An Optimisation Model for Design of Multiple Sub-unit Pressure Irrigation Systems

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ABSTRACT

This report develops a non-linear optimisation model for the design and operation of drip irrigation systems on flat terrain. The analysis is based on dividing the field to be irrigated into sub-units, evaluating various irrigation shift patterns with the corresponding pipe and pump sizes in order to identify a minimum cost solution. The decision variables considered are the lengths of two given pipe sizes for the laterals, the diameters of all other pipes, the size of the pump, the dimensions of sub-units, the shift pattern and the irrigation time for each shift. The optimisation procedure involves a complete enumeration approach which minimises some of the capital cost of the system and the present value of operating costs. A FORTRAN computer code has been developed to verify the model for the least cost solution.
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1. INTRODUCTION

The use of drip or trickle irrigation systems is increasing rapidly because they offer excellent control in the rate of application of water. Therefore, these systems lead to significant reductions in water consumption compared with traditional methods of irrigation. Drip irrigation is a system which supplies water directly to the soil and provides plants with adequate moisture to meet their evapotranspiration demands. It offers unique agronomical, agrotechnical, and economic advantages for the efficient use of water. Drip/trickle irrigation can be an effective means for the application of fertiliser and other chemicals to plants. It has been shown that a saving of fertiliser can be obtained using drip irrigation systems. A considerable reduction in labor and energy cost can also be achieved. One disadvantage of drip systems is their high capital cost. There is scope for major savings in this area through the optimum design of these systems.

2. LITERATURE REVIEW

In general, all water distribution systems that are designed for domestic, industrial or irrigation use are either branched or looped networks. The use of optimization techniques provides an opportunity to reduce the costs for water supply authorities (Dandy et al. 1993). Although the economical design of hydraulic networks has been an area of interest for a long time, it has received particular emphasis since the 1960's due to the emergence of high speed computers (Goulter 1990, Perez et al. 1991). Much research has been carried out on the optimisation of both branched and looped networks by using various techniques. Dandy et al. (1993) outlined the following four main optimisation techniques which, have been applied to water distribution networks:

- Linear programming (Alperovits and Shamir 1977, Quindry et al. 1981);
- Nonlinear programming (El-Bahrawy and Smith 1985);
- Partial enumeration(Gessler 1982, Loubser and Gessler, 1990);

Most irrigation systems are branched networks. Therefore, the review of previous works will be focused mainly on branched networks. Since the cost of pipe is a linear function of its length (Shamir, 1974), if pipe lengths with given diameters are selected as decision variables, constraints on head at nodes will appear as linear inequalities. Thus optimization can be carried out by using the linear programming technique. Karmeli et al. (1968), Gupta (1969), and Gupta et al. (1972) deal with optimum design of branched networks using the linear programming technique. Alperovits and Shamir (1977) present a linear programming gradient (LPG) approach which also applies to looped networks.
Bhave (1979) developed a method based on the critical path concept to reduce the size of the linear programming model to find the optimum trunk main diameters of a branched system. Fujiwara and Dey (1987) propose a computationally efficient two-stage method for networks on flat terrain with a single source node. In the initial stage of their work, the Lagrange multiplier method was used to find optimum pipe sizes. They use the analytical solution obtained in the first stage to select a restricted candidate list of pipe sizes for input to the L.P. model. They claim that numerical experiments show that the proposed two-stage method, needs much less computer time than the L.P. method alone.

The optimization of pressurized irrigation systems (drip and sprinkler) as branched networks has been studied by several authors. Most of the researchers tackle the problem of determining the optimum pipe sizes of either a single pipe or simple branched systems (Oron and Walker, 1981).

Pleban et al. (1984) proposed a design procedure to minimize the capital cost of multiple outlet pipelines that were composed of more than one diameter. The suggested optimization technique was formulated by using the Lagrange multiplier method. A system of nonlinear equations for pressure variation along the pipelines was solved using the Newton-Raphson method. Their technique is applicable in the laterals and manifold lines for sprinkler and trickle irrigation systems, it is limited to uniform slopes, equal outlets spacing, and equal outlet discharge over a specified range of pressure heads.

The graphical method is another approach to achieve a minimum cost. The Food and Agricultural Organization of the United Nations (FAO, 1988) suggested the following three simple graphical methods for reducing the cost of pipelines in branched networks:

- Using the shortest path, without intermediate junction (proximity layout);
- Finding the optimum position of a node from associated hydrants;
- Reducing the total cost of the network by shortening the length of the larger sizes for a fixed length (least cost layout).

However, when the number of hydrants increases, these graphical methods will be complicated. In practice it is easier to achieve a solution by computer methods. Hassanli and Dandy (1994) developed a model to optimise the layout of branched pipe network for the multiple sub-unit pressure irrigation systems using the genetic algorithms. In their model the cost of pipes was based on the pipe capacity. The algorithm which is presented in this work does overcome the problem explained in the graphical method of FAO (1988).
Wu et al. (1986) showed that among different possible energy gradient lines, which connect the inlet upstream pressure to the downstream pressure at the end of pipe, the one which produces the minimum cost is a curve just below the straight line between upstream and downstream pressure. However, their examination indicates that there is only 2% difference in cost between the optimum shape and a linear pressure gradient. Their method is limited to individual pipes with a single size.

Perez et al. (1993) considered the effect of the pipe thickness instead of diameter on the system cost. They explained that higher pressure implies thicker, and consequently, more expensive pipes. As a result, reduction in the static pressure can lead to savings in piping costs. For this reason, they proposed the use of the pressure reducing valves (PRVs) in the system. Their method was based on a dynamic programming formulation. Although this method may reduce the system cost significantly, it is not applicable for the most drip irrigation systems except for those in hilly areas.

A few studies have been reported on the optimization of pressurized irrigation systems considering the field geometry and partitioning the field into a multiple sub-unit system. Oron and Karmeli (1979) developed a nonlinear optimization model using Generalized Geometric Programming (GGP) and Branched and Bound (B&B) technique. They applied the combined GGP and B&B procedure to an irrigation system to find the optimum values for the number of laterals and manifold, the number of sprinklers on laterals, the diameter of manifold and laterals and the discharge of laterals and sprinklers. They concluded that finding the optimum numbers of laterals and sprinklers will lead to finding the optimum sub-unit size. Their analysis was limited to minimising the capital cost for a fixed layout of a sprinkler irrigation system.

The minimum cost of an irrigation system is not always found during the design process, because of the difficulties in selecting the most economic layout among the many alternatives (Oron, 1982). Oron (1982) examined the alternative layouts of a sprinkler irrigation system. Oron noted that due to the difference in the size of subdivisions of two similar field areas, there was a trade off among the system components of each particular layout. He added that differences in system cost occur due to the changing the percentage of different pipe lengths in each particular layout.

Hassanli and Dandy, (1993) examined the influence of various field dimension ratios for a constant field area on the system cost. They concluded that the optimum length/width ratio lies between 1.04 and 1.5. They also examined the influence of various irrigation intervals and irrigation times for various combinations of field dimensions on the system cost.
Oron and Walker (1981) presented an optimization model for sprinkler irrigation systems. Their model was based on the work of Oron and Karmeli (1979) but extended this to various field sizes with various dimensions. In their work the water source was assumed to be located out of the field and the system cost that consisted of capital and operating costs was examined as a function of field geometry, consumptive use (mm/day) and pressure head at the water source. They showed that the optimum division of the field into sub-units is greatly affected by the field geometry. It depends not only on the area of the field but also dimensional (width/length) ratios and the operating conditions. Although this work is a good application of the optimization concept of pressure irrigation systems which is based on partitioning the field into sub-units, it seems the division of field does not include all possible and feasible sub-unit sizes. The optimal solutions obtained by Oron and Walker are for continuous pipe diameters of sprinkler irrigation systems with specified pipe configuration.

Holzapfel et al. (1990) developed a nonlinear optimization model for the design and management of drip irrigation systems. In this model, the objective function represents the benefit of the crops and is a function of water application and the costs of implementation and operation. As in Oron (1982) and Oron and Walker (1981), multiple sub-unit systems are considered, but their model is more elaborate than the other two studies. The main reason for this complexity is due to maximizing the field benefits instead of minimizing the system cost. As Holzapfel et al. explain, a sensitivity analysis of the model showed that the system cost and the operating cost are relatively small compared with the benefits obtained.

As noted above, few studies have been carried out on the optimization of drip irrigation systems based on the partitioning the field into sub-units. Although some literature is available on multiple sub-unit systems, no information is available for partitioning a field into optimum sub-unit sizes while identifying the optimum irrigation shift patterns via the best combination of sub-units to be irrigated simultaneously.

The purpose of this study is to investigate both the optimum size and optimum dimensions of sub-units in a multiple sub-unit system, while also examining the effect of the number of possible shifts and shift patterns on the system cost. This is carried out by selecting the optimum diameter for all pipes via a trading off between the cost of pipes and energy. The analysis is performed by developing an optimisation model based on the complete enumeration approach for drip irrigation in a multiple sub-unit system.
3. SYSTEM LAYOUT AND IRRIGATION PARAMETERS

The model developed in this study will identify the optimum drip irrigation system for a flat rectangular field. The assumed layout of the irrigation system is shown in Fig. 1. It consists of a pump, filter and fertilizer units at the centre of the field, one pressure regulator for each subunit and one on-off valve for each main and submain pipe. It is assumed that the field is supplied from groundwater. The pipe system consists of two main pipes which deliver the water from the pump to the submain pipes and a set of multiple outlet pipes (laterals and manifold) within the sub-units.

![Diagram of a multiple sub-unit drip irrigation system with 24 sub-units](image)

**Fig. 1. Layout of a multiple sub-unit drip irrigation system with 24 sub-units**

The concept of irrigation interval \((F)\) and irrigation time \((T)\) for one cycle of irrigation are illustrated in Fig. 2. The irrigation interval is the time in days between the commencement of one irrigation cycle and the next. The irrigation time (duration) is the length of an irrigation event. That is, the period during which water is being released from the emitters for one particular shift. The number of irrigation shifts \((N_{sh})\) The number of irrigation shifts \((N_{sh})\) refers to schedule of irrigation with different irrigation times and flow rates from emitters (ie. one shift operation involves watering the whole field, two shift operation involve watering half the field simultaneously).
Fig. 2 An example of irrigation interval and irrigation time for three different numbers of irrigation shifts

The relationship between \( F, T \) and \( N_{sh} \) may be defined as follows:

\[
T = \frac{D_h(F - N_f)}{N_{sh}}
\]  

(1)

where \( T \) = irrigation time (duration) for each shift (hr); \( N_f \) = number of days free of irrigation per irrigation cycle (days); \( D_h \) = time available per day for irrigation (hr). The shift pattern in this study refers to the combination of sub-units being irrigated simultaneously (Figure 3). In Figure 3 II, JJ = the number of sub-units being irrigated simultaneously in the X and the Y directions (respectively) in one shift. Both II and JJ are factors of the number of sub-units in the X and Y directions (respectively). The multiple outlet pipes receive
water from the submains via the supply pipes and distribute it through the emitters with a slow rate of application.

3.1 Number of Irrigation Shifts

In this model, irrigation shift refers to the number of sets of sub-units which are to be irrigated simultaneously during a specified irrigation interval. In each shift the number of irrigated sub-units consists of the product of a set of sub-units in the X-direction ($II$) and the number of sub-units in the Y-direction ($JJ$). On the basis of the field divisions the total number of shifts varies from 1 to 100. However, as the number of shifts increases the number of sub-units which must be irrigated simultaneously decreases, as a result, the irrigation time for simultaneous irrigated sub-units decreases. Since the whole system is scheduled to be irrigated during a specified irrigation interval and the design flow rate ($Q_{pu}$) is constant under any operating condition, any decrease in irrigation time leads to an increase in pipe and emitter flow rates, as a result, the head loss of corresponding pipes is increased. Therefore, only a limited number of shifts are feasible. This is due to the violation of the head loss constraints. In the present model, only three cases (1, 2 and 4 shifts) are considered for cost analysis. Figure 3 shows different configurations of irrigation shifts and associated shift patterns.

4. ADVANTAGE OF PARTITIONING A FIELD INTO SUB-UNIT

For drip irrigation the advantages of partitioning a field into sub-units are as follows:

- In the case of limited available water, the irrigation system may be designed in such a way that the field will be irrigated unit by unit with a desirable control.

- Usually having higher pressure the more energy must be consumed, the large fields and also large sub-units need long pipes which make larger head loss and higher system cost.

- When a field is divided into smaller sizes the size of the pipes and control unit including: the valves, pressure regulators, discharge regulators, etc. can be reduced. However, according to Oron and Walker (1982) "Irrigation systems which consist of a relatively large number of small diameter control
Fig. 3  An example of different shift numbers with associated shift patterns in a multiple sub-unit drip irrigation system  
\((N_{sux} = 4 \text{ and } N_{suy} = 4)\)
units are probably more flexible in operation, although their cost might be higher as compared to a system with a smaller number of control units."

- Dividing the whole field into sub-units with proper dimensions leads to more effective control of the irrigation systems and enhances the reliability of the system.

- By partitioning a field into sub-units different set of sub-units may be irrigated separately, a part of the field therefore will be remained dry and agricultural activities such as: fertilization, plowing, fruit picking, spraying, and other soil treatments can be carried out more easily and efficiently.

Oron et al. (1981) suggest due to the possibility of irrigating only one part of a field at a time the design and operation may be carried out on the basis of partitioning the system into sub-units. They also highlighted the other advantages of multiple sub-unit systems.

5. CHARACTERISTIC OF MODEL

The model has been developed for fields with known dimensions on flat terrain. The water source is assumed to be groundwater provided by a pump located at the centre of field. All submain pipes that feed the sub-units via supply pipes are perpendicular to the mainlines and are fed from both sides of the mainlines (see Figure 1). All pipes are made from polyethylene, and emitters are fixed on the laterals at a fixed spacing. Each supply, submain and mainline pipe is controlled by one independent valve, which is located just at the beginning of the corresponding pipe. One filter unit is assumed to be located just after the pump. Water is assumed to be extracted from groundwater by means of a turbine pump system. The main and submain pipes are buried while sub-unit pipes (laterals, manifold, supply) are laid on the ground. Total system cost consists of capital and installation costs plus the present value of the operating costs over the expected life of the project.

6. FORMULATION OF MODEL

6.1 Objective Function

The drip irrigation design model described in this paper consists of an objective function that minimizes the sum of the capital cost and present value of operating cost subject to appropriate constraints. The system is assumed to be permanent with semi-automation, thus labor cost is considered to be small
compared to the capital and energy costs. The main components of cost of a drip irrigation system are the cost of pipes, pump, emitters, accessories, and energy.

The objective function is defined as follows:

\[ Z = C_p + C_{pu} + C_{em} + C_{ac} + C_{op} \]  \( (2) \)

where \( Z \) = objective function to be minimized; \( C_p \) = the total cost of pipes; \( C_{pu} \) = the cost of the pumping system; \( C_{em} \) = the cost of emitters; \( C_{ac} \) = the cost of accessories; \( C_{op} \) = the present value of the operating cost. All costs are expressed in Australian dollars (A$ 1.00 = US$0.70 approximately).

The cost of pipes can be expressed as:

\[ C_p = C_l + C_m + C_s + C_{sm} + C_{ml} \]  \( (3) \)

where \( C_l, C_m, C_s, C_{sm}, C_{ml} \) = the cost of lateral, manifold, supply, submain and mainline pipes (respectively). A typical pipe configuration and the other accessories are shown in Figure 1.

The cost per unit length of pipes (other than laterals) may be expressed by the following nonlinear function of diameter (Oron and Karmeli, 1979).

\[ C_i = K_1 D_i^2 + K_2 D_i + K_3 \]  \( (4) \)

where \( C_i \) = the cost per unit length of the \( i \) th pipe ($/m); \( D_i \) = the internal diameter of the \( i \) th pipe (mm); \( K_1, K_2 \) and \( K_3 \) = constants.

Least squares can be used to identify the constants in Equation 4 from pipe cost data. In this model, sub-unit pipes (laterals, manifold, supply) were assumed to be laid on the ground, while submain and mainline pipes are assumed to be buried, hence installation cost is added to Equation 4 for submain and mainline pipes.

### 6.2 Sub-unit Dimensions and Pipe Lengths

According to the piping configuration shown in Figure 1 the length of different pipes and sub-unit dimensions are obtained using the following equations:
\[ P_{sux} = \frac{F_x}{N_x} \] (5)

where \( P_{sux} \) = the length of sub-units in the X-direction (m); \( F_x \) = the length of field in the X-direction (m); \( N_x \) = the number of sub-units in the X-direction (assumed to be even).

\[ P_{suy} = \frac{F_y}{N_y} \] (6)

where \( P_{suy} \) = the length of sub-units in the Y-direction (m); \( F_y \) = the length of field in the Y-direction (m); \( N_y \) = the number of sub-units in the Y-direction (assumed to be even). The higher numbers of \( N_x \) and \( N_y \) provide more sub-units with smaller area within the field. In this model up to 10 divisions in the both directions are considered. The length of different pipes based on sub-unit dimensions are computed as follows:

\[ L_l = \frac{P_{sux}}{2} - d_x \] (7)

\[ M_l = P_{suy} - d_y \] (8)

\[ S_l = \frac{P_{sux}}{2} \] (9)

\[ SM_l = \frac{F_y}{2} - \frac{P_{suy}}{2} \] (10)

\[ ML_l = \frac{F_x}{2} - P_{sux} \] (11)

where \( L_l, M_l, S_l, SM_l, ML_l \) are the length of lateral, manifold, supply, submain and main line pipes respectively (m); \( d_x \) = spacing between emitters (m); \( d_y \) = spacing between laterals (m).

6.3 Number of Different Components in the System

The number of sub-units created in each iteration of field division depends on the length and the width of sub-units as below:
\[ N_{su} = \frac{F_x \cdot F_y}{P_{sux} \cdot P_{suy}} \]  \hspace{1cm} (12)

where \( N_{su} \) is the number of sub-units within the field.

\[ N_{eml} = \frac{P_{sux}}{2d_x} \]  \hspace{1cm} (13)

\[ N_{lm} = 2 \frac{P_{suy}}{d_y} \]  \hspace{1cm} (14)

\[ N_{ems} = \frac{P_{sux}}{d_x} \cdot \frac{P_{suy}}{d_y} \]  \hspace{1cm} (15)

\[ N_{em} = \frac{P_{sux}}{d_x} \cdot \frac{P_{suy}}{d_y} N_{su} \]  \hspace{1cm} (16)

where \( N_{eml}, N_{lm}, N_{ems} \) and \( N_{em} \) are the number of emitters on each lateral, the number of laterals on each manifold, the number of emitters in each sub-unit and the total number of emitters in the system (respectively).

\[ N_{l} = 2 N_{su} \frac{P_{suy}}{d_y} \]  \hspace{1cm} (17)

\[ N_{m} = N_{su} \]  \hspace{1cm} (18)

\[ N_{s} = N_{su} \]  \hspace{1cm} (19)

\[ N_{sm} = \frac{F_x}{P_{sux}} \]  \hspace{1cm} (20)

where \( N_{l}, N_{m}, N_{s}, N_{sm} \) are the number of laterals, manifold, supply and submain pipes in the system respectively.

According to the piping configuration shown in Figure 1, in addition to the laterals and emitters, there is one manifold, one supply pipe, and one volumetric valve within each sub-unit. The valve is located just at the beginning of supply pipe to control the flow into each sub-unit. The number of mainlines = 2 if \( N_x > 2 \), otherwise the system will deliver water without mainlines. For each
submain and mainline pipe, one volumetric valve is considered which is located at the beginning of the corresponding pipe.

6.4 Cost of System

6.4.1 Cost of Pipes

The details of system cost are as follows: Two discrete available pipe sizes are assumed for laterals.

\[
C_l = (L_1 CL_2 + L_2 CL_2) N_l
\]  
(21)

where \( L_1 \) and \( L_2 \) are the length of the two segments of each lateral correspond to the two given sizes (m); \( CL_1 \) and \( CL_2 \) are the cost of the two given pipe sizes for laterals ($/m), (known).

\[
C_m = \left( K_1 D_m^2 + K_2 D_m + K_3 \right) \left( P_{suy} - d_y \right) N_{su}
\]  
(22)

\( D_m \) = internal diameter of manifold (mm). \( K_1, K_2, K_3 \) = constant for the pipe cost equation.

\[
C_s = \left( K_1 D_s^2 + K_2 D_s + K_3 \right) \left( \frac{P_{sux}}{2} \right) N_{su}
\]  
(23)

\( D_s \) = internal diameter of supply pipe (mm).

For a pump system located at the centre of the field and the pipe configuration shown in Figure 1, the costs of submain and mainline pipes are

\[
C_{sm} = \left( K_1 D_{sm}^2 + K_2 D_{sm} + K_3 + \phi \right) \left( \frac{F_y}{2} - \frac{P_{suy}}{2} \right) N_{sm}
\]  
(24)

\( D_{sm} \) = internal diameter of submain pipes (mm); \( \phi \) = the cost of installation per unit length ($/m).

\[
C_{ml} = \left( K_1 D_{ml}^2 + K_2 D_{ml} + K_3 + \phi \right) \left( \frac{F_x}{2} - P_{sux} \right) N_{ml}
\]  
(25)

\( D_{ml} \) = internal diameter of mainline pipes (mm); \( N_{ml} \) = the number of mainline pipes.

13
6.4.2 Cost of Pumping System

6.4.2.1 Characteristic of Selected Pump

Groundwater is a common source of water for drip irrigation systems. In this analysis, it is assumed to be available at a specified depth. Submersible pumps may be appropriate for this sort of work. Among the various type of submersible pumps, the turbine pump that can provide the required discharge and pressure head of the multiple sub-unit system is selected. Generally, turbine pumps suit bore holes of 152mm (6") casing or larger and have capacities of 4 to 63 liters per second. These pumps consist of a series of centrifugal impellers located below the water level and connected to a vertical shaft which extends through a discharge tee, or head at the surface. The shaft, in turn, is rotated by either a vertical shaft electric motor, with a vertical belt drive from an engine or motor or by a right angle gear drive coupled to an engine motor, or tractor which, is at the surface. (Southern Cross Manufacturing Pty. Ltd.).

Among the different types of turbine pumps produced by Southern Cross, type LAJ is most appropriate for discharges between 30 to 57 liters per second and pressure heads between 9 to 110m. In this case, type LAJ at a speed of 2945 rpm satisfies discharge and the range of pressure heads of system. Characteristic curves for this type of pump are shown in Figures 4.

6.4.2.2 Derivation of Pump Cost Equation

In this study a vertical shaft electric motor drive is assumed. This type of electric motor drive head consists of the standard solid shaft drip proof type. The cost of the pumping system is assumed to be a function of its head and discharge (Holzapfel et al. 1990) as follows:

\[ C_{pu} = K Q_{pu}^a H_{pu}^b \]  \hspace{1cm} (26)

where \( C_{pu} \) = the cost of pump system ($); \( Q_{pu} \) = design discharge of pump (m³/s); \( H_{pu} \) = total design head provided by the pump (m); \( K, a \) and \( b \) =constant coefficients.

In order to fit the pump cost equation and identify the constant coefficients, \( K, a, b \) different alternatives of pump sizes in terms of head, discharge and shaft diameter were evaluated. A combination of depth of water table from 5 m up to 40 m in 5 m steps and total pressure head including: working pressure and head
losses from 14 m up to 28 m in 2 m steps as well as a set of discharges between 20 and 55 liters per second for three different shaft sizes were examined. For each case, the head loss of the foot valve, pipe and shaft combination of pump system have been considered as well. Then, by using pump characteristic curves for each discharge and corresponding total head the number of pump stages, the pump efficiency and the required pump power were determined. Consequently, by using these data as well as the list of pump price (issued by Southern Cross) the corresponding price for different parts of the pump system including: the turbine pump, the electric motor, the column and shafts were found. As a result, for each particular assumed head and discharge, the total cost of the pump system was used to fit the pump price equation (Eq. 26) to the data. In this part of the analysis the LINEST routine for regression analysis from the Microsoft EXCEL package was used.

The design discharge of the pump is the total discharge of sub-units irrigated simultaneously in each shift.

\[ Q_{pu} = Q_E \frac{P_{sux}}{d_x} \frac{P_{suy}}{d_y} N_{suw} \]  

(27)

where \( Q_E \) = discharge of emitters (L/s); \( N_{suw} \) = number of sub-units being irrigated simultaneously.

The design discharge may be expressed in terms of irrigation interval, irrigation time and the number of shifts as follows:

\[ Q_{pu} = 2.78 \times 10^{-7} \left( \frac{K_c \ ET_0 \ F}{E_a \ T \ N_{sh}} \right) \cdot F_x F_y \]  

(28)

where \( ET_0 \) = potential evapotranspiration rate (mm/day); \( K_c \) = crop coefficient for the worst cases and design conditions; \( E_a \) = application efficiency of drip irrigation (%), (known); \( F_x \) and \( F_y \) = field length and width in the \( x \) and \( y \) directions (m), known. The term in brackets in Equation (28) represents the average depth of application per unit time (mm/hr).

Since the design should meet the peak irrigation requirement, \( K_c \) is taken equal to 1, this corresponds to a dry area with light to moderate wind and large mature citrus trees. It includes different free ground cover with clean cultivation and no weed control, (FAO, 1984). The effect of crop characteristics on the relationship between the crop evapotranspiration (\( ET_c \)) and the potential evapotranspiration (\( ET_0 \)) is shown in Figure 5. The wide variation between the major group of crops is largely due to the resistance to transpiration of different
Fig. 4 Characteristic curves for LAJ type turbine pump
(Southern Cross Manufacturing, Pty. Ltd)
Fig. 5 $ET_0$ as compared to $ET_C$ for different crops (FAO, 1984)

Fig. 6 Example of crop coefficient curve developed for cotton (Wu et al. 1986)
plants. Total crop water requirements during a year or growth season is not constant. Factors affecting the values of the crop coefficient \( K_C \) are the crop characteristics, crop planting or sowing date, rate of crop development, length of growing season and the climatic conditions. \( K_C \) varies in terms of plant activities or stage of growth and rate of evapotranspiration. As an example, Figure 6 shows the relationship of crop water coefficient \( K_C \) in terms of different stages of plant activities for cotton. In practice the required irrigation can be adjusted by changing the irrigation times and irrigation intervals.

The dynamic pumping head including all head losses within the system and the required pressure for system operation as well as the depth of groundwater may be formulated as below:

\[
H_{pu} = \sum HL + H_w + H_{wt}
\]  

(29)

where \( \sum HL \) = the sum of all head losses from the pump to most distant emitter (m); \( H_w \) = working pressure head on emitters (m); \( H_{wt} \) = depth of water table (m).

6.4.3 Cost of Control Head

The control head in this multiple sub-unit drip irrigation system which serves all sub-units consists of: the volumetric valves, the fertilizer and chemical tank equipment as well as the filtering equipment. An example of a typical control head with corresponding equipment is shown in Figure 7. The main components of control head are defined in more details as follows:

6.4.3.1 Fertilizer and Chemical Injection Equipment

Injectors may be used to apply fertilizers or other chemicals directly into the drip irrigation systems. Correct application of fertilizer or chemical equipment is essential if higher yields are to be obtained in drip irrigation systems. A fertilizer tank, in which the required fertilizer or other chemicals are dissolved in water may be connected to the main system by means of two small pipes. This forces the water to flow through the inlet small pipe (tubing) into the tank and pushes the fertilizer solution through the outlet pipe back into the system (see Figures 7 and 8).
6.4.3.2 Filtering Equipment

Filters in the drip irrigation system are essential in order to reduce the risk of blockage or clogging in emitters due to soil particles and organic materials suspended in the water. This type of filter commonly has either a single or double screen. Head loss data for a clean filter are supplied by the manufacturers and should be taken into account in the design of drip irrigation systems. Sometimes in addition to the filters in the control head, small screen filters can be installed at the inlet to laterals. These extra filters are useful when laterals are portable or when the water has a high level of suspended materials. The type, size and the number of required filters depend on the quantity of the water and the discharge in the control head. The filtration system sometimes comprises several filters. However, filters do not overcome the problems of precipitation of calcium carbonate deposit. To solve this problem the system must be flushed periodically with a solution of hydrochloric acid, and then with compressed air under high pressure.

6.4.3.3 Valves and Controller Unit

Figure 7 displays the function of various type of valves used at the head of a typical drip irrigation system. The automatic metering valves are set in the system to allow the passage of a given volume of water, after which it shuts down automatically. Some valves also function as water meters. Several valves can be hydraulically operated in sequence, thus minimizing labor requirements while increasing the efficiency of water application. An automatic metering valve is selected on the basis of the required volume of water and the design flow-rate. The amount of head loss for any type of valve is normally specified by manufacturers. In this model for each mainline, submain and supply pipe one automatic metering valve has been considered. In the present model, for each set of 8 sub-units one controller unit has been recommended. The recommended type of controller is powered by electricity supplied by a battery or other sources. It controls and adjusts the pressure as well as the flow-rate of sub-units.

The cost of the control head considering all accessories in the system may be expressed as follows:

\[ C_{ac} = C_{fil} + C_{fer} + C_{con} + C_{val} \]  \hspace{1cm} (30)

\( C_{fil} \) = the cost of the filter ($); \( C_{fer} \) = the cost of the fertilizer ($); \( C_{con} \) = the cost of the controller ($); \( C_{val} \) = the cost of the valves ($).
Although the cost of the above accessories could be presented as a function of the diameter, in this analysis a constant appropriate size with known cost and reasonable friction head loss are assumed for each one.

![Diagram of control head for drip irrigation system]

1. Main valve  
2. Tap  
3. Water meter & volumetric valve  
4. Non return valve  
5. Inlet pipe to fertilizer applicator  
6. Air valve  
7. Pressure gage  
8. Pressure reducing valve  
9. Fertilizer input pipe  
10. Water filter  
11. Flushing valve  
12. Field supply valve  
13. Fertilizer application tank

**Fig. 7  Components of a typical control head for a drip irrigating system**

![Diagram showing location of fertiliser, chemical solution tank and various valves in a typical irrigation system]

**Fig. 8  Location of fertiliser, chemical solution tank and various valves in a typical irrigation system**

6.4.3.4  
Emitters

The emitters are installed on the laterals beside the plants. In some drip irrigation systems the number of emitters around each plant is increased in order to supply the required volume of irrigation water to match the different stages of plant growth or plant activities. (Holzapfel et al. 1990). The total cost of emitters is based on the number and the unit cost as below
\[ C_{em} = N_{su} \left( \frac{P_{sux}}{dx} \frac{P_{suy}}{dy} \right) C U_{em} \]  

where \( C U_{em} \) = the unit cost of emitters ($).

### 6.4.4 Annual Operation Cost

The cost of operation and maintenance (O&M) is one of the significant costs of an irrigation project. An efficient operation program provides potential savings in the project costs. In this model, a semi-automatic system is proposed. Therefore, the labor cost is considered to be small compared to the capital and energy costs. In the analysis of annual operating cost, only energy cost is considered. It would be a good idea to consider the management cost as well, but as this model has been focused on efficient design from an engineering point of view, only the system cost in terms of technical design criteria is considered. The cost of energy to operate the system on an annual basis can be represented by the unit cost of energy multiplied by the total energy required over the operating season. The annual energy requirement depends on the annual irrigation requirement and the power of the pump for providing such water. The power of the electric motor may be expressed as:

\[ P_m = \frac{\gamma Q_{pu} H_{pu}}{\eta_m \eta_p} \]  

where \( P_m \) = electric motor power (kW); \( \gamma = \rho g \); \( \rho \) = density of water (1000 Kg/m³); \( g \) = acceleration due to gravity (9.81 m/s²); \( \eta_m \) = electric motor efficiency, (known); \( \eta_p \) = pump efficiency, (known).

The annual energy requirement may be obtained using the annual irrigation requirement, power of pump and the annual hours of pump operating as follows:

\[ A_{en} = P_m A_{ir} \left( \frac{E_a T N_{sh}}{K_c ET_0 F} \right) \]  

where \( A_{en} \) = annual energy requirement (kWh); \( A_{ir} \) = annual irrigation requirement (mm). The term in brackets is the reciprocal of the depth of application per unit time (mm/hr)
Annual operating cost during the expected life of project considering the discount rate is converted to present value as follows:

\[ C_{op} = A_{en} C_{en} \left[ \frac{1 - (1 + i)^{-n}}{i} \right] \]  

(34)

where \( C_{en} \) = cost of energy ($/kWh), (known); \( i \) = discount rate, (known); \( n \) = project life (years), (known).

### 6.4.5 Total Cost

Evaluation of a multiple sub-unit drip irrigation with respect to various sub-unit sizes under a specified number of irrigation shifts, and achieving an optimum solution among various alternatives is the main aim of this study. The total system cost consists of the capital and the present value of operating cost (electric energy). The capital cost includes: the cost of emitters, laterals, manifold and supply pipes within the sub-units, the cost of submain and mainlines, the cost of the pump system (turbine pump, vertical hollow shaft electric motor) and the cost of control head (filter, fertiliser tank, volumetric valves, controller units).

### 6.5 Discharge

In order to identify the size of pump and piping system, it is essential to determine the design discharge and the discharge in each individual pipe in each shift pattern. In the following sections the discharge of different pipes associated with the different irrigation shifts and shift patterns are presented.

#### 6.5.1 Sub-unit Discharge

The flow rate of different elements of a drip irrigation system is based on crop evapotranspiration and the operating conditions. In practice, an operating schedule based on the available time, the soil holding capacity and the other constraints is developed. Thus the amount of water which should be stored in the soil to meet the plant water requirement is directly affected by evapotranspiration rate.

\[ q_T = K_c \ ET_0 \ dx \ dy \]  

(35)

\[ q_T \] = plant water requirement (L/day).
The discharge of emitters and the other elements is affected by the irrigation interval, the number of shifts, the irrigation duration and the application efficiency as follows:

$$N_{sh} = \frac{N_{sux} \times N_{suy}}{II \times JJ} \quad (36)$$

$$T = \frac{D_h (F - N_f)}{N_{sh}} \quad (37)$$

$$Q_E = \frac{K_c ET_0 F}{Ea} T d_x d_y \quad (38)$$

The irrigation interval (F) is estimated using Eq. (72) in which the water that can be stored in the root zone and maximum daily evapotranspiration are taken into account.

$$Q_i = N_{emi} Q_E \quad (39)$$

$$Q_m = N_{lm} Q_L \quad (40)$$

$$Q_{su} = Q_m = Q_s = Q_E \frac{P_{sux}}{d_x} \frac{P_{suy}}{d_y} \quad (41)$$

where $Q_E$, $Q_i$, $Q_m$, $Q_s$, $Q_{su}$ = discharge in emitters (L/hr); discharge in laterals manifolds, supply pipes and the sub-units (L/s); respectively; $N_{sux}$, $N_{suy}$= the number of sub-units in the X and Y directions respectively.

### 6.5.2 Submain Line Discharge

The discharge of submain pipes varies not only with the number and the size of sub-units supplied by those lines, but also varies with different number of irrigation shifts and shift patterns. As a result, the size and the number of sub-units that are created by the field divisions as well as the number of applied shifts with the corresponding shift patterns are the main factors which affect the discharge of submain lines. For example, the discharge of the submain lines for one solution in which $N_x$=6 and $N_y$ varies from 2 to 10 under 3 applied operating programs with 1, 2 and 4-shifts may be formulated as follows:
For $N_x = 6$
when $N_y = 2$

$$Q_{sm} = 2Q_{su} \quad \text{if } N_{sh} = 1, 2 \text{ or } 4$$  \hspace{1cm} (42)

when $N_y = 4$ (see Fig. 9)

$$Q_{sm} = 4Q_{su} \quad \text{if } N_{sh} = 1, 2$$  \hspace{1cm} (43)

$$Q_{sm} = 4Q_{su} \quad \text{if } N_{sh} = 4 \text{ and } II = 3, JJ = 2$$  \hspace{1cm} (44)

$$Q_{sm} = 2Q_{su} \quad \text{if } N_{sh} = 4, \text{ and } II = 6, JJ = 1$$  \hspace{1cm} (45)

when $N_y = 6$

$$Q_{sm} = 6Q_{su} \quad \text{if } N_{sh} = 1, 2 \text{ or } 4$$  \hspace{1cm} (46)

when $N_y = 8$ (see Fig. 10)

$$Q_{sm} = 8Q_{su} \quad \text{if } N_{sh} = 1, 2$$  \hspace{1cm} (47)

$$Q_{sm} = 8Q_{su} \quad \text{if } N_{sh} = 4, \text{ and } II = 3, JJ = 4$$  \hspace{1cm} (48)

$$Q_{sm} = 4Q_{su} \quad \text{if } N_{sh} = 4, \text{ and } II = 6, JJ = 2$$  \hspace{1cm} (49)

when $N_y = 10$

$$Q_{sm} = 10Q_{su} \quad \text{if } N_{sh} = 1, 2 \text{ or } 4$$  \hspace{1cm} (50)

Fig. 9  An example of multiple sub-unit system with 24 sub-units (4 sub-units supplied by each submain line)
6.5.3 Mainline Discharge

As shown in Figure 1, there are 2 mainlines in the distribution system, which deliver the irrigation water from the source to the submain lines. However, when the division of the field in the X-direction is 2 ($N_x = 2$) mainlines are not required and water is delivered only by submain lines. The mainline discharge depends on the number of connected submain lines supplied by each mainline in each shift, the size and the number of sub-units connected to the submain lines, the number of shifts as well as the shift patterns. For example, the discharges of the mainlines for the cases given in Section 6.5.2 ($N_x = 6$ for different $N_y$) may be formulated as follows:

For $N_x = 6$
when $N_y = 2$

\[ Q_{ml} = 4Q_{su} \quad \text{if} \quad N_{sh} = 1 \quad (51) \]
\[ Q_{ml} = 2Q_{su} \quad \text{if} \quad N_{sh} = 2 \text{ and } II = 6, JJ = 1 \quad (52) \]
\[ Q_{ml} = 4Q_{su} \quad \text{if} \quad N_{sh} = 2 \text{ and } II = 3, JJ = 2 \quad (53) \]
\[ Q_{ml} = 2Q_{su} \quad \text{if} \quad N_{sh} = 4 \quad (54) \]

when $N_y = 4$ (see Fig. 9)

\[ Q_{ml} = 8Q_{su} \quad \text{if} \quad N_{sh} = 1 \quad (55) \]
\[ Q_{ml} = 4Q_{su} \quad \text{if} \quad N_{sh} = 2 \text{ and } II = 6, JJ = 2 \quad (56) \]
\[ Q_{ml} = 8Q_{su} \quad \text{if} \quad N_{sh} = 2 \text{ and } II = 3 \text{ and } JJ = 4 \quad (57) \]
\[ Q_{ml} = 4Q_{su} \quad \text{if} \quad N_{sh} = 4 \quad (58) \]

when $N_y = 6$

\[ Q_{ml} = 12Q_{su} \quad \text{if} \quad N_{sh} = 1 \quad (59) \]
\[ Q_{ml} = 6Q_{su} \quad \text{if} \quad N_{sh} = 2 \text{ and } II = 6, JJ = 3 \quad (60) \]
\[ Q_{ml} = 12Q_{su} \quad \text{if} \quad N_{sh} = 2 \text{ and } II = 3 \text{ and } JJ = 6 \quad (61) \]
\( Q_{ml} = 6Q_{su} \) if \( N_{sh} = 4 \) \hspace{1cm} (62)

when \( N_y = 8 \) \hspace{1cm} (see Fig.10)

\( Q_{ml} = 16Q_{su} \) if \( N_{sh} = 1 \) \hspace{1cm} (63)

\( Q_{ml} = 8Q_{su} \) if \( N_{sh} = 2 \) and \( II = 6, JJ = 4 \) \hspace{1cm} (64)

\( Q_{ml} = 16Q_{su} \) if \( N_{sh} = 2 \) and \( II = 3, JJ = 8 \) \hspace{1cm} (65)

\( Q_{ml} = 4Q_{su} \) if \( N_{sh} = 4 \) and \( II = 6, JJ = 2 \) \hspace{1cm} (66)

\( Q_{ml} = 8Q_{su} \) if \( N_{sh} = 4 \) and \( II = 3, JJ = 4 \) \hspace{1cm} (67)

when \( N_y = 10 \)

\( Q_{ml} = 20Q_{su} \) if \( N_{sh} = 1 \) \hspace{1cm} (68)

\( Q_{ml} = 10Q_{su} \) if \( N_{sh} = 2 \) and \( II = 6, JJ = 5 \) \hspace{1cm} (69)

\( Q_{ml} = 20Q_{su} \) if \( N_{sh} = 2 \) and \( II = 3, JJ = 10 \) \hspace{1cm} (70)

\( Q_{ml} = 10Q_{su} \) if \( N_{sh} = 4 \) and \( II = 3, JJ = 5 \) \hspace{1cm} (71)

Fig. 10  An example of multiple sub-unit system with 48 sub-units (8 sub-units supplied by each submain)
7. CONSTRAINTS

On the basis of both the characteristics of the model, and the performance of the system, the objective function is minimized subject to a number of constraints. The model allows the number of shifts \( N_{sh} \) to be chosen as a decision variable. The irrigation interval can be determined by identifying the amount of water which can be stored in the soil and the consumptive use of crops (Keller and Bliesner, 1990) as follows:

\[
d = \frac{(FC - PWP)}{100} \cdot R \cdot \gamma_s \cdot f \cdot \left( \frac{P_w}{100} \right)
\]  
(72)

where \( d \) = depth of water which can be stored in the root zone (mm); \( FC \) = Field capacity (% by weight); \( PWP \) = permanent wilting point (% by weight); \( R \) = depth of crop root zone (mm); \( \gamma_s \) = specific gravity of soil (dimensionless); \( f \) = fraction of available moisture depletion allowed. This involves an estimate being made of \( P_w \). This should be checked using Equation 76 once \( Q_E \) and hence \( W_d \) have been determined. Then:

\[
F = \frac{d}{K_c ET_0}
\]  
(73)

This equation ensures that the consumptive use of water in one irrigation cycle just equals the depth of water which can be stored in the root zone in the soil. The duration of irrigation per shift (T, hr) can then be determined using Equation 37. Having selected \( N_{sh} \) and hence \( T \), the emitter discharge \( (Q_E, \text{L/hr}) \) can be determined using Equation 38. The emitter discharge used should satisfy the following constraints:

(a) the wetted area as a percentage of the total irrigated area lies within a defined range in order to ensure that there is a reasonable volume of moisture stored in the soil (Keller and Bliesner, 1990);

(b) the rate of application does not exceed the infiltration capacity of the soil.

The wetted area associated with a single emitter depends on the emitter discharge and soil properties. Karmeli et al. (1985) give the following empirical relationship relating wetted diameter \( (W_d, \text{m}) \) to the emitter discharge rate:

\[
W_d = \alpha + \beta Q_E
\]  
(74)

where values of \( \alpha \) and \( \beta \) for different soils are given in Table 1.
TABLE 1. Parameters of dripper wetting diameter relating to emitter discharge for various soil types

<table>
<thead>
<tr>
<th>Soil type</th>
<th>$\alpha$</th>
<th>$\beta$</th>
</tr>
</thead>
<tbody>
<tr>
<td>Fine soil</td>
<td>1.2</td>
<td>0.1</td>
</tr>
<tr>
<td>Medium soil</td>
<td>0.7</td>
<td>0.11</td>
</tr>
<tr>
<td>Coarse soil</td>
<td>0.3</td>
<td>0.12</td>
</tr>
</tbody>
</table>

For non overlapping wetted areas, the percentage wetted area is given by:

$$P_w = \frac{\pi (W_d)^2}{4 d_x d_y}$$  \hspace{1cm} (75)

in order to satisfy the minimum and maximum acceptable levels of $P_w$, $W_d$ must lie within the following range.

$$\left( \frac{4 P_w^{\text{min}} d_x d_y}{\pi} \right)^{1/2} \leq W_d \leq \left( \frac{4 P_w^{\text{max}} d_x d_y}{\pi} \right)^{1/2}$$  \hspace{1cm} (76)

where $P_w^{\text{min}}$ and $P_w^{\text{max}}$ = minimum and maximum acceptable values of the percentage wetted area (respectively). Constraints (76) effectively constrain $Q_E$ through Equation (74). Where overlap occurs, Karmeli et al. (1985) recommend the following constraint for efficiency reasons:

$$W_d \leq 1.6 \, d_x$$  \hspace{1cm} (77)

The rate of application from the emitters should not exceed the infiltration capacity of the soil. ie

$$Q_E \leq I_{\text{soil}} \left( \frac{d_x d_y P_w}{100} \right)$$  \hspace{1cm} (78)

where $I_{\text{soil}}$ = infiltration capacity of the soil (mm/hr).

Constraints (76), (77) and (78) effectively limit the number of shifts which can be used. Having selected $N_{sh}$, the model allows for various shift patterns to be considered. A shift pattern is defined by $II$ and $JJ$ which are the number of sub-units being irrigated simultaneously in the X and Y directions respectively (see Fig. 3).
7.1 Uniform Distribution of Discharge

The hydraulic constraints are the most significant in this model. In order to achieve an uniform water distribution along the manifold and laterals within the sub-units, the pressure head variation along those pipes is limited. The head loss (as the only factor affecting the pressure variation in the pipe system on flat terrain) is determined by using the Hazen-Williams equation:

\[ HL = \frac{KLQ^{1.852}}{C^{1.852}D^{4.87}}F(n_0) \]  \hspace{1cm} (79)

where \( HL \) = the head loss of pipe (m); \( K \) = a constant (10.68 in SI units); \( L \) = the length of pipe (m); \( Q \) = discharge in the pipe (m\(^3\)/s); \( C \) = Hazen-Williams roughness coefficient; \( D \) = internal diameter of pipes (m); \( F(n_0) \) = a correction function to account for the variation in discharge of multiple outlets. According to Oron and Walker (1981); the discharge correction function for multiple outlet pipes may be expressed as:

\[ F(n_0) = 0.63837n_0^{-1.8916} + 0.35929 \]  \hspace{1cm} (80)

where \( n_0 \) is an integer variable expressing the number of outlets on a given pipe.

The Hazen-Williams coefficient is usually taken to be 150 for polyethylene and PVC pipes, (Oron and Walker, 1981). However, considering the additional roughness due to the emitters on the laterals and laterals on the manifolds, values of 130 for laterals, 140 for manifolds and 150 for the other pipes are assumed.

Since, in drip irrigation systems, water is applied as discrete or continuous drops through the emitters, uniformity of emitter flow is very important. It depends on two factors: the emitter characteristics, and the water pressure variation along the lateral lines and manifolds. In general, the flow rate through the emitters is controlled by the hydraulic pressure and the flow path dimensions of the emitters. Variations in emitter characteristics due to manufacture are assumed to be small in this analysis.

Three major groups of emitter types are: orifice or nozzle emitters, long flow path emitters and the special type emitters such as pressure compensated, vortex and porous-pipe. The orifice and nozzle types usually have fixed geometry so the flow area is constant. According to Solomon et al. (1978) Jensen (1983), Wu et al. (1986) the flow and hydraulic pressure variation of emitters may be expressed as follows:
\[ Q_E = K_e h^x \]  \hspace{1cm} (81)

where \( h \) = the pressure head on the emitters (m); \( K_e \) = the proportional factor that characterizes the emitter dimensions; \( x \) = a factor that characterizes the type of flow rates, \( x = 1 \) for laminar flow, \( x = 0.57 \) for turbulent flow and \( x = 0.50 \) for fully turbulent flow (Wu et al. 1986)).

As indicated in Equation 82 if emitter characteristics are constant the emitter flow due to the variation of pressure head will be controlled by the hydraulic pressure at the emitters. There will be an emitter flow variation caused by the pressure profile along the irrigation lines. The degree of emitter flow variation is important because it is one of the major components of the irrigation efficiency. It may be expressed by the emission uniformity (\( EU \)) or uniformity coefficient (\( UC \)) as defined by Christiansen (1942) for sprinkler irrigation systems. In a well design drip irrigation system, the emission uniformity for the emitters should be above a specified level. Karmeli and Keller (1975) define the emission uniformity for a dripper system as:

\[ EU = 100 \left( 1 - 1.27 \frac{\mu}{\sqrt{N_p}} \right) \frac{Q_n}{\overline{Q}_E} \]  \hspace{1cm} (82)

where \( \mu \) = emitter coefficient of manufacturing variation; \( N_p \) = number of emitters from which each plant receives water; \( Q_n \) = minimum emission rate (L/hr); \( \overline{Q}_E \) = average emission rate (L/hr). Keller and Bliesner (1990) recommend that \( EU \) should lie in the range 85% to 90% for dippers on flat terrain with fewer than 3 dippers per plant. An acceptable value of \( EU \) can be obtained by limiting the variation of pressure (Keller and Karmeli, 1974) of the emitters within a sub-unit to 20% (see Appendix C). For a working pressure of 10 m, this allows a total pressure loss within a subunit of 2 m in the manifold and laterals.

The uniformity coefficient for emitter flow rates can be presented as:

\[ UC = 1 - \frac{\Delta \overline{Q}}{\overline{Q}} \]  \hspace{1cm} (83)

where \( \Delta \overline{Q} \) = the mean of the absolute deviation from the mean emitter flow rate (L/hr); \( \overline{Q} \) = the mean flow rate for the emitters (L/hr).

As explained previously the flow variation from emitters should not exceed a specific level. The relationship between the emitter flow variation and the uniformity coefficient is shown in Figure 11. The variation of the emitter flow
rates is directly proportional to the maximum and minimum flow rates at the emitters as shown in Equation 84.

\[ q_{\text{var}} = \frac{q_{\text{max}} - q_{\text{min}}}{q_{\text{max}}} \]  

(84)

where \( q_{\text{var}} \) = the emitter flow variation; \( q_{\text{max}} \) = the maximum emitter flow along the laterals (L/hr); \( q_{\text{min}} \) = the minimum emitter flow along the laterals (L/hr).

The pressure and the emitter flow variation are related by \( x \)-value shown in the emitter flow function expressed as:

\[ q_{\text{var}} = 1 - (1 - H_{\text{var}})^x \]  

(85)

\( H_{\text{var}} \) = the variation of pressure head along the laterals (%). It may be expressed as:

\[ H_{\text{var}} = \frac{H_{\text{max}} - H_{\text{min}}}{H_{\text{max}}} \]  

(86)

\( H_{\text{max}} \) = the maximum pressure along the multiple outlet pipes (m); \( H_{\text{min}} \) = the minimum pressure along the multiple outlet pipes (m).

The value of \( x \) showing the relationship between emitter flow rate and the pressure depends on the flow regime discharges from the emitters. Figure 12 displays the relationship between emitter flow variation and the pressure variation for different flow regimes. In a well designed drip irrigation system, the variation of discharge from emitters should not be more than 10%, hence the pressure variation (within a sub-unit with orifice type emitters) should be less than 20% (Wu et al. 1986). On the basis of the above assumption in this model, if the pressure head at the split point of the manifold is assumed to be 12 m the minimum allowable pressure at the most distant emitter will be 10 m. Since the laterals have a greater length compared to the manifolds, the greater portion of the head loss (1.8 m) is permitted to occur in the laterals. Using Equation 86 to determine the numerical flow variation along the laterals on the basis of the above assumption gives

\[ H_{\text{var}} = \frac{11.80 - 10.00}{11.8} = 15.25\% \]  

(87)
Fig. 11  Relationship between emitter flow variation and uniformity coefficient. (Howell et al. 1986)

Fig. 12  Relationship between emitter flow variation and the pressure variation for different \( x \)-values (Wu et al. 1986)
For an $x$-value of 0.50 (which applies to most of the orifice type of emitters) a maximum pressure variation of 15.25% leads to an approximate emitter flow variation of 7.5%.

As mentioned previously, the only basic factor which affects the pressure variation on flat terrain is the head loss in each pipe. Using the Hazen-Williams equation the head loss in different pipes of system may be expressed using the following equations:

The head loss in both segments of laterals is expressed as follows (see appendix D for derivation):

\[
HL_l = 3.745 \left( \frac{2.78 \times 10^{-7} Q_E}{CH_l d_x} \right)^{1.852} \left[ \frac{\left( L_1 + L_2 \right)^{2.852} - L_2^{2.852}}{D_b^{4.87}} + \frac{L_2^{2.852}}{D_s^{4.87}} \right]
\]

where $HL_l$ = head loss in the two segments of laterals (m); $CH_l$ = Hazen-Williams roughness coefficient for laterals, (known); $D_b$, $D_s$ = internal diameters of large and small size of laterals respectively (m), (known).

On the basis of the assumption of 2 m allowable head loss within the manifold and laterals, the head loss in the manifold may be expressed as follows:

\[
HL_m = 2.0 - HL_l
\]

where $HL_m$ = head loss in manifold in m.

Total head loss from the most distant dripper to the water source includes: the head losses of the most distant lateral, manifold, supply, submain and mainline pipes in series, the head loss of accessories including: valves, filter, chemical tank, pump shaft plus the operating pressure of drippers and depth of water table. This should equal the total system pressure that is provided by the pump. Total system pressure or total dynamic pumping head is expressed as:

\[
T_{dh} = HL_p + HL_{ac} + H_w + H_{wt}
\]

where $T_{dh}$ = the maximum pressure head at the water source provided by the pump (m); $HL_p$ = the head loss in pipes (m); $HL_{ac}$ = the head loss of accessories including the head loss of filter, ($HL_f$, m), fertilizer ($HL_{fer}$, m),
pump shaft ($HL_{sh}$, m) and head loss of valves ($HL_{va}$, m). $H_w$ = working pressure (m), $H_{wt}$ = groundwater depth (m).

The head loss of pipes may be presented as:

$$HL_p = HL_l + HL_m + HL_s + HL_{sm} + HL_{ml}$$  \hspace{1cm} (91)

where $HL_s$, $HL_{sm}$, $HL_{ml}$ = the head loss in the supply, submain and the mainline pipes respectively (m).

The head loss of the supply, submain, and mainline pipes based on the Hazen-Williams equation are as following:

$$HL_s = 10.68 \frac{P_{suy}}{CH_s^{1.852} D_s^{4.87}} \left( \frac{Q_E}{d_x} \cdot \frac{P_{sux}}{d_y} \right)^{1.852}$$  \hspace{1cm} (92)

where $CH_s$ = Hazen-Williams roughness coefficient; $D_s$ = internal diameter of supply pipe (m).

$$HL_{sm} = 10.68 \frac{\left( \frac{F_y}{2} - P_{suy} \right) \left( Q_E \cdot \frac{P_{sux}}{d_x} \cdot \frac{P_{suy}}{d_y} N_{suy} \right)^{1.852}}{CH_{sm}^{1.852} D_{sm}^{4.87}}$$  \hspace{1cm} (93)

where $CH_{sm}$ = Hazen-Williams roughness coefficient of submain pipes; $D_{sm}$ = internal diameter of submain pipes (m); $N_{suy}$ = the number of sub-units in the Y-direction or the maximum sub-units which may be supplied by each submain line.

$$HL_{ml} = 10.68 \frac{\left( \frac{F_x}{2} - P_{sux} \right) \left( Q_E \cdot \frac{P_{sux}}{d_x} \cdot \frac{P_{suy}}{d_y} n \cdot N_{suy} \right)^{1.852}}{CH_{ml}^{1.852} D_{ml}^{4.87}}$$  \hspace{1cm} (94)

where $HL_{ml}$ = the head loss of mainlines (m); $CH_{ml}$ = Hazen-Williams roughness coefficient of mainlines; $D_{ml}$ = internal diameter of mainlines (m); 

- $n = 0$ if $N_x \leq 2$, 
- $n = 2$ if $2 \leq N_x \leq 6$ and 
- $n = 4$ if $6 < N_x \leq 10$.

The above head loss equations are based on the worst case (the maximum possible head loss). However as the number of field divisions increases, not
only the length of submain and mainlines, but also the number of outlets on both pipes increases. As a result, the discharge decreases along the pipe length. In order to determine the head loss on the basis of the exact value of discharge in each segment of both pipes, the head loss in each section of those pipes is calculated separately.

Fig. 13  Different layout of multi exit emitters
7.2 Size of Emitters

In the past the emitter flow rates of drip irrigation systems were selected just large enough to meet plant water requirements on a continuous basis. These small flow rates required small orifices or emitters that caused clogging problems. To minimize clogging, the emitter diameters were increased which led to increases in the emitter flow rates and changed the irrigation duration from a continuous to an intermittent system. In the design of a drip irrigation system it is necessary to make sure that an appropriate size is chosen for the emitters. Very small sizes may cause clogging problems and very large emitter sizes may cause runoff and subsequently, lead to soil erosion. Single-outlet emitters can be used to irrigate small spots, or can be arranged around larger plants to serve the same function as dual or multiple outlet emitters or spray. Multiple-outlet emitters are used in orchards where larger tree may each require several emission points. In Figure 13 various emission point layouts for a wide spaced tree crop are shown.

8. OPTIMIZATION PROCEDURE

The model evaluates all combinations of sub-unit sizes, pipe sizes, shift numbers and shift patterns. The system cost is evaluated for various sizes of created sub-units under three different numbers of irrigation shifts (1, 2 and 4).

Optimisation is carried out by complete enumeration of all alternatives. The following values are assumed to be known:
(1) The dimensions of the field, $F_x$ (m) and $F_y$ (m);
(2) The depth of the water table $H_{wt}$ (m);
(3) The potential evapotranspiration, $ET_0$ (mm/day), the crop coefficient, $K_c$;
(4) The minimum and maximum percentage of wetted area, $P_w^{'}, (%)$;
(5) The application efficiency of drip irrigation, $E_a$ ( %);
(6) The annual irrigation requirement for the crop, $A_{ir}, (mm)$;
(7) The field capacity,$FC$ and the permanent wilting point $PWP$, of soil;
(8) The depth of root zone, $R, (m)$, soil infiltration rate, $I_{soil} (mm/hr)$ and soil bulk density $\gamma_s (g/cm^3)$;
(9) The portion of the available moisture depletion $f, (%)$;
(10) The spacing between emitters, $d_x$, and laterals, $d_y$, respectively (m);
(11) The pipe cost coefficients $K_1$, $K_2$, $K_3 \phi$; the Pump cost parameters $K$, $a$ $b$;
(12) Efficiencies for the electric motor, $\eta_m$, and pump, $\eta_p$, respectively;
(13) The discount rate, $i$, and expected project life, $n, (years)$;
(14) A list of available diameters for all pipes;
(15) Two diameters for laterals and their cost per unit length;
(16) Hazen-Williams coefficients for all pipes;
(17) Cost information for all components;
(18) The head loss through the filter, fertiliser unit, valves and pump.

Acceptable range for the discharge from the emitters, can be determined using the acceptable range for the percentage wetted area, $P_w$, and Equations (78) and (82).

The optimisation processes for the main program and the subroutine which optimisms the sub-units are shown by flow charts in Figures 14 and 15.
Fig. 14  Flow chart of main program for optimisation of a multiple subunit drip irrigation system for different operating conditions
Fig. 15  Flow chart of subroutine optimising the sub-units
9. MODEL ASSUMPTIONS AND DATA INPUT

In the present optimization model the general configuration of pipes within the field (main and submain lines) and within the sub-units (lateral, manifold and supply lines) is fixed. However, since the area and the dimensions of sub-units in the both X and Y directions change in each iteration of the field division, the length and the size of all pipes change as well. The model was developed for a field with given area and known dimensions for which the water source is located at the centre of field. The model can be easily applied to any size and dimensions of field.

9.1 Case Study

The model was applied using the data given in Table 2. In this table the coefficients for pipe cost \(K_1\), \(K_2\) and \(K_3\) were obtained by regression analysis of cost data for PVC pipes. The parameters for pump costs \((K, a, \text{and } b)\) were found by nonlinear regression analysis of the costs of various submersible pumps. The main purpose of this study is to identify an optimum design for drip irrigation based on multiple sub-unit systems. The model enables an examination of the influence of various sub-unit sizes, and shift patterns on the system cost and will find the global optimum solution among various local optima under a known operating program.

10. RESULTS AND DISCUSSION

As explained previously, the main purpose of this study is to develop an optimization model for drip irrigations based on multiple sub-unit system with the following characteristics:

- Each given field can be easily divided into various sub-units with different area and dimensions.

- The optimum solution for each iteration of field division can be achieved by finding decision variables including: the optimum lengths of lateral segments, the optimum size of the manifold and supply pipes for an accepted discharge uniformity, the optimum size of submain and mainline pipes by caring out a trade-off between the cost of pipes and the cost of corresponding energy, the number of shifts and patterns.

- The model enables an examination of the influence of various sub-unit sizes, and shift patterns on the system cost and will find the global optimum solution among various local optima under a known operating program.
A number of effects were evaluated. These are discussed in the following sections.

**TABLE 2. Input data for a case study**

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<th>Variable(s) (1)</th>
<th>Value (2)</th>
<th>Units (3)</th>
<th>Variables (4)</th>
<th>Value (4)</th>
<th>Units (5)</th>
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<td>mm</td>
<td>$K_1$</td>
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</tr>
<tr>
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<td>m</td>
<td>$K_2$</td>
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<td>--</td>
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<tr>
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<td>m</td>
<td>$K_3$</td>
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<td>m</td>
<td>$\phi$</td>
<td>2</td>
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<td>m</td>
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<td>mm</td>
<td>$a$</td>
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<td>mm</td>
<td>$b$</td>
<td>0.9038</td>
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<td>m</td>
<td>$\eta_p$</td>
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<td>%</td>
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<td>m</td>
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<td>%</td>
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<td>$R$</td>
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<td>$f$</td>
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<td>hr</td>
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<td>$i$</td>
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<td>%</td>
</tr>
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<td>$</td>
<td>$P_{w}^{min}$</td>
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<td>%</td>
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<td>$C_{en}$</td>
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<td>$$/kWh$$</td>
<td>$P_{w}^{max}$</td>
<td>65</td>
<td>%</td>
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10.1 Effect of Sub-unit Area

Determining the optimum area of sub-units is one of the aims of the model developed in this study. The effect of sub-unit areas and sub-unit dimensions on the system cost were examined by increasing the number of sub-units in the model from 4 to 100. The results obtained under different number of shifts are given in Tables 3, 4 and 5. The minimum cost solution involves one shift operation and corresponds to a sub-unit area of 3 ha with dimensions of 400 m×75 m (Table 3). It has a system cost of $262782 or 5475 $/ha (Table 3). Table 3 includes other cases with the same sub-unit area, but higher system costs, due to the differences in sub-unit dimensions. For example, the sub-units with an area of 3 ha but with dimensions, 200 m×150 m and 100 m×300 m, lead to system costs of $270130.2 (5627.7 $/ha) and $272486 (5676.8 $/ha) respectively. Although the optimum ratio of the X to the Y dimension for fields with one sub-unit (one control head) is somewhere between 1.0 and 1.5 (Hassanli and Dandy, 1993). The optimum ratio for a field with multiple sub-units is different due to the effect of other parameters such as the cost of the submain and main line pipes and the pump. The effect of sub-unit area on the system cost for one shift operation is shown in Figure 16. According to the constraint shown in Eq. 76, for the schedule with 1 shift operation the value of $P_w$ is very low. It is close to the minimum limit of allowable $P_w$.

The same analysis was carried out for 2-shift and 4-shift operations. The details are given in Tables 4 and 5 and shown in Figures 17 and 18. The results show that the system cost variation in terms of sub-unit area is different for the various number of shifts. As the number of shifts increases the system cost increases due to increase in flow rate of pipes. On the other hand, as the sub-unit area decreases the system cost also decreases to reach the optimum cost and then increases. The increase in system cost from the optimum level for the smaller sub-unit area is due to the increase in the number of submain lines, valves, length of submain and main pipes and also the increase of corresponding head losses. The higher cost for very large sub-unit areas could be due to using pipes with larger diameters. As shown in Figure 18 the maximum feasible sub-unit size is 6 ha, for 4-shift operation. This is due to the fact that for larger sizes of sub-units under high shift operation, the head loss in the laterals exceeds the allowable head loss because of the greater length and higher flow rate. The optimum system cost for 2-shift occurs at a sub-unit area of 1.33 ha with dimensions of 133.3 m by 100 m, and for 4-shift occurs at sub-unit area of 2 ha with dimensions of 133.3 m by 150 m. This difference in the optimum size of sub-units for different shifts may be due to the use of discrete pipe sizes.
Fig. 16.  Total minimum system costs for various subunit areas under 1-shift operation

Fig. 17.  Total minimum system costs for various subunit areas under 2-shift operation

Fig. 18.  Total minimum system costs for various subunit areas under 4-shift operation
### TABLE 3  Total minimum costs as well as Capital and Operation costs for various sub-unit sizes under 1-shift operation condition

<table>
<thead>
<tr>
<th>Sub.area [m²]</th>
<th>P.sux m</th>
<th>P.suy m</th>
<th>Tot.head m</th>
<th>Mot.pow kw</th>
<th>No.shift</th>
<th>Cap.cost $</th>
<th>Op.cost $</th>
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Sub.area= the area of sub-units (m²)  Mot.pow.= the power of motor (Kw);  Cap.cost= the capital cost of system ($)  Op.cost= the present value of operation cost ($)  Tot.head= total head provided by the pump (m)  Tot.cost = the total minimum cost of system in each iteration ($).

### 10.2 Effect of Irrigation Shifts

Multiple sub-unit irrigation systems allow the application of a number of different shifts in the operating program. Irrigating a set of sub-units instead of irrigating the whole system simultaneously increases the flexibility and reliability of system. A high number of shifts requires high emitter flow, which may overcome emitter clogging problems. It is also more flexible in relation to sharing irrigation water for a specified set of sub-units when the available water is either provided from different sources or the field belongs to different owners.
TABLE 4. Total minimum, Capital and Operating costs for various subunit sizes and feasible shift patterns under 2-shift operation

<table>
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<th>Mot.pow KW</th>
<th>Cap.cost $</th>
<th>Op.cost $</th>
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TABLE 5. Total minimum costs, Capital and Operation costs for various sub-unit sizes and shift patterns under 4-shift operation condition

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<th>P.suy m</th>
<th>Tot.head m</th>
<th>Mot.pow Kw</th>
<th>Cap.cost $</th>
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**20000**

| 133.3 | 150 | 49.1 | 29.4 | 242004 | 51508 | 293512 |

| 13333.3 | 133.3 | 100 | 57.2 | 33.9 | 241149 | 59391 | 300540 |
| 10000   | 133.3 | 75  | 55.8 | 33.38| 247485 | 58491 | 305975 |
| 10000   | 133.3 | 75  | 53.1 | 31.75| 243684 | 55632 | 299316 |
| 8000    | 133.3 | 60  | 56.8 | 35.19| 245343 | 61649 | 306992 |
| 30000   | 100    | 300  | 46.7 | 28.23| 277308 | 49456 | 326764 |
| 30000   | 100    | 300  | 53.7 | 32.45| 264853 | 56847 | 321700 |
| 15000   | 100    | 150  | 50.2 | 30.31| 265170 | 53108 | 318277 |
| 15000   | 100    | 150  | 51.8 | 31.29| 258400 | 54814 | 313214 |
| 15000   | 100    | 150  | 46.8 | 28.3 | 253403 | 49585 | 302988 |
| 10000   | 100    | 100  | 50.8 | 30.39| 258329 | 53245 | 311574 |
| 10000   | 100    | 100  | 52.4 | 31.34| 251546 | 54903 | 306449 |
| 7500    | 100    | 75   | 52.8 | 31.9 | 258965 | 55891 | 314856 |
| 7500    | 100    | 75   | 54.4 | 32.87| 252192 | 57598 | 309790 |
| 7500    | 100    | 75   | 54.6 | 32.99| 241919 | 57809 | 299728 |
| 6000    | 100    | 60   | 56.3 | 34.03| 259665 | 59620 | 319185 |
| 6000    | 100    | 60   | 57.9 | 35   | 252788 | 61327 | 314116 |
| 24000   | 80     | 300  | 49.9 | 30.13| 302285 | 52795 | 355080 |
| 12000   | 80     | 150  | 50.5 | 30.51| 256073 | 53455 | 308528 |
| 12000   | 80     | 150  | 50.3 | 30.4 | 243933 | 53262 | 297194 |
| 8000    | 80     | 100  | 51.4 | 30.77| 254377 | 53905 | 308282 |
| 6000    | 80     | 75   | 60.2 | 36.36| 250964 | 63702 | 314666 |
| 6000    | 80     | 75   | 53.7 | 32.47| 245229 | 56895 | 302123 |
| 4800    | 80     | 60   | 57.3 | 34.6 | 253806 | 60226 | 314433 |
However, as the number of irrigation shifts increases, the irrigation time for a set of sub-units irrigated simultaneously decreases, and as a result pipe flows and system costs increase. The value of irrigation interval, irrigation duration, emitter discharge and the percentage of area wetted is associated with each selected number of shifts (1, 2 and 4) are illustrated in Table 6.

**TABLE 6. The value of $F$, $T$, $Q_E$ and $P_w$ for selected number of shifts**

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<th>$N_{sh}$</th>
<th>$F$</th>
<th>$T$</th>
<th>$Q_E$</th>
<th>$P_w$</th>
</tr>
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<td>hr</td>
<td>L/hr</td>
<td>%</td>
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The optimum cost of a system for various sub-unit dimensions under three different numbers of shifts (1, 2 and 4) are given in Tables 3, 4 and 5. The global minimum cost system was obtained using one shift. The details of the design are given in Table 8. The optimum configuration does not require mainline pipes and only the minimum size of laterals is required. Tables 9 and 10 contain, similar information but for the optimum design under 2 and 4 shift operation. Once again only the smallest sized lateral is used in each design. Each of these systems is a local optimum which corresponds to a higher cost than the global optimum cost of the system under 1-shift operation. (Table 8). In fact, the optimum design with one shift operation represents a 6.2% cost saving compared to the optimum for two shift operation and 10.5% compared to the optimum for four shift operation.

### 10.3 Effect of Shift Pattern

For many particular number of shifts (greater than one) there are various possible combinations of sub-units in the X and Y directions which can be irrigated simultaneously. Figure 3 shows an example of 5 possible shift patterns under 2-shift and 4-shift operation for a drip irrigation system with 16 sub-units. As the number of irrigation shifts increases, the possibility of using more shift patterns increases as well. Under 2-shift operation, two different system costs and under 4-shift operation 3 system costs exist which correspond to different shift patterns. In two shift operation, that pattern No. 5 will lead to a lower system cost than pattern No. 4 as the former involves lower flow in the mainlines than the latter. Similarly pattern No. 2 involves the lowest cost for four shift operation as each submain and each mainline is supplying only two sub-units at a time. The details of system cost for the feasible shift patterns associated with 3 different shift numbers for sub-unit area of 3 ha are shown in
Table 8. Note that only contiguous shift patterns were considered in this study. The following numerical examples illustrate the influence of shift pattern on the system cost. As mentioned above, the optimum design for two shift operation given in Table 8 uses shift pattern No. 5 (Figure 3). If the same sub-unit size is used (133.3 m by 100 m) but the shift pattern is changed to No. 4, the system cost increases from $280,198 to $285,334 (1.83% increase in system cost).

Similarly the optimum design for four shift operation (Table 10) uses shift pattern No. 2. For the same size of subunits and shift pattern No. 1 the system cost increases from $293,512 to $304,130 (3.6% increase in the system cost). In this study only contiguous shift patterns were considered. Some further cost saving can be achieved by using non-contiguous patterns. For example, irrigating the four sub-units on the left and at the same time as the four sub-units on the right in Figure 3 under two shift operation. The influences of shift patterns on the system cost for each sub-unit under 2-shift and 4-shift are given in Tables 4 and 5. The variation of system cost for different shift patterns but for the same sub-unit size and the same shift number is due to an increase in the size of pipes and in the energy requirements.

**TABLE 7. System cost, Capital and operating costs for shift patterns associated to 3 different shift numbers (1, 2 and 4)**

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<th>II</th>
<th>JJ</th>
<th>Nsh</th>
<th>Cap.cost ($)</th>
<th>Op.cost ($)</th>
<th>Tot.cost ($)</th>
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### TABLE 8 Minimum cost design and some associated decision variables for 1-shift operation

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<th>Minimum cost</th>
<th>Percent of total cost</th>
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### TABLE 9 Minimum cost design and some associated decision variables for 2-shift operation

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TABLE 10  Minimum cost design and some associated decision variables under 4-shift operation

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<th>Items</th>
<th>Tot.pipe length m</th>
<th>Diameter mm</th>
<th>Discharge L/s</th>
<th>Head loss m</th>
<th>Minimun cost $</th>
<th>Percent of tot.cost %</th>
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</table>

10.4 Relationship between System Cost and the Pressure Head

In Tables 3, 4 and 5 the variation of system cost against the total head provided by the pump due to the total head loss, minimum required operating pressure and the depth of groundwater is represented. According to these tables the lowest system cost does not correspond to the minimum total head nor does the highest cost correspond to the maximum total head. But in spite of an irregular change in the system cost due to the effect of sub-unit areas and the shift patterns, (apart from one case which corresponds to the optimum solution) as the total dynamic head increases the system cost increases as well. This is expected since an increase in the dynamic head potentially can increase the size of pump and also the operating cost.

10.5 Cost of Different Pipes in Multiple Sub-unit System

The cost of five different pipes that deliver and distribute the irrigation water throughout the system is displayed in Figure 19. As it is clear, the lateral pipes constitute a large portion of the system cost. Furthermore, the findings indicate that the effect of sub-unit sizes on the lateral cost is not large, as the laterals are limited to two small sizes and usually the smaller size is used. Furthermore, the size of sub-units does not have a considerable effect on the total length of laterals. However, the costs of manifold and supply pipes are affected by sub-
unit sizes since as the size of sub-units decrease the rate of flow which is delivered by these two pipes is decreased, therefore, a smaller pipe size is selected. But the cost of main and submain lines increase as the size of sub-units decreases. This is due to the configuration of pipes in the distribution system. As the size of sub-units decreases the number of sub-units increases, as a result, the length and the number of submain and the length of mainlines increase. For sub-units with a length of 400m, the cost of mainlines is zero, since the system works without mainlines.

![Diagram showing the cost of different pipes in the system for optimum solution (Nsh=4)](image)

**Fig. 19.** Cost of different pipes within the multiple sub-unit system for optimum solution
11. SUMMARY AND CONCLUSIONS

An optimization model for a drip irrigation system has been developed. The model partitions a field into sub-units with an assumed layout and configuration of the piping system. The model evaluates various shift patterns and determines the minimum cost design for each. The design variables are the length of each of two diameters of laterals, the diameters of the manifold, supply line, submain and mainline pipes as well as the size of pump required.

In addition, the model identifies the optimum sizes of sub-units as well as the optimum shift pattern. The cost includes the capital and installation cost of all pipes, the pump, emitters, valves and accessories and the present values of electricity costs of the system. The model can be applied to a level rectangular field with a groundwater source at the centre. It can be applied to various field sizes and crops in different regions. This can be achieved by specifying the input data such as: dimensions of the field, emitter and lateral spacing, potential evapotranspiration and crop coefficient, and the annual crop irrigation requirement.

When applied to a particular case study, the model showed that one shift operation was more efficient that multiple shift operation. In general, it would appear that the minimum number of shifts should be used, consistent with achieving a reasonable flow rate through the emitters. The model identified the minimum dimensions of sub-units for one, two and four shift operation. In each case these corresponded to using the smaller size of laterals. This is reasonable given that the laterals constitute 30 to 36% of the system cost in this case (Tables 8 to 10). In general, it is considered that efficient designs will use the smallest possible size of laterals. The optimum design for one shift operation does not have any mainline pipes and only two submains. Again this gives some general guidance to try to reduce the number of feeder pipes where possible. In this case the optimum ratio of the X to Y dimension of the sub-units is 5.33 to 1 (X parallel to the laterals). This differs from the general experience with optimizing single sub-units where this ratio lies in the range 1 to 1.5 but is reasonable when the other costs are considered.

12. ACKNOWLEDGMENTS

The support of the Shiraz University (Iran) by providing a scholarship at the University of Adelaide to the first author is gratefully acknowledged. The authors also would like to thank John Gransbury from Hydro-plan, irrigation engineering consultant in Australia for his helpful advice.
APPENDIX A. REFERENCES


Keller, J., and Blisener, R.D., (1990), Sprinkle and Trickle Irrigation , Published by Van Nostrand Reinhold, New York.


APPENDIX B. NOTATION

The following symbols are used in this paper.

\( A_{en} \) = annual energy requirement (Kwt);
\( A_{ir} \) = annual irrigation requirement (mm);
\( a \) = pump cost coefficient;
\( b \) = pump cost coefficient;
\( CH_l \) = Hazen-Williams coefficient for laterals;
\( CH_m \) = Hazen-Williams coefficient for manifolds;
\( CH_s \) = Hazen-Williams coefficient for supply lines;
\( HL_{vals} \) = subunit valve head loss (m);
\( C_{valsm} \) = submain valve cost ($);
\( C_{valml} \) = main line valve cost ($);
\( CL_1 \) = cost of larger size of laterals ($);
\( CL_2 \) = cost of smaller size of laterals ($);
\( CL_l \) = cost of laterals ($);
\( C_m \) = cost of manifolds ($);
\( C_s \) = cost of supply pipes ($);
\( CU_{em} \) = cost of each unit of emitters ($);
\( C_p \) = total cost of pipes ($);
\( C_{pu} \) = cost of pumping system ($);
\( C_{em} \) = cost of emitters ($);
\( C_{ac} \) = cost of accessories ($);
\( C_{op} \) = cost of annual operation ($);
\( C_{en} \) = cost of energy ($);
\( C_i \) = cost of \( i \)th pipe ($);
\( D_i \) = internal diameter of \( i \)th pipe (mm);
\( D_b \) = internal diameter of larger size of laterals (mm);
\( D_s \) = internal diameter of smaller size of laterals (mm);
\( D_m \) = internal diameter of manifolds (mm);
\( D_s \) = internal diameter of supply pipes (mm);
\( D_h \) = daily time available (hours);
\( d \) = depth of water stored in the soil (mm);
\( d_x \) = spacing between emitters (m);
\( d_y \) = spacing between laterals (m);
\( ET_0 \) = potential evapotranspiration (mm/day);
\( E_a \) = application irrigation efficiency (%);
\( EU \) = emission uniformity (%);
$F_x =$ length of field in the X direction (m);
$F_y =$ length of field in the Y direction (m);
$f =$ portion of allowable water depletion (%);
$F =$ irrigation interval (days);
$FC =$ field capacity (% weight);
$F(n_c)$ = correction factor for discharge;
$HL =$ head loss of pipes (m);
$H_w =$ working pressure on the emitters (m);
$H_{pu} =$ total head provided by pump (m);
$H_{var} =$ pressure variation in emitters (m);
$H_{max} =$ maximum pressure in emitters (m);
$H_{min} =$ minimum pressure in emitters (m);
$H_{wt} =$ groundwater level (m);
$HL_l =$ lateral head loss (m);
$HL_m =$ manifold head loss (m);
$HL_f =$ filter head loss (m);
$HL_{fer} =$ fertiliser head loss (m);
$HL_{vals} =$ subunit valve head loss (m);
$HL_{valsm} =$ submain valve head loss (m);
$HL_{valml} =$ main line valve head loss (m);
$HL_{sh} =$ pump shaft head loss (m);
$h =$ pressure head on the emitters (m);
i = discount rate (%);
II = number of subunits being irrigated in the X direction simultaneously;
JJ = number of subunits being irrigated in the Y direction simultaneously;
$K =$ pump cost parameter;
$K_1 =$ pipe cost parameter;
$K_2 =$ pipe cost parameter;
$K_3 =$ pipe cost parameter;
$K_c =$ crop coefficient;
$K_e =$ a constant characterised the emitter dimensions;
$L_1 =$ length of larger size of laterals (m);
$L_2 =$ length of smaller size of laterals (m);
$L_l =$ length of each lateral (m);
$N_{em} =$ number of emitters;
$N_l =$ number of laterals;
$N_{sm} =$ number of submains;
$N_{ml} =$ number of main lines;
$N_p =$ number of emitters allocated to each plant;
$N_x =$ number of submains in the X direction;
\( N_Y \) = number of submains in the Y directions;
\( N_{sh} \) = number of irrigation shifts;
\( N_{su} \) = number of subunits;
\( n_o \) = number of outlets on the pipes;
\( n \) = project life (years);
\( P_{sux} \) = subunit length (m);
\( P_{suy} \) = subunit width (m);
\( P_m \) = pump power (kW);
\( PWP \) = permanent wilting point (% weight);
\( Q_E \) = emitter flow rate (L/hr);
\( Q_n \) = minimum emission rate (L/hr);
\( \overline{Q_E} \) = average emission rate (L/hr);
\( Q_{pu} \) = pump flow rate (m^3/s);
\( Q_o \) = discharge at the inlet of laterals (m^3/s);
\( \Delta Q \) = the mean of the absolute deviation from the mean emitter flow (L/hr);
\( q_{\text{var}} \) = discharge variation from emitters (%);
\( q_{\text{max}} \) = maximum discharge from emitters (L/hr);
\( q_{\text{min}} \) = minimum discharge from emitters (L/hr);
\( R \) = depth of soil which is to be considered (root zone, mm);
\( T \) = irrigation time (hours);
\( \eta_p \) = pump efficiency (%);
\( \eta_m \) = electric motor efficiency (%);
\( \mu \) = emitter coefficient of manufacturing variation;
\( \gamma_s \) = bulk volume of soil (g/cm^3);
\( \gamma \) = specific weight of water (N/m^3);
\( UC \) = uniformity coefficient;
\( x \) = a constant;
\( Z \) = objective function ($);
APPENDIX C: EMISSION UNIFORMITY

Karmeli and Keller (1975) defined emission uniformity, EU. (%) as follows:

\[ EU = 100 \left( 1 - 1.27 \frac{\mu}{\sqrt{N_p}} \right) \frac{Q_n}{Q_E} \]  \hspace{1cm} C.1)

The discharge from an orifice type emitter \( Q \) (L/h) is given by:

\[ Q = K_e (h)^x \]  \hspace{1cm} C.2)

where \( h \)=pressure head on the emitter (m); \( K_e \) = a constant; \( x \)= a constant.

For an average working head of 10m, a minimum value of 9m , and taking \( x=0.5 \) for this case, gives:

\[ \frac{Q_n}{Q_E} = \left( \frac{9}{10} \right)^{0.5} = 0.9487 \]  \hspace{1cm} (C.3)

Assuming, \( \frac{\mu}{\sqrt{N_p}} = 0.04 \) gives a value of 90.0% for EU.

Keller and Karmeli (1974) states that under good management the overall application efficiency should approach 0.9 of EU.
APPENDIX D. DERIVATION OF HEAD LOSS IN LATERALS

Consider a pipe of uniform diameter $D$ (m), length $L$ (m) and spacing of emitters $d_x$ (m). If discharge from each emitter is $Q_E$ ($m^3/s$), the discharge along the pipe is shown in Figure D.1. The discharge into left hand end of the pipe is $Q_0$ ($m^3/s$). If the spacing of emitters is small, the discharge in the pipe may be considered to be linear function of $l$, the distance from the left hand end,

i.e. $Q_l = \frac{Q_0(L-l)}{L}$ (D.1)

The head loss in any small length of pipe $dl$ (m) is given by applying the Hazen-Williams equation (Eq. 21).

$$d(HL) = \frac{10.68}{C^{1.852}D^{4.87}} \left[ \frac{Q_0(L-l)}{L} \right]^{1.852} dl$$ (D.2)

Where $C$ = Hazen-Williams coefficient for the pipe.

Integrating Equation (D.2) from 0 to $l$

gives: $HL = \frac{3.745Q_0^{1.852}L}{C^{1.852}D^{4.87}} \left[ 1 - \left( \frac{L-l}{L} \right)^{2.852} \right]$ (D.3)

Clearly if $l$ equals $L$, Equation (D.3) becomes:

$$HL = \frac{3.745Q_0^{1.852}L}{C^{1.852}D^{4.87}}$$ (D.4)

Consider a lateral consisting of a length $L_1$ (m) of diameter $D_b$ (m) and length $L_2$ (m) of diameter $D_s$ (m) with Hazen-Williams coefficient $C_H$ throughout.

Applying Equations (D.3) and (D.4) to find the total head loss in the lateral, $HL_1$, gives:
\[ HL_l = \frac{3.745}{CH_l^{1.852}} \left[ \frac{Q_0^{1.852}(L_1 + L_2)}{D_b^{4.87}} \left\{ 1 - \left( \frac{L_2}{L_1 + L_2} \right)^{2.852} \right\} + \left( \frac{Q_0 L_2}{L_1 + L_2} \right)^{1.852} \frac{L_2}{D_s^{4.87}} \right] \]  

(D.5)

Substituting \( Q_0 = \frac{2.78 \times 10^{-7} Q_E (L_1 + L_2)}{d_x} \) and simplifying yields:

\[ HL_l = 3.745 \left( \frac{2.78 \times 10^{-7} Q_E}{CH_l d_x} \right)^{1.852} \left[ \left( \frac{(L_1 + L_2)^{2.852}}{D_b^{4.87}} - \frac{L_2^{2.852}}{D_s^{4.87}} \right) + \frac{L_2^{2.852}}{D_s^{4.87}} \right] \]

(D.6)

**Fig. D.1** Discharge in multiple outlet pipes
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