (1994).

Item	Values Used in this Study	Values Used by Dhuyvetter et al.	Cost Difference $ ha^{-1}	Cost Difference $ acre^{-1}
Tape cost	$1344 ha^{-1} ($545 acre^{-1})	$647 ha^{-1} ($261 acre^{-1})	697	284
Maintenance[a]	$1836 ha^{-1} ($748 acre^{-1})	–	1836	748
Trenching[b]	$247 ha^{-1} ($100 acre^{-1})	$161 ha^{-1} ($65 acre^{-1})	86	35
Total			2619	1067

[a] The present value of the total cost for maintenance of the drip irrigation systems over the useful life of the system.
[b] The total length of trench in this study was estimated as the sum of lengths of main, submain, and manifold. The Dhuyvetter et al. (1994) study used sum of lengths of mainline, submain, and flushline.

The difference in tape cost due to tape spacing and cost of drip tape between the two studies is $697 ha^{-1} ($284 acre^{-1}). Based on the 1.22–m (4–ft) tape spacing used in this study, 8197 m ha^{-1} (10,890 ft acre^{-1}) of tape at a unit cost of $0.164 m^{-1} ($0.05 ft^{-1}) costs $1344 ha^{-1} ($545 acre^{-1}). Dhuyvetter et al. (1994) used 1.52–m (5–ft) tape spacing and tape cost of $0.0984 m^{-1} ($0.03 ft^{-1}), which amounts to 6579 m ha^{-1} (8712 ft acre^{-1}) of tape and a cost of $647 ha^{-1} ($261 acre^{-1}).

For the cost of maintenance and repair we consider an annual expense of $62 ha^{-1} ($25 acre^{-1}) for the general irrigation equipment and approximately $136 ha^{-1} ($55 acre^{-1}) for replacement of 10% of drip tapes which are assumed damaged due to rodents, machinery use, etc. The annual maintenance and repair cost estimate is conservative compared with that by Dhuyvetter et al. (1994) corresponding value (for SDI) of $7.73 ha^{-1} ($3.13 acre^{-1}). Another approach would be to follow Sharmasarkar et al. (2001), who used an annual cost of maintenance and repairs equal to 2.5% of the irrigation system investment cost. Note that the user is free to adjust cost of maintenance and repair as necessary based on experience, other literature, or information from the irrigation system manufacturer. The 10% annual replacement rate for drip tapes is based on a 10–year life; the useful life is a user input and can be changed. To put this estimate of useful life in perspective, Sharmasarkar et al. (2001) used a base value of a 15–year life for surface drip irrigation of sugar beets in Wyoming, while the analyses by Dhuyvetter et al. (1994) and O'Brien et al. (1998) found subsurface drip irrigation to be unprofitable (compared to center pivot irrigation for corn in Kansas) for a system life of less than 10 year.

We also consider the cost of a pump [$500 for 0.4 to 4 ha (1 to 10 acres)] and its operating cost of $8.65 to $14.85 ha^{-1}y^{-1} ($3.5 to $6 acre^{-1} y^{-1}). The total costs for operation, maintenance, and repair included in the cost analysis of this study represents the present value of the total cost that will be incurred over the useful life of the system. Hence the costs appear to be inflated compared with the estimates of Dhuyvetter et al. (1994). Also note that Dhuyvetter et al. (1994) do not include estimates for the cost of the irrigation well and pump.

Although the total length of trench is not significantly different between the two studies [75 m ha^{-1} in our study vs. 72 m ha^{-1} in Dhuyvetter et al. (1994)], the unit cost of excavation, $3.28 m^{-1} ($1.00 ft^{-1}), is considerably higher than a cost of $2.23 m^{-1} ($0.68 ft^{-1}) used by Dhuyvetter et al.

(1994). Hence the total cost of excavation was $86 ha^{-1} (35 acre^{-1}) higher than the estimates of Dhuyvetter et al. (1994).

The cost of pipelines, filtration, and chemical injection systems, etc. would also be lower on a per unit area basis for larger areas such as those studied by Dhuyvetter et al. (1994). The cost differences call attention to the importance of economies of scale for larger systems, a factor that favors or necessitates high–value crops for smaller areas.

Drip tape constitutes 20 to 30% of the total cost of the drip irrigation systems designed in this study. Optimization of drip tape based on its diameter and running length may provide better insight to design a least–cost system. There is always a decision regarding whether to select a thin–walled drip tape (having a short life period) or a thick walled tape. A study from the economic view comparing the use of thin–walled drip tapes and thick–walled drip tapes needs to be done to understand this issue better.

In analyzing the economics, there is a need to compare the B/C ratio of drip irrigation with the B/C ratio of other types of irrigation or non–irrigation. This analysis will enable comparison of the profitability of the two projects. A decision on changing from one type of irrigation to drip irrigation, or from non–irrigation to drip irrigation, can be made by analyzing the feasibility of the projects.

Conclusions

The increasing area in the production of vegetables in North Dakota warrants the widespread use of drip irrigation systems. Understanding the design procedure for drip irrigation systems and analyzing the economics of crop production is essential for farmers. This study focused on developing a computer model for fast and easy design and optimization of drip irrigation systems for small acreages and for analyzing the B/C ratio of producing alternative crops. The program was used to design drip irrigation systems for 0.4–, 0.8–, 1.6–, and 4.0–ha (1–, 2–, 4–, and 10–acre) irrigated areas of carrot, cabbage, onion, and sweet corn with one, two, and four irrigated zones and two possible well locations. Considering the custom charges for farm operations and cost of producing the crop, the B/C ratios of using drip irrigation systems for these crops were analyzed. The ranges of B/C ratios were 2.32 to 2.94 for carrot, 1.17 to 1.48 for cabbage, 0.43 to 0.54 for onion, and 1.03 to 1.30 for sweet corn. These B/C ratios correspond with irrigation system costs ranging from $8612 ha^{-1} (3485 acre^{-1}) for a 0.4–ha (1–acre) system with four irrigation zones and the well located at the corner to $4332 ha^{-1} ($1753 acre^{-1}) for a 4.0–ha (10–acre) system with four irrigation zones and the well located at the center.

The model can assist an irrigation designer determine and select components for small–scale drip irrigation systems while optimizing costs. The model runs on a personal computer with Windows 95® or later operating systems and TK Solver software (release 3). A Visual Basic® executable file, a sample TK Solver file, and a brief instruction set for the program will be sent to interested parties for handling and postage costs by requesting the materials from the authors.

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References

Aakre, D. 1996. custom farm work rates on North Dakota farms, 1995 by North Dakota farming regions. Bull. EC–499. Fargo, N. Dak.: North Dakota State Univ. Ext. Serv.

Chapin Watermatics. 1997. Price List. Watertown, N.Y.: Chapin Watermatics, Inc.

Dandy, G. C., and A. M. Hassanli. 1996. Optimum design and operation of multiple subunit drip irrigation systems. *J. Irr. Drain. Engr.* 122(5): 265–275.

Dhuyvetter, K. C., F. R. Lamm, and D. H. Rogers. 1994. Subsurface drip irrigation for field corn: an economic analysis. Bull L–909. Manhattan, Kans.: Kansas State Univ. Coop. Ext. Serv.

Eves, H. 1976. Mensuration formulas. In *Standard Mathematical Tables*, ed. W. H. Beyer, 7–19. West Palm Beach, Fla.: CRC Press.

Grainger. 1997. Catalog. Chicago: Grainger Industrial Supply, Inc.

Greenland, R. G., and B. Brademeyer. 1994. Oakes irrigation field trials: 1994 studies. Fargo, N. Dak.: North Dakota State Univ.

_____. 1995. Oakes Irrigation Field Trials: 1995 Studies. Fargo, N. Dak.: North Dakota State Univ.

Howell, T. A., D. S. Stevenson, F. K. Aljibury, H. M. Gitlin, I.–P. Wu, A. W. Warrick, and P. A. C. Raats. 1983. Design and operation of trickle (drip) systems. In *Design and Operation of Farm Irrigation Systems*, ed. M. E. Jensen. St. Joseph, Mich.: ASAE.

Karmeli, D., G. Peri, and M. Todes. 1985. *Irrigation Systems: Design and Operation*. Cape Town, South Africa: Oxford University Press.

Lee, C. W., D. C. Johnson, and R. G. Greenland. 1995. A research report on production and marketing of vegetable crops adapted to North Dakota conditions. Bismarck, N. Dak.: North Dakota Agric. Prod. Utilization Comm.

Lundstrom, D. R., and E. C. Stegman. 1988. Irrigation scheduling by the checkbook method. Bull. AE–792 (Rev.), Fargo, N. Dak.: North Dakota State Univ. Ext. Serv.

Microsoft. 1995. Microsoft® Visual Basic® 4.0 Programming System for Windows: Programmer's Guide. Seattle, Wash.: Microsoft Corp.

Narayanan, R. 1997. Optimization of drip irrigation systems for alternative crops in North Dakota. Unpublished M.S. thesis. North Dakota State Univ., Fargo, N. Dak.

O'Brien, D. M., D. H. Rogers, F. R. Lamm, and G. A. Clark. 1998. An economic comparison of subsurface drip and center pivot sprinkler irrigation systems. *Applied Engineering in Agriculture* 14(4): 391–398.

Oslund Chemical Co. Representative. 1997. Personal communication. Fargo, N. Dak.

Reff, T. 1985. Estimating farm machinery costs. Circular EC–883. Fargo, N. Dak.: N. Dak. St. Univ. Ext. Serv.

Scherer, T. F. 2000. North Dakota 1999 Annual irrigation survey. *Irr. J.* (Jan/Feb): 16–31.

Sharmasarkar, F. C., S. Sharmasarkar, L. J. Held, S. D. Miller, G. F. Vance, and R. Zhang. 2001. Agroeconomic analyses of drip irrigation for sugarbeet production. *Agron. J.* 93(3): 517–523.

Steele, D. D., R. G. Greenland, and B. L. Gregor. 1996. Subsurface drip irrigation systems for specialty crop production in North Dakota. *Applied Engineering in Agriculture* 12(6): 671–679.

Sunseeds Representative. 1997. Personal communication. Morgan Hill, Calif.

UTS. 1996. TK Solver® 3.0 for Windows User's Guide. Rockford, Ill.: Universal Technical Systems, Inc.

Vennard, J. K., and R. L. Street. 1982. *Elementary Fluid Mechanics*, 6th Ed. New York: John Wiley & Sons.

Von Bernuth, R. D., and K. H. Solomon. 1986. Design principles. In *Trickle Irrigation for Crop Production*, eds. F. S. Nakayama and D. A. Bucks, 27–133. Amsterdam: Elsevier.

Wade Rain. 1993. Irrigation products catalog. Fresno, Calif.: Wade Mfg. Co.