MODELING AND OPTIMIZATION
OF
DRIP IRRIGATION SYSTEM

A DISSERTATION

Submitted in partial fulfillment of the
requirements for the award of the degree
of

MASTER OF TECHNOLOGY
in
IRRIGATION WATER MANAGEMENT

By

ARAYA ZERAY

DEPARTMENT OF WATER RESOURCES DEVELOPMENT AND MANAGEMENT
INDIAN INSTITUTE OF TECHNOLOGY ROORKEE
ROORKEE -247 667 (INDIA)
JUNE, 2010

CANDIDATE'S DECLARATION

I hereby certify that the work presented in this dissertation entitled, "**MODELING AND OPTIMIZATION OF DRIP IRRIGATION SYSTEM**" in partial fulfillment of the requirement for the award of degree of **Master of Technology in Irrigation Water Management** submitted in the Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, is an authentic record of my own work carried out during the period from July 2009 to June 2010 under the supervision of Dr. **Ram Pal Singh**, Professor, Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, and Dr. **Ashish Pandey**, Assistant Professor, Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, Uttarakhand, India.

The matter embodied in this dissertation has not been submitted by me for award of any other degree.

Place: Roorkee

Dated: June, 2010

(ARAYA ZERAY)

This is to certify that the above statement made by the candidate is correct to the best of my knowledge.

(Dr. Ashish Pandey)
Assistant Professor
Department of Water Resources
Development and Management
Indian Institute of Technology Roorkee
Roorkee – 247 667, Uttarakhand (INDIA)

RP Singh

(Dr. Ram Pal Singh)
Professor
Department of Water Resources
Development and Management
Indian Institute of Technology Roorkee
Roorkee – 247 667, Uttarakhand (INDIA)

ACKNOWLEDGMENT

I am very thankful and it is my desire to express my heartfelt gratitude to my supervisors Dr. Ram Pal Singh, Professor and Dr. Ashish Pandey, Assistant Professor, Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, for their guidance and constant encouragement throughout the period of this dissertation work.

I also express my sincere gratitude to Dr. Nayan Sharma, Professor and Head, Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, and Dr. M. L. Kansal, Professor and Chairman DAC, Department of Water Resources Development and Management, Indian Institute of Technology Roorkee, Roorkee, for providing all necessary supports and facilities during the period of this dissertation work.

This work would have been only a pipedream without the permission from the Hamelmalo Agricultural College (HAC), Eritrea and sponsorship from Indian Technical and Economic Cooperation (ITEC).

Special appreciation is extended to Mr. Semere Amlesom, Dean, Hamelmalo Agricultural College (HAC), Eritrea, for his constant follow up and motivation including a visit to IIT Roorkee, during my M. Tech study.

Thanks to all my friends at IIT Roorkee and HAC, for their help whenever needed throughout my M. Tech study and in preparation of this dissertation.

Most importantly, I am very much indebted to my family, for their encouragement, support and blessings throughout my study which enabled me to attain this stage.

Place: Roorkee

Dated: June, 2010

(ARAYA ZERAY)
M.Tech (IWM), 29th Batch
Enrolment No. 08547002

ABSTRACT

In this study, a non linear model for the optimal design of drip irrigation system is developed for both flat and uniform slope fields. The objective function is to minimize the cost which is the sum of capital and, operating cost and, the design variables are diameter of main, submain, manifold and lateral lines, size and number of emitters, dimension of subunit, irrigation interval, application time, and number of shifts per day. To solve the model a computer code in C++ was written. The program was designed as a two stage optimization processes. In the first stage, identification of all the possible combinations of emitter discharge and number of emitters per tree based on the irrigation requirement and available time for irrigation per day was found out. In the second stage, for each possible combination the field was divided into subunits, then subunit pipe (manifold and lateral in this case) diameters as a function of emission uniformity (EU) and, main and submain diameters based on cost were decided to determine subunit dimension with minimum cost. Further, to test the capability of the model two sets of published data, the first with flat topography and the second with uniform slope topography were used. The model identified 11 and 3 combinations of emitter discharge and number of emitters per tree for the first and second cases respectively. Optimum costs which are equal to \$216937 with subunit dimension of 200m×75m (4 lph emitter discharge and 2 numbers of emitters per tree) and \$31413 with subunit dimension of 75m×150m (2 lph and 1 emitter per tree) were found out for the first and second data sets respectively.

Keywords: Drip irrigation, optimum design, modeling, C++, drip subunit.

List of Tables

List of Figures

Symbols and Abbreviations

Symbol	Description	Symbol	Description
ΔE_l	Elevation difference along lateral	C_{sv}	Cost of subunit valve
ΔE_m	Elevation difference along manifold	CV	Coefficient of variation
ΔE_{ma}	Elevation difference along main	C_{vv}	Cost of volumetric valve
ΔE_s	Elevation difference along submain	D1	Diameter of smaller pipe
ΔH_{max}	allowable head loss in sub-unit	D2	Diameter of bigger pipe
Ae	Application efficiency	D_{ma}	Diameter of main pipe
A_{er}	Annual energy requirement	Dnext	Diameter of next smallest pipe
A_{NIR}	Annual irrigation requirement	D_s	Diameter of sub-main
A_{sh}	Area irrigated per shift	E_m	Efficiency of motor
A_{su}	Area of sub-unit	E_p	Efficiency of pump
A_w	Wetted area	Epo	Position of first outlet
Bd	Bulk density of soil	ET_c	daily peak water use of crop
C_a	Cost of accessories	EU	design emission uniformity
C_{ch}	Cost of control head	EU_{cv}	EU due to manufacturers variation
C_{co}	Cost of connectors	EU_h	EU due to hydraulic variation
C_e	Cost of emitters	F	Christiansen friction factor
C_{ed}	Cost of ends	FC	Moisture content at field capacity
C_{en}	Cost per unit energy	g	acceleration due to gravity
C_{fi}	Cost of fittings	GIR	Gross irrigation requirement
C_{ft}	Cost of fertilizer tank	H_l	Inlet pressure of lateral
C_l	Cost of lateral	h_{f1}	Friction loss in smaller size pipe
C_m	cost of manifold	h_{f2}	Friction loss in larger size pipe
C_{ma}	Cost of main	h_{fa}	Allowable head loss in manifold
C_{mf}	Cost of media filter	H_{fl}	Friction loss in lateral
C_{mv}	Cost of main valve	H_{fm}	Friction loss in manifold
C_o	Cost of operation	H_{fma}	Friction loss in main
C_p	Cost of pipes	H_{fs}	Friction loss in submain
C_{pe}	Cost per emitter	H_m	Inlet pressure of manifold
C_{pu}	Cost of pump	H_{ma}	Inlet pressure of main
C_s	cost of submain	H_{min}	minimum pressure
C_{sf}	Cost of screen filter	H_o	operating pressure
C_{sp}	Cost of subunit pressure regulator	H_s	Inlet pressure of submain

hs	friction loss in the suction pipe
Hwt	depth of water table
i	Interest rate
I_a	application rate
I_f	Irrigation frequency
I_n	Irrigation interval
K,v,w	Pump cost constants
K_1, K_2, K_3	Pipe cost constants
K_e	Emitter discharge coefficient
L_1	Length of bigger manifold
L_2	Length of smaller manifold
L_{fx}	Length of the field in x direction
L_{fy}	Length of the field in y direction
L_l	Length of lateral
LCH	location of control head
L_m	Length of manifold
L_{ma}	Length of main line
L_s	Length of submain line
L_{sx}	length of subunit in x direction
L_{sy}	length of subunit in y direction
MAD	Management allowed deficit
n	economic life of project
N_c	No.of connectors
N_e	No. Of emitters per tree
N_{ed}	No. of ends
N_{el}	No. of emitters per lateral
N_f	No. of fittings
NIR	Net irrigation requirement
N_l	No. of laterals per manifold
N_s	No. of submains
N_{sh}	Total number of shifts
N_{sis}	No. of sub-units irrigated at a time
N_{sp}	No. of subunit head regulator
N_{su}	No. of subunits
N_{sv}	No. of subunit valves
N_{sx}	No. of sub-unit in x direction
N_{sy}	No. of sub-unit in y direction
N_x	No. of division in x direction
N_y	No. of division in y direction
P_m	Power of motor
PWP	permanent wilting point
q	discharge
Q_a	Available discharge
q_a	Average emitter discharge
Q_d	Design system capacity
q_e	discharge of emitter
q_h	mean discharge due to hydraulic variation
Q_l	inlet discharge of lateral
Q_m	inlet discharge of manifold
q_m	minimum emitter discharge
Q_{ma}	inlet discharge of main pipe
$q_{min,h}$	minimum discharge due to hydraulic variation
Q_r	Required system capacity
Q_s	inlet discharge of submain
R_z	Effective root zone depth
S_e	Spacing of emission points
S_l	Spacing of lateral
T_a	application time per set
T_{av}	Available irrigation time per day
TL_l	Total Length of lateral
TL_m	Total Length of manifold
TL_{ma}	Total Length of main line
TL_s	Total Length of submain line
TN_e	Total No. of emitters
Toff	Days without irrigation
x	Emitter discharge exponent
Z	Total cost of the system

Table of Contents

CHAPTER - I

INTRODUCTION

A reliable and suitable supply of water availability for agriculture can result, vast improvements in agricultural production and assure economic returns to the grower. Effective agronomic practices coupled with proper soil and water conservation methods are pre- requisites for achieving sustainable irrigated agriculture. “Around 1950, irrigation around the world increased at an unprecedented rate. But by the 1960s, the increases couldn't keep up with increases in population. The growth of irrigation as total area per thousand people on the earth leveled off sharply beginning in about 1962 and has even begun declining in recent years” (www.livinghistoryfarm.org). Water management which optimizes the delivery of water to the farms, and on the farm itself, is the key to successful irrigation projects. However scarcity of water accompanied by the unscientific water management in major irrigation projects are becoming serious problems, rendering the supply of agricultural product incapable of coping with the demand of the rapidly growing population. In addition, the problem will be further aggravated due to the expected climatic change which will have pronounced negative impact on overall water quantity and quality, thereby making utilizable water, especially for conventional irrigation system, a diminishing resource. Indeed the very low water application efficiency 30 to 50% **INCID (1994)** of conventional irrigation system reduces the per unit production capacity of the available water leaving a potential area under-irrigated or totally un-irrigated. Parallel to this, large areas are being continually converted into the non-irrigable land class due to water logging and salinity as a result of poor water and chemical application by conventional irrigation system.

Sixty percent of the world's grain is produced using irrigation. So, if today's farmers are going be able to keep up with expanding demand for food and if the era of quickly expanding irrigation is over they are going to have to learn how to get "*more crop per drop*" (www.livinghistoryfarm.org).

Moreover, to assure sustainable irrigated agriculture, irrigation practices should be environmentally friendly, economically viable and lead to high irrigation performance. This requires systems to be designed and operated in such a way that water is applied at a rate, duration, and frequency that maximizes water and nutrient uptake by the crop, while minimizing the leaching of nutrients and chemicals out of the root zone, **Hanson et al. (2006)**. This is best met by adopting drip irrigation system which offers excellent control in the application of water. Drip irrigation system with typical 90% efficiency may result in about 50% water savings and 40% yield increase (www.docstoc.com). However, the biggest disadvantage of drip irrigation system is the high initial investment cost. Major savings may be made in this area through the **optimum design** of the system.

All the merits of drip irrigation system can be proved, and remain superior to compensate for the high capital cost, if and only if it is properly designed, managed, and maintained to achieve higher uniformity of water application. From field evaluation results, **Pitts et al. (1993)** concluded that poor design, management, and maintenance are the main reasons for low uniformity distribution of micro-irrigation. In their study, the average distribution uniformity of micro-irrigation system was 70%, with only a quarter of the observed above 85%, which is similar to those from sprinkler and furrow irrigation system. **Wu, (1997)**, commented that the hydraulic design of micro-irrigation systems to achieve high system uniformity has led design engineers to over-design irrigation systems arbitrarily. He emphasized that the commonly used emitter flow variation of 10-20% are equivalent to uniformity coefficient of 98-95%, or coefficient of variation of emitter flow of only 3-7%.

Hence, **modeling** and **optimization** of drip irrigation system to make a major saving in the capital cost while, at the same time achieving the desired level of distribution uniformity of water application is crucial.

The main aim of the study is to design cost effective drip irrigation system to optimize the use of water for better quantitative and qualitative agricultural produce, with a focus on the following specific objectives:

1. To develop an optimization model for the design and operation of drip irrigation systems.
2. To test the validity of the developed model.

CHAPTER - II

LITERATURE REVIEW

Design of drip irrigation systems is complex because it comprises the selection of emitters, pipes and respective layout, and decisions on pressure head and its variation along the system, as well as pressure and discharge regulators and filters **Keller** and **Bliesner (1990)**. Since the last two decades a variety of criteria and calculation procedures (using optimization and/or simulation methods) have been used to size the pipe system and limit pressure and discharge variations in the system with an aim to get target emission uniformity and economic objectives. This chapter provides a brief review of the relevant literature on optimum design of drip irrigation system.

2.1 Optimization Methods

In many engineering problems, there may be a number of possible solutions. It is important to evaluate each alternative solution for choosing the best from the interest point of view, i.e. economic or convenience. Optimization is the science of choosing the best amongst a number of possible alternatives. Understanding its effectiveness and relevance, many researchers have employed different optimization methods for the design of drip irrigation system. Thus, this section is devoted to review some of the relevant works already done.

Kang et al. (1996) employed finite element method combined with golden section search to develop a method for designing micro-irrigation lateral on non-uniform slopes, based on the required average emitter discharge and uniformity of water application.

Perez et al. (1993) used a dynamic programming to study the effect of pipe wall thickness instead of diameter. They explained that lower pressure implies thinner, and consequently, less expensive pipes. Hence, they proposed the use of pressure reducing valves to reduce the static pressure in the system to make saving in piping cost. Although, this method may reduce the system cost significantly, it is not applicable for the most irrigation systems except for those in hilly cases.

Lakhdar and **Dalila (2006)** presented computational model for the design and analysis of micro-irrigation lateral. Their work was based on equations of mass and energy conservation within an elemental control volume on the lateral.

Juana et al. (2004) suggested approximate analytical relationship for the design of rectangular drip irrigation unit. In their study, uniformity indices of water distribution in rectangular drip irrigation units was expressed as a function of lengths and diameters of laterals and submain, spacing of emitters and laterals, ground slopes, parameters of the emitter discharge equation, and equivalent lengths characterizing local losses. Result of this study shows, the proposed expressions which do not require iterative calculation, simplify studies of sensitivity of variables involved in optimum hydraulic design and offer greater precision than might be needed in irrigation practice. **Juana et al. (2005)** extended the work on the analytical relationship for the design of rectangular drip irrigation unit to trapezoidal drip irrigation unit.

Hassanli and **Dandy (1996)** employed Genetic Algorithms for the optimal layout and pipe size of a multiple subunit drip irrigation system which minimizes the sum of the capital cost plus the present value of annual operating cost. The enumeration approach was utilized for the optimum design of subunits for a maximum allowable pressure variation of 20% in the manifold and lateral.

Khemaies and **Moncef (2009)** derived a nonlinear differential equation for the design of trickle irrigation lateral laid on level ground. The solution of this equation yields the pressure head grade line implicitly in and integral form, from which analytical relation between the inlet discharge and pressure head at the inlet and at the distal ends of the non tapered lateral line was established.

Valiantzas (2002) suggested analytical continuous-uniform outflow approach that takes into account the effect of the number of outlets on the multi-diameter lateral hydraulics for hydraulic analysis and optimum design of multi-diameter irrigation laterals. This method, which provides simple equations for direct calculation of maximum, minimum and inlet pressure head along multi diameter pipe, minimizes the error due to the assumption of equal outflow, by introducing an adjusted spatially variable outflow equation.

Jain et al. (2002) developed a method for the design of single, paired and tapered micro-irrigation lateral using power function for lateral discharge to express the relationship between the inlet discharge and inlet pressure head of lateral. Aiming to keep the flow variation within the specified limit, a step by step lateral design method was developed with the golden section search method employed to determine the length of the tapered section of the lateral.

Oron (1982) noted the importance of selecting the most economic layout among the many alternatives to minimize the cost of an irrigation system. He examined the alternative layout of sprinkler irrigation and found 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 the difference in system cost occurs due to the changing in the percentage of different pipe length in each particular layout.

Monserrat (2009) proposed a method for allocating supply discharge to plots, which gives prior attention to the user's requirement. He presented a formula to calculate the optimum number and size of blocks (plots) which minimizes the cost of the system. In his study he considered only the effect of manifold, lateral, and valves.

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 times for various combinations of field dimensions on the system cost.

Saad and **Marino (2002)** developed a linear optimization model to design a micro- irrigation system with tapered, downhill manifold lines. In their model, they minimized the equivalent annual cost of the hydraulic network and the annual pumping cost, and maximizing the emission uniformity previously established to the subunit.

Holzapfel et al. (1990) developed a non-linear model for the design and management of drip irrigation system that maximizes the profit at the farm level. In their model the objective function consists of benefits from crop yield, which is a function of water application, and costs of implementation and operation of the drip system. Their model was applicable to flat areas. **Saad** and **Frizzone (1996)** extended the work of Holzapfel et al. (1990) to optimization of layout, design and management of drip irrigation system in both flat and sloping areas. These models require optimal level of resources other than water and reliable water production function of the crop, which are very difficult to exist in most situations.

Hassanli and **Dandy (1995)** presented a non linear model for the optimum design and operation of drip irrigation systems. They employed a complete enumeration approach, to minimize the sum of the capital cost of the system and present value of operating costs by dividing the field into subunits and evaluating various shift pattern and the corresponding pipe and pump sizes.

2.2 Simulation Methods

Simulation is the process of duplicating the behavior of an existing or proposed system. It consists of designing a model of the system and conducting experiments with this model either for better understanding of the functioning of the system or for evaluating various strategies for its management. In addition to their unique capability to deal with water resource systems, the existence of micro-computers to handle and manipulate huge data encourages scientists and practitioners to use simulation models. The following are some of the earlier studies on drip irrigation system which employed simulation method.

Pedras and **Pereira (2001)** developed computer simulation model that works with Windows operating system, for the design and performance analysis of micro-irrigation system. Their model provides user-friendly menu for entering, viewing and editing of emitter, pipe and other relevant data. The function of the design mode was to select emitter and pipes, from commercially available, to attain the target performance indicator of the system like emission uniformity.

Kang and **Nishiyama (1997)** presented micro-irrigation design model suitable for both subunits with uniform lateral lengths (in regular fields) and non-uniform lateral lengths (in irregular fields). The model requires input of required average emitter discharge, required emission uniformity, one lateral parameter (length or diameter) and one manifold parameter (length or diameter) to find optimal values of another lateral parameter, another manifold parameter, best manifold position and operating pressure by simulation using personal computer.

Pedras and **Pereira (2008)** developed a DSS MIRRIG for the design and evaluation of micro-irrigation system. They consider several alternatives using different emitter types, different pipe sizes and layouts with and without pressure regulators, as well as different pressure head and discharge at the upstream end of the system.

Most of the studies related to drip irrigation system design are problem specific. The study may be focused on subsystem design such as lateral, manifold, subunit, emitter or single situation oriented such as only for flat topography, uniform topography, limited emitter or pipe size. Moreover little attention is given to the effect of the combination of emitter size and number of emitters per tree. Though frequent and slow application of water are the prerequisite for achieving the merits of drip, many designs are with irrigation interval exceeding four days and irrigation shifts per day more than two. In addition, the computer models developed by many researchers may not be easy and/or convenient for direct use, or for understanding and modifying to suit the desired situation.

However, this study is intended to extend the previous works on optimization of drip system by considering:

- Identification of the possible combinations of emitter discharge and number of emitters per tree which satisfy the agronomic and time parameter constraints.
- Designs for both flat and uniform slope topography as well as control head located at the center of the field and at center of one of the edges of the field.
- Development of computer model which is suitable to many situations and can be easily modified and adopted.

CHAPTER - III

THEORETICAL CONSIDERATION AND MODEL DEVELOPMENENT

3.1 Drip Irrigation System

Drip irrigation is the *slow* and *frequent localized* (practically only to the plant's root area) application of water to soil drop by drop through mechanical devices called emitters or drippers located at selected points along the water delivery lines called laterals. It makes possible to apply water precisely *where* and *when* it is needed and to apply it with a higher degree of uniformity.

3.1.1 Advantages

Apart from saving of water several features standout indicating the superiority of the method such as:

1. ***Improved plant response***: Frequent irrigation ensures the soil moisture at an optimum level (near the field capacity). A well-designed and maintained drip system also results in high distribution uniformity. These features together with effective irrigation scheduling, can improve plant growth and yield.
2. ***Increased irrigation efficiency***: Drip system can improve irrigation efficiency by:
    - Reducing evaporation from the soil surface
    - Reducing or eliminating runoff.
    - Reducing deep percolation.
    - Eliminating the need to drastically over irrigate some parts of the field.
3. ***Improved chemical application***: Since irrigation is frequent, chemical application can be better timed, making it possible to closely match fertilizer delivery with plant nutritional needs. Moreover, because deep percolation and runoff are lessened or eliminated chemicals are less likely to be lost by moving past the root zone or washed away from the field with the water. Potential harm to the environment is therefore reduced.
4. ***Reduced weed growth***: the limited (localized) wetted area results in reduced weed growth
5. ***Reduced salinity hazard***: the very frequent irrigation attainable through drip irrigation system results in more diluted salts in the soil moisture solution and pushes (leaches) the salt to the sides of the wetted volume of the soil. Hence, water of higher salt content can be used with the system.

6. ***Adaptability to difficult soil and terrain conditions***: the slow rate of water application improves the penetration of water into problematic soils.

3.1.2 Disadvantages

1. **Maintenance requirement:** prone to clogging, and rodents, dogs and other animals in search of water can damage the lateral line.
2. **Cost:** for crops of very high population density the system, may be uneconomic because of the large number of laterals and emitters required.
3. **Restricted root zone**: While crops grown under drip systems have been shown to respond well, the drip system manager must remember that the system is meant to apply small frequent irrigations. So crops grown under drip system do not have large reserves of water stored in the soil and therefore, cannot endure long periods between irrigations.
4. **Salinity**: Another problem of drip irrigation system is the accumulation of salts in the interface between the irrigated and non-irrigated zones in the soil, whenever there is any appreciable salinity of the soil and /or of the irrigation water. Since the root zone itself is kept constantly at a higher moisture level, there is no direct harmful effect to the crop, but in the next growing these salts, if not leached away, may damage the crop if planted on top of that interface.

3.1.3 Components

Systems vary according to topography, size and shape of irrigated area, crop type and planting pattern, drip equipment, etc. however, a drip irrigation system will typically include most of the following elements, as shown in Fig. 3.1.

Pumping unit: The pumping station consists of power unit (internal combustion engine or electric motor) pump and appurtenances. In the design and selection of pumping equipment for a trickle irrigation system, high efficiency is the principal requirement.

Network of pipes: (Finkel, 1982) explained the different component of the drip irrigation pipe network as follows:

a. Main pipe: a rigid pipeline, conveying the water from the source to submains.

b. Submain pipe: a many-valved pipe, distributing the water to the various subunits within the unit. Each subunit, controlled by a valve on the submain, is an area irrigated simultaneously from a single control point. Its size is determined by considerations of field geometry and topography, water supply, irrigation demands, as well as by uniformity requirements within the subunit. The submain is generally a black polyethylene pipe, in most cases laid on top of the ground. The diameter can be anywhere between 32 and 90 mm, and pressure rating 4 atm.

c. Manifold pipe: a flexible or rigid pipe, generally of 20 to 75 mm diameter, distributing the water between the laterals that belong to a single subunit. The manifold and its laterals are designed and operated as a single unified system, which is controlled by a single valve. When possible, the manifold should supply laterals on both sides, but water supply characteristics as well as and topographical and geometrical considerations may limit the supply to laterals on one side only.

d. Lateral: as a rule is a flexible (soft) polyethylene or PVC pipe, laid on top of the ground, carrying the emitters. Its diameter will be generally between 12 to 25 mm, and its pressure rating 4 atm (unless the system is portable, when structural strength may dictate a 6 atm pipe).

System control head: for every drip irrigation subsystem which is operated according to a common irrigation regime, there must be a control head. This is a complex of instruments and controls, in charge of measurement and regulation, or control, of discharges and pressure, of water filtration, of fertilizer mixing. These components could be located at various points in the system, but it is convenient and efficient to concentrate them at a single, easily accessible point (Finkel, 1982).

a. Main valve: a simple valve, for starting and turning off of the system, or disconnecting it from water supply. Its size is 1 to 6inches. Head loss should not exceed 1m.

b. Volumetric valve (with or without a counter (water meter)), measures the volume passing through it and after a certain, preset quantity has passed, turns the water flow off (single operation) or transfers the flow to the next valve (series operation). This should be selected according to discharge range and to head loss (which should not exceed 2m). The size of the valve is specified by nominal diameter, from 1.5 to 6inches. Corresponding nominal discharges (with head loss of about 2m) vary from 5 to 200m^3/h.

c. Non-return valve and air valve: their main function is to prevent irrigation system water (and especially water containing fertilizers) from returning to the water supply system. Generally, these valves have negligible head loss.

d. Fertilizer tank: connected to the main pipe at two points, separated by a vacuum valve (or pressure reducing valve). The head loss should be of the order of 1 to 2m.

e. Vacuum (or pressure reducing) valve: creates the differential pressure necessary for the operation of fertilizer tank.

f. Filter: two main types of filters, the strainer and the gravel/sand filter (which should be followed by a filter of the strainer type). The size of the strainer type filter is specified in relation to the cross sectional area of the main pipe. It should be at least about 2 times larger and preferably much more. For most emitters a 160-mesh strainer (opening of 0.09 mm) or even a 120-mesh strainer (opening of 0.125 mm) is sufficient. Media filter, best suited to filter organic matter, consists of a vertical 1m high and 10 to 50 cm in diameter, filled with graded or small basaltic gravel. Vortex filter (or hydrocyclone), best suited to filter sand particles, works on the principle of centrifugal force. Head loss is high (4 to 5m). Both the media and vortex filters should be followed by strainer type.

g. Valve and discharge regulators for each subunit.

Emission devices: are those small dispensing devices used to control the discharge of water in drip irrigation systems. They reduce the line water pressure in to atmospheric pressure, providing water at a low, controlled discharge.

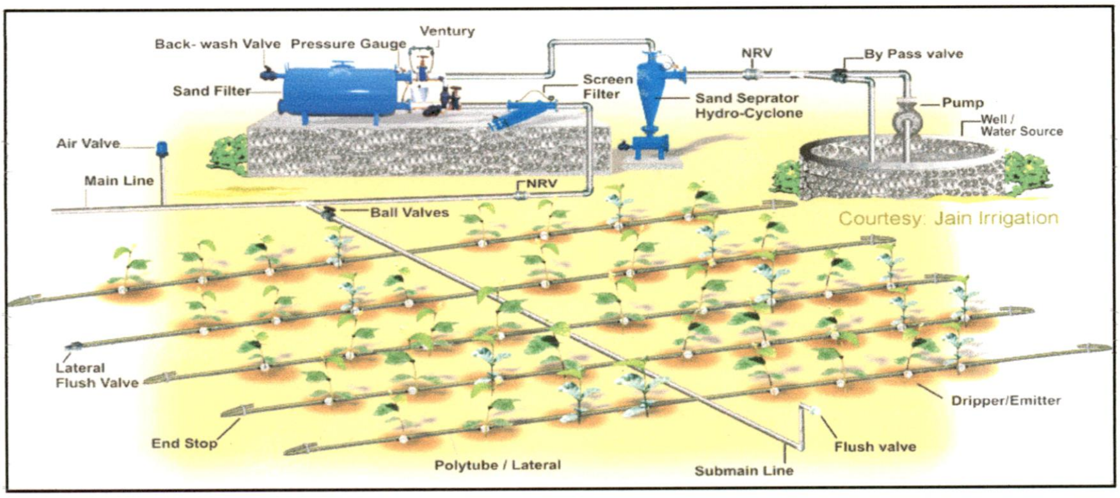

Fig. 3.1 Layout of drip irrigation system

3.1.4 Required Data for the design

The first step in the design of drip irrigation system is the compilation of basic farm data. The main data to be compiled for the design of drip irrigation systems can be summarized as follows.

1. **Topographical map of the field:** this should show the contour lines, selected elevations of the ground surface roads, fences, existing pipe lines, channel or ditch, water sources, farm and field boundaries.
2. **Water sources data**: - this includes availability of water for irrigation (quantity) and its quality, elevation of free water surfaces or available pressure, water rights, and its cost.
3. **Soil Data**: - an analysis of various layers in the soil profile provides information about the texture, structure, aeration, water table and drainage conditions, P^H, salt concentration, field capacity, wilting point and bulk density. These characteristics are useful in, evaluating the water requirements and irrigation intervals, and determining the need for drainage and leaching.
4. **Crop type information:** - Type of crops, growing season, sensitivity to salt and moisture, need for fertilizer application, root zone depth at the period of peak moisture demand and consumptive use.
5. **Miscellaneous data:-**
   - Manpower availability and cost
   - Equipment and cost; various makes of equipment and their costs should be considered. The final choice is made on the basis of dependability, labor requirements, suitability for the specific situation and the cost involved.
   - Additional data: - these include items such as the life span of the various elements of the equipment, interest, estimated costs for maintenance and repair, and energy costs.

3.2 Model Development

A model defined as a simplified representation of the real system is an important tool in system analysis, to describe the system and its components. The objective of the analysis during planning is to find the system design with best possible combination of elements to meet the desired objective. The use of models is often less expensive and convenient than conducting comprehensive surveys or other conventional approaches. As stated above the complexity of the drip irrigation system calls for use of model. This model shall be helpful in studying the effects of each design variable such as discharge of emitter, irrigation interval, diameter of pipes, number of shifts, area per shift, dimension of subunit etc. The main concept in drip irrigation system is to achieve the required distribution uniformity. This uniformity distribution depends on the pressure head variation in the system. Head loss due to friction in the system components is the main factor for pressure head variation. Many non linear relationships exist to estimate head loss due to friction, as a function of discharge, length, diameter, and material of the pipe. Therefore in this study, a non linear mathematical model is developed and is written in computer code so that computation time can be reduced. Another advantage of the computer model is also to facilitate the sensitivity analysis. The minimization process is done by selecting suitable diameter of each pipe for each possible configuration (which dictates the discharge and length). Suitable diameter in this context is the diameter which results in head loss due to friction less than the maximum allowable set by the required uniformity and minimum cost.

3.2.1 Layout of the System

In this study, depending on slope and location of control head, three configuration of the irrigation system are assumed.

1. Flat topography and control head at the center of field
2. Flat topography and control head at center of one of the edges of field.
3. Uniform slope topography and control head at the center of the upper edge of field.

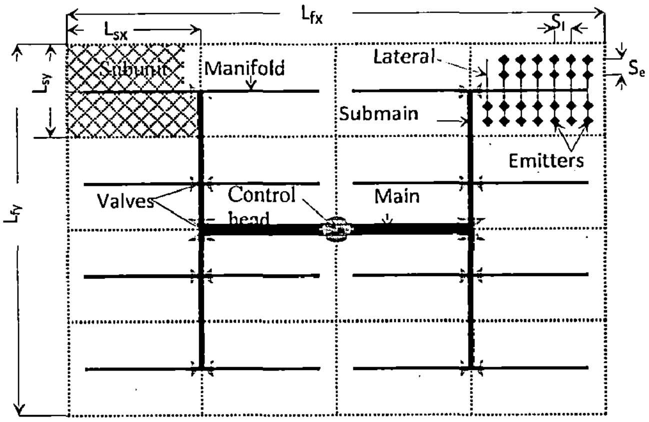

Fig. 3.2 Layout on flat topography and control head at center of the field

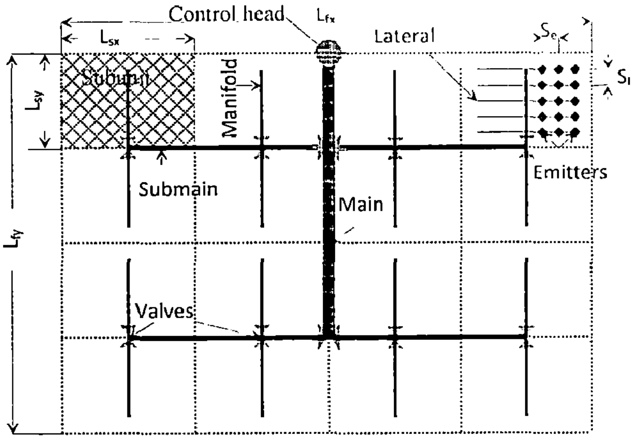

Fig. 3.3 Layout on flat topography and control head at center of one of the edges

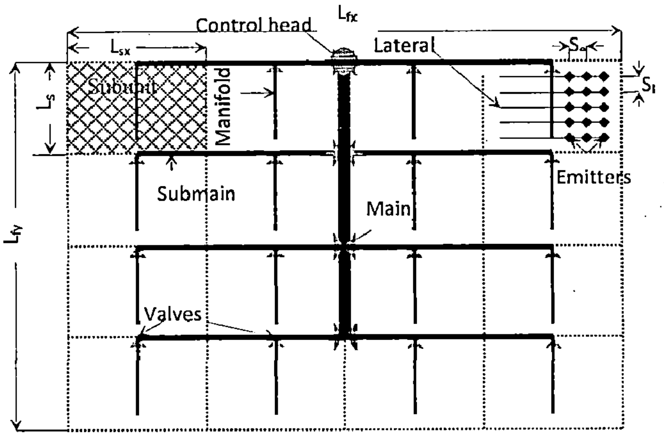

Fig. 3.4 Layout on uniform slope topography and control head at center of one of the edges

3.2.2 Discharge and Inlet Pressure of the Distribution Components

In pipe network, the discharge at a point is a function of the pressure head at that specific point. To design a pipe section with a target of achieving acceptable discharge variation along the pipe, determination of pressure head along the pipe, affected by friction loss and elevation difference is necessary. This section explains inlet pressure and discharge of the main distribution components necessary to produce the required pressure and discharge.

Discharge

Inlet lateral discharge (Q_l) is given by the product of the emitter discharge (q_e) and number of emitters per lateral (N_{el})

$$Q_l = q_e * N_{el} \tag{1}$$

Inlet manifold discharge (Q_m) is given by the product of lateral discharge and number of laterals per manifold (N_l)

$$Q_m = Q_l * N_l \tag{2}$$

Inlet submain discharge (Q_s) is the total discharge of subunits irrigated simultaneously under that submain. Hence, it depends on configuration of the system and pattern of irrigating the subunits

$$Q_s = \frac{N_{sis}}{N_s} * Q_m \tag{3}$$

Where,

Nsis = total number of subunits irrigated simultaneously

Ns = number of submain

Inlet discharge of the mainline (Q_{ma}) is the system capacity

$$Q_{ma} = N_s * Q_s \tag{4}$$

Where,

Q = discharge (lph)

Subscript e, l, m, s, and ma, stand for emitter, lateral, manifold, submain, and main respectively

Pressure

Inlet lateral pressure (H_l): a properly designed drip irrigation system should have an inlet lateral pressure capable of producing the emitters operating pressure after accounting for both friction loss (H_{fl}) and pressure change due to elevation along the lateral length (ΔE_l). It is given as (Keller and Bliesner 1990):

$$H_l = H_o + KH_{fl} + \Delta E_l \tag{5}$$

Inlet manifold pressure (H_m):

$$H_m = H_l + KH_{fm} + \Delta E_m \tag{6}$$

Inlet submain pressure (H_s):

$$H_s = H_m + H_{fs} + \Delta E_s \tag{7}$$

Inlet mainline pressure (H_{ma}):

$$H_{ma} = H_s + H_{fma} + \Delta E_{ma} \tag{8}$$

Where,

K = 0.75 for single diameter lateral or manifold

K = 0.65 for two diameter lateral or manifold

K = 0.50 for more than two diameter lateral or manifold

H = pressure head

H_f = friction head

ΔE = elevation difference

Subscripts l, m, s, and ma stand for lateral, manifold, submain and main respectively

The pressure head required at the pump (H_{pu}) is equal to the sum of the following (Cuenca, 1989)

- Pressure head required at the critical point in the field (H_i).
- Total friction head loss from the pump to the critical point (H_f).
- Elevation head from the water source to the critical point (ΔEi).

- Friction head loess in the suction side of the pump (hs).
- Velocity head at the critical point ($V_i^2/2g$).

$$H_{pu} = H_i + H_f + \Delta E_i + h_s + \frac{V_i^2}{2g} \tag{9}$$

3.2.3 Amount of different components of the system

The amount and size of different components of the drip system are determined by referring to the respective layouts (Fig.3.2 to 3.4). In all the layouts the position of the first emission point along the lateral and the first lateral along the manifold is assumed at half of the full spacing.

Number of subunits (N_{su}): dividing the field into subunits permits to irrigate part of the field at a time, achieve a more uniform emitter discharge, increase flexibility in irrigation practices, select smaller pipe and other component sizes throughout the field and use an increased number of emitters per plant during the growing stages of plants.

$$N_{su} = \frac{A}{L_{sx} * L_{sy}} \tag{10}$$

Where,

A = area of the field (m^2)

L_{sx} = length of the subunit in the X-direction (m)

L_{sy} = length of the subunit in the Y-direction (m)

3.2.3.1 Flat topography and control head at the centre of field

Length of single lateral (L_l) is given by:

$$L_l = 0.5(L_{sy} - S_e) \tag{11}$$

Where,

S_e = spacing between emission points along the lateral (m)

Number of lateral (N_l) is determined by:

$$N_l = 2\frac{L_{sx}}{S_l} \tag{12}$$

Where,

S_l = spacing between laterals (row of plants) (m)

Therefore, the total length of lateral (TL_l) in the field is determined as the product of length of a single lateral, number of laterals in a subunit and number of subunits in the field.

$$TL_l = \frac{A}{S_l}\left(1 - \frac{S_e}{L_{sy}}\right) \tag{13}$$

Length of manifold line (L_m) is given by:

$$L_m = L_{sx} - 0.5S_l \tag{14}$$

Number of manifold line is equal to the number of subunits

Total length of manifold line (TL_m) is calculated as length of manifold multiplied by the number of subunits.

$$TL_m = \frac{A}{L_{sy}}\left(1 - \frac{S_l}{2L_{sx}}\right) \tag{15}$$

Length of submain line (L_s) is given by:

$$L_s = 0.5(L_{fy} - L_{sy}) \tag{16}$$

Where

L_{fy} = length of field in the Y-direction (m)

Number of submain line (N_s) is determined as:

$$N_s = \frac{L_{fx}}{L_{sx}} \tag{17}$$

Where

L_{fx} = length of field in the X-direction (m)

Therefore, total length of sub-main line (TLs) is:

$$TL_s = \frac{A}{2\,L_{sx}}\left(1 - \frac{L_{sy}}{L_{fy}}\right) \tag{18}$$

Length of main line (L_{ma}) is:

$$TL_{ma} = L_{fx} - 2L_{sx} \tag{19}$$

3.2.3.2 Flat topography and control head at center of one of the edges of field.

Length of single lateral (L_l) is given by:

$$L_l = 0.5(L_{sx} - s_e) \tag{20}$$

Number of lateral (N_l) is determined by:

$$N_l = 2\frac{L_{sy}}{S_l} \tag{21}$$

Therefore, the total length of lateral (TLl) in the field is determined as the product of length of a single lateral, number of laterals in a subunit and number of subunits in the field.

$$TL_l = \frac{A}{S_l}\left(1 - \frac{S_e}{L_{sx}}\right) \tag{22}$$

Length of manifold line (L_m) is given by:

$$L_m = L_{sy} - 0.5s_l \tag{23}$$

Number of manifold line is equal to the number of subunits

Total length of manifold line (TL_m) is calculated as:

$$TL_m = \frac{A}{L_{sx}}\left(1 - \frac{S_l}{2L_{sy}}\right) \tag{24}$$

Length of submain line (L_s) is given by:

$$L_s = 0.5(L_{fx} - L_{sx}) \tag{25}$$

Number of submain line (N_s) is determined as:

$$N_s = \frac{L_{fy}}{L_{sy}} \tag{26}$$

Therefore, total length of submain line (TL_s) is:

$$TL_s = \frac{A}{2\,L_{sy}}\left(1 - \frac{L_{sx}}{L_{fx}}\right) \tag{27}$$

Length of main line (L_{ma}) is:

$$TL_{ma} = L_{fy} - L_{sy} \tag{28}$$

3.2.3.3 Uniform slope topography and control head at center of the upper edge of field.

Length of single lateral (L_l) is given by:

$$L_l = 0.5(L_{sx} - s_e) \tag{29}$$

Number of lateral in subunit (Nl) is determined by:

$$N_l = 2\frac{L_{sy}}{S_l} \tag{30}$$

Therefore the total length of lateral (TL_l) in the field is determined as the product of length of a single lateral, number of laterals in a subunit and number of subunits in the field.

$$TL_l = \frac{A}{S_l}\left(1 - \frac{S_e}{L_{sx}}\right) \tag{31}$$

Length of manifold line (Lm) is given by:

$$L_m = L_{sy} - 0.5s_l \tag{32}$$

Number of manifold line is equal to the number of subunits

Total length of manifold line (TL_m) is calculated as:

$$TL_m = \frac{A}{L_{sx}}\left(1 - \frac{S_l}{2L_{sy}}\right) \tag{33}$$

Length of submain line (Lsm) is given by:

$$L_s = 0.5(L_{fx} - L_{sx}) \tag{34}$$

Number of submain line (N_s) is determined as:

$$N_s = 2\frac{L_{fy}}{L_{sy}} \tag{35}$$

Therefore, total length of submain line (TL_s) is:

$$TL_s = \frac{A}{L_{sy}}\left(1 - \frac{L_{sx}}{L_{fx}}\right) \tag{36}$$

Length of main line (L_{ma}) is:

$$TL_{ma} = L_{fy} - L_{sy} \tag{37}$$

Valves and accessories (such as fittings, ends) are essential and complementary components of drip irrigation system. These components share large portion of the capital cost, hence for accurate estimation of the total capital cost, determination of their quantity is very necessary. In all the three cases the quantity of valves, fittings, connectors and ends are determined as follows,

Number of fittings is a function of the total length and the standard length of the pipe. Generally, pipes used for manifold and lateral line are manufactured in lengths providing the option to use single line for the whole length without the use of fitting. However, pipes used for main and submain pipes need fittings as they are manufactured, usually, in shorter length than is required in the field. Number of subunit valves and pressure regulators are each equal to the number of subunits in the system. Number of end plugs and connectors for each pipe type is equivalent to the number of the respective pipe types.

3.2.4 Objective Function

The planning and design of irrigation systems should aim at maximizing the returns and minimizing both the initial capital outlay and the costs per unit volume of water used, thus contributing both directly and indirectly to the overall reduction of the production costs and the increase of returns (FAO, 2001). Therefore, the drip irrigation system model introduced in this study minimizes an objective function given by the sum of capital cost and the operating cost. The total cost of the drip irrigation system equals the cost of pipes, pump, emitters, control head, accessories and the operating cost. It is expressed as:

$$Z = C_p + C_e + C_{pu} + C_{ch} + C_a + C_o \qquad (38)$$

Where,

Z = total cost of the system
C_p = cost of pipes
C_e = cost of emitters
C_{pu} = cost of pump
C_{ch} = cost of control head
C_a = cost of accessories
C_o = operating cost

3.2.4.1. Cost of pipes

The pipe network includes mainline, submain, manifold and lateral, hence the cost of pipes can be expressed as:

$$C_p = C_{ma} + C_s + C_m + C_l \qquad (39)$$

Where,

C_{ma} = cost of mainlines
C_s = cost of submain lines
C_m = cost of manifolds
C_l = cost of laterals

The cost per unit length of pipe is expressed by the nonlinear function of pipe diameter (Oron and Karmeli, 1979).

$$C_i = K_1 D_i^2 + K_2 D_i + K_3 \qquad (40)$$

Where,

Ci = cost per unit length of pipe i

Di = diameter of pipe i (mm)

K_1, K_2 and K_3 are coefficients

To determine the total cost of the pipes, the unit cost is multiplied by the total length of each type of pipe. Hence

Total cost of laterals (C_l):

$$C_l = (K_1 D_l^2 + K_2 D_l + K_3) TL_l \tag{41}$$

Total cost of manifold (C_m):

$$C_m = (K_1 D_m^2 + K_2 D_m + K_3) TL_m \tag{42}$$

Total cost of submain (C_s):

$$C_s = (K_1 D_s^2 + K_2 D_s + K_3) TL_s \tag{43}$$

Total cost of main line (C_{ma}):

$$C_{ma} = (K_1 D_{ma}^2 + K_2 D_{ma} + K_3) TL_{ma} \tag{44}$$

3.2.4.2 Cost of emitters

The cost of emitters is determined by multiplying the total number of emitters by the unit cost of emitter.

Total number of emitters (TN_e) is given by, the product of number of emitters per plant, number of emitters per lateral, number of laterals per subunit and number of subunits in the field, and is expressed as:

$$TN_e = N_e \frac{L_{sx} \, L_{sy}}{S_e \, S_l} N_{su} \tag{45}$$

Hence the cost of emitters is given by:

$$C_e = TN_e * C_{pe} \tag{46}$$

Where,

C_{pe} = cost per emitter

3.2.4.3 Cost of pumping unit

In pressurized irrigation system pump is used to develop the pressure head required:

- To provide the operating pressure of the emission devices.

- To overcome the head loss due to elevation difference between the water source and the highest point in the system.
- To compensate the head loss due friction in the pipe networks.

The cost of the pumping system is a function of its power and discharge (Holzapfel et al., 1990) as follows:

$$C_{pu} = KQ_d^v H_{pu}^w \qquad (47)$$

Where,

C_{pu} = cost of the pumping unit

Q_d = system capacity (m^3/s)

H_{pu} = total pressure head of the system (m)

K, v, and w are constants

3.2.4.4 Control head

The control head as explained previously consists of valves, fertilizer equipments and filters. In this study the following control head components are considered:

- one main valve and one volumetric valve , equal size to the main pipe diameter
- complete set of fertilizer tank and
- one strainer type and one media filter are considered.

The number of subunit valves and pressure regulators are determined as discussed previously. Hence, the total cost of control head is the summation of all the aforementioned components and is expressed as:

$$C_{ch} = C_{mv} + C_{vv} + C_{ft} + C_{sf} + C_{mf} + C_{sv} * N_{sv} + C_{sp} * N_{sp} \qquad (48)$$

Where,

C_{mv} = cost of main valve

C_{vv} = cost of volumetric valve

C_{ft} = cost of filter tank and its accessories

C_{sf} = cost of strainer type filter

C_{mf} = cost of media type filter

C_{sv} = unit cost of subunit valve

N_{sv} = number of subunit valves

C_{sp} = unit cost of subunit pressure regulators

N_{sp} = number of subunit pressure regulators

3.2.4.5 Accessories

The cost of accessories includes the cost of total fittings, connectors and ends used in the system. It can be expressed as follows.

$$C_a = C_{fi} + C_{co} + C_{ed} \tag{49}$$

Where

C_a = total cost of accessories

C_{fi} = total cost of fittings

C_{co} = total cost of connectors

C_{ed} = total cost of ends

Each pipe type (main submain manifold and lateral) in the system requires different size of accessories which results in different per unit cost of the same type of accessories. Therefore the total cost of each type is the aggregate sum of the cost of accessories for main, submain, manifold and lateral. Hence;

$$C_{fi} = (C_f)_{ma} * (N_f)_{ma} + (C_f)_s * (N_f)_s + (C_f)_m * (N_f)_m + (C_f)_l * (N_f)_l \tag{50}$$

$$C_{co} = (C_c)_{ma} * (N_c)_{ma} + (C_c)_s * (N_c)_s + (C_c)_m * (N_c)_m + (C_c)_l * (N_c)_l \tag{51}$$

$$C_{ed} = (C_{ed})_{ma} * (N_{ed})_{ma} + (C_{ed})_s * (N_{ed})_s + (C_{ed})_m * (N_{ed})_m + (C_{ed})_l * (N_{ed})_l \tag{52}$$

Where,

C is unit cost and N is number, with the subscript f, c, ed, ma, s, m, and l stand for fittings, connectors, ends, main, submain, manifold and lateral respectively

3.2.4.4 Annual operating cost

In drip irrigation system the cost of operation, which is primarily dominated by the cost of energy required to pump the water, is very significant. The annual operating cost is a function of the annual energy consumption and this in turn depends on the annual irrigation requirement and the power of the pump. For a given layout, one way of reducing the operating cost is to design the system such that the head loss in the pipe network and the operating pressure of emission device is as minimum possible. Therefore efficient operation schedule (selecting optimal time parameters) and proper selection of pipe network components (to minimize pressure requirement) can reduce the operating cost significantly. The power of the motor is expressed (Keller and Bliesner, 1990) as:

$$P_m = 2.78 \times 10^{-7} \frac{\gamma Q_d H_{pu}}{E_p E_m} \tag{53}$$

Where,

P_m = power of motor (kw)

γ = unit weight of water (kN)

E_p =pump efficiency (decimal)

E_m = motor efficiency (decimal)

The annual energy requirement (A_{er}) may be obtained using the annual irrigation requirement, power of the motor and the annual hours over which the pump is in operation as follows:

$$A_{er} = P_m \frac{A_{NIR} * A}{A_e Q_d} \tag{54}$$

Where,

A_{er} = annual energy requirement (kwh)

A_{NIR} = annual net irrigation requirement (mm)

Annual operating cost during the expected life of the irrigation system is converted to present value using the series present worth discount factor as follows:

$$C_o = A_{er} * C_{en} \frac{[(1+i)^n - 1]}{i(1+i)^n} \tag{55}$$

Where,

C_o = annual operating cost

C_{en} = cost per unit energy

i = discounting rate (decimal)

n = expected life of the project (year)

3.2.5 Agronomic and management constraints

The design of drip irrigation system can be divided in to two phases, preliminary design steps subject to the agronomic and management considerations and final design steps subject to the hydraulic and economic consideration of system components. Depending on the agronomic and management constraints of the system, farm data are synthesized in order to determine preliminary design parameters. The preliminary design parameters that need to be established are; irrigation requirements, irrigation interval, application time application rate, discharge required per plant and system capacity.

3.2.5.1 Irrigation requirements

Net irrigation requirement (NIR): is the quantity of water which should be applied during irrigation in order to replenish the water used by the crop during evapotranspiration. This depth of water to be stored in the soil from each irrigation event is estimated based on the equation suggested by (Karmeli et al., 1985)

$$\mathrm{NIR} = 10 * (\mathrm{FC} - \mathrm{PWP}) * \mathrm{Bd} * \mathrm{R_z} * \mathrm{MAD} * \mathrm{A_w} \tag{56}$$

Where,

NIR = net irrigation requirement (mm)

FC = percentage moisture content at field capacity on weight basis

PWP =percentage moisture content at permanent wilting point on weight basis

Bd = bulk (apparent) density of the soil

R_z = effective root zone depth (m)

MAD = management allowed deficit (decimal)

A_w = wetted portion of the area (decimal)

Soil survey and tests should be done to determine the field capacity and permanent wilting point of the soil. Management allowed deficit (MAD) should be established depending on the crop sensitivity to stress.

Depth of water to be applied in each irrigation event, which is called the gross irrigation requirement (GIR), is determined as:

$$\mathrm{GIR} = \frac{\mathrm{NIR}}{\mathrm{A_e}} \tag{57}$$

Where,

GIR = gross irrigation requirement (mm)

A_e = farm application efficiency (decimal)

Application of required water that can be stored in the soil is also affected by other parameters such as the, the soil infiltration rate, Size of emitters, and Available time for irrigation.

3.2.5.2 Irrigation frequency and irrigation interval

Irrigation frequency is the time it takes the crop to deplete the soil moisture to a given soil moisture level. After establishing the net irrigation requirement for each application, the irrigation frequency at a peak water use rate can be determined as:

$$I_f = \frac{NIR}{ET_c} \tag{58}$$

Where,

I_f = irrigation frequency (day)

ET_C = peak water use of the crop (mm/day)

For practical reasons, irrigation frequency should be rounded to a natural number of days (Karmeli et al., 1985) and recalculating the net and gross irrigation requirement is necessary as follows:

$$NIR = I_f * ET_c \tag{59}$$

The matter arises as to whether the irrigation system should apply the net irrigation requirement in **I_f, I_f-1, I_f-2...** right down to **1** day. If irrigation is to be completed in 1 day, the system become idle for the remaining **I_f-1** days, and the cost of the system would be exorbitant, since larger sizes of irrigation component would be required. On the other hand, for all practical purposes and in order to accommodate the time for cultural practices, it is advisable that irrigation is completed in less than the irrigation frequency. The days required to complete one irrigation in the area under consideration is called the irrigation interval. It is related with irrigation frequency as:

$$I_n = I_f - T_{off} \tag{60}$$

Where,

I_n = irrigation interval (day)

T_{off} = number of day without irrigation in one interval

3.2.5.3 Required system capacity

It is the minimum discharge necessary in order to irrigate the system at a gross irrigation requirement of (GIR) mm per irrigation, with an irrigation interval of I_c days and available time for irrigation of T_{av} hours per day. This minimum value corresponds to a utilization of the whole interval I_n for irrigation. It is given by

$$Q_r = \frac{A * GIR}{T_{av} * I_c} \tag{61}$$

Where,

Q_r = required system capacity (lph)

T_{av} = available time for irrigation per day (h)

The value of available time (T_{av}) is limited on one hand by the number of hours per day and on the other by the ratio of the total water requirement to the system capacity (Finkel, 1982). That is

$$\frac{A * GIR}{Q_r} \leq T_{av} \leq 24 \tag{62}$$

The maximum number of hours of operation per day should not exceed 90% of the available time (i.e., 21.6 h/day). This is necessary to allow some margin of safety for system failure or other unexpected downtime. However, systems should be operated as nearly continuously as is practical, at least 12 h/day to keep investment cost low (Keller and Bliesner, 1990).

3.2.5.4 Discharge per Plant

The emitter discharge is constrained by the requirements that it should supply the necessary amount of water in a specified time, and that it will not exceed its available water supply.

$$\frac{S_e * S_l * GIR}{T_{av}} \leq N_e * q_e \leq \frac{Q_r * S_e * S_l}{A_{sh}} \tag{63}$$

Apart from this, there is an upper limit to emitter discharge caused by the danger of runoff and erosion, especially on steep slopes. This limit should be determined experimentally for each field or soil type (Finkel, 1982).

3.2.5.5 Application rate and Application time

The application rate (also called specific discharge of an emitter) is a function of the emitter discharge, number of emitters and the area served by emitter or group of emitters. It can be expressed as:

$$I_a = \frac{q_e * N_e}{S_e * S_l} \tag{64}$$

Where,

I_a = application rate (mm/h)

q_e = emitter discharge (lph)

N_e = number of emitters per tree

$S_l * S_e$ = area per tree (m^2)

Application time (also known as irrigation duration) is the length of time needed to apply the gross irrigation requirement, by means of a given system, it is calculated as:

$$T_a = \frac{GIR}{I_a} \qquad (65)$$

Where,

T_a = application time (h)

The application time must not exceed the total available time for irrigation per day, so that the whole area may be irrigated ones before the next irrigation is due. In most cases it is much smaller than that and irrigation is done in shifts. Each shift is a unit irrigation operation, where an area of A_{sh} is irrigated at one time. This area may consist of one or more subunits. The value of A_{sh} will depend mainly on available water and time, so that there is enough discharge for the shift, and that all shifts may be irrigated during the cycle. In this case the number of shifts will be

$$N_{sh} = \frac{A}{A_{sh}} \qquad (66)$$

Where,

N_{sh} = total number of shifts

A_{sh} = area irrigated per shift (m^2)

This number is constrained by the available discharge or required system capacity, whichever is minimum and available time for irrigation.

$$\frac{I_a * A}{Q_r} \leq N_{sh} \leq \frac{T_{av} * I_c}{T_a} \qquad (67)$$

3.2.5.6 Designed System capacity

The capacity of the system is the continuous flow rate required to irrigate the specified area within the selected operating schedule. It may be estimated as a function of the area per shift and application rate

$$Q_d = A_{sh} * I_a \qquad (68)$$

Where,

Q_d = designed discharge capacity of the system (lph)

The designed system capacity (Q_d) should be less than or equal to the available flow rate (Q_a)

$$Q_d \leq Q_a \tag{69}$$

If not, one or a combination of the following may be considered (Karmeli et al., 1985):

- Reduction in total irrigated area
- Reduction in number of days without irrigation
- Increase in the irrigation time to maximum 24 hours

3.2.5.7 Wetted portion of area

The value of wetted portion of area is determined generally experimentally, or is estimated, depending on many considerations. On one hand it should be reduced as much as possible, thus saving water which would not have reached the roots of the crop at all, facilitating the passage and operation of agricultural machineries and equipments, and reducing the irrigation network component size. On the other hand low values reduce the utilization of soil moisture storage capacity, make the crop more vulnerable to emergencies such as drought and water supply failure, limit root development, reduce tree anchorage against strong winds etc. In arid area wetted portion of area should not be less than 1/3 when rainfall is plenty and irrigation is mostly supplementary, it can be reduced to 1/5, on the other hand values of wetted portion of area more than 50% are generally wasteful (Finkel, 1982).

3.2.6 Hydraulic Design

The hydraulic design of drip systems is essentially centered on ensuring that water is conveyed to each emitter at a pre-determined pressure head that would cause satisfactory flow. To ensure the desired discharge uniformity from each emitter in the system, the pressure head at each emitter should be kept at equivalent level of uniformity. The change in pressure head is due to pipe friction and elevation difference, hence for a given layout the pipe friction loss is manipulated to keep the pressure head difference in the acceptable range. This is done by selecting suitable pipe diameter from the commercially available pipes while at the same time minimizing the cost of the pipes.

Generally plastic pipes are convenient for drip irrigation system. Plastic pipes are very smooth, with a uniform inside diameter and produces turbulent flow of water which leads to the use of Darcy-Weisbach formula combined with Blasius' empirical formula to estimate the friction loss (Finkel, 1982). The combined formula is given below

$$H_f = 46.54 \times 10^{-2}\ L\ \frac{Q^{1.75}}{D^{4.75}} \tag{70}$$

Where,

H_f = friction loss (m)

L = length of pipe (m)

Q = discharge through the pipe (lph)

D = inside diameter of the pipe (mm)

The inside diameter of the pipe is related to the nominal diameter (outside diameter) as follows **Finkel, (1982)**,

$$D = D_n - 2t \tag{71}$$

Where

Dn = nominal diameter of the pipe (mm)

t = wall thickness of the pipe (mm)

the wall thickness depends on the grade, in grade 4 it is approximately equal to $(\frac{1}{15}D_n + 0.55)$ and in grade 6 it is approximately equal to $(\frac{1}{8}D_n)$.

3.2.6.1 Subunit Network Design

A subunit is a system consists, generally, of a control valve, a manifold pipe and laterals with emitters and irrigates a portion or whole (if the field is small) field. The number and size of subunit are determined by the time parameters of the system, the irrigation interval, duration of irrigation and the number of shifts per day. They are also dependent on the total area to be irrigated and the peak daily water use. The design of subunit system is to keep the operating pressure within a range that results the target emission uniformity.

Design emission uniformity:

Emission Uniformity (EU) is a uniformity distribution which is defined to show the variation by the ratio of minimum to the mean. For drip irrigation, it is expressed as the ratio of the minimum emitter flow rate to the mean flow rate within subunit or system (Keller and Karmeli, 1974)

Emission uniformity expresses the emitter flow variation of a drip irrigation system affected by hydraulic variation, manufacturer's variation, emitter grouping and plugging.

The emitter flow variation caused by hydraulic design of a drip irrigation system is determined by friction loss in the system and energy changes due to field slopes. Both the minimum and average emitter flow can be determined by the minimum and average water pressure in the system based on hydraulic design (Barragan and Wu, 2005). The emission uniformity caused by hydraulic variation in a drip irrigation system is given by:

$$EU_h = \frac{q_{min,h}}{\bar{q}_h} \tag{72}$$

Where,

EU_h = emission uniformity due to hydraulic variation

$q_{min,h}$ = minimum discharge due to hydraulic variation

q_h = mean discharge due to hydraulic variation

The manufacturer's variation is determined by sampling and testing the emitters under a given constant water pressure. Since the minimum flow rate may not be determined in the samples collected, the average flow rate of the lowest one-fourth of the emitter flow readings is used.

Considering emitters are taken by random samples and a normal distribution can be assumed for manufacturer's variation, the emission uniformity caused by manufacturer's variation can be expressed as (Barragan et al., 2005)

$$EU_{cv} = 1 - \frac{1.27\ CV}{\sqrt{n}} \tag{73}$$

The coefficient value of 1.27 specifies the location of the low quarter mean of samples on a normal distribution.

In the design phase, it is not possible to measure the rates of emission of the intended system. The variation to be expected in emission rates must be estimated by some analytical procedures. Unfortunately, it is not practical to consider all the influencing factors in a formula for emission uniformity. An emission uniformity formula taking both hydraulic variation and manufacturer's variation into consideration proposed by Keller and Karmeli (1974) for drip irrigation system design is expressed as:

$$EU = \left(1 - \frac{1.27\ CV}{\sqrt{n}}\right) \frac{q_m}{q_a} \tag{74}$$

Where,

EU = design emission uniformity, percent.

n = number of emitters per plant

CV = manufacturer's coefficient of variation.

q_m = minimum emitter discharge computed with the minimum pressure using the nominal relationship between emitter discharge and pressure head

q_a, = average emitter discharge (of all the emitters under consideration)

Since the emitter flow is directly affected by the pressure at the emitter, the pressure variation is an indication of uniformity in drip irrigation system and can be used as design criteria for hydraulic design (Barraga and Wu, 2005). The total friction pressure head loss for a subunit is contributed by the friction pressure head loss for lateral and the friction pressure head loss for manifold

A drip irrigation system is a low energy system, so slope effect cannot be neglected. A general equation proposed by (Keller and Bliesner, 1990) for drip irrigation system design of a rectangular subunit with a single size for both the lateral and the manifold and a single size lateral and multiple sizes for manifold (Barragan and Wu, 2005) is shown below.

$$\Delta H_{max} = 2.5(H_o - H_{min}) \tag{75}$$

Where,

ΔH_{max} = maximum allowable pressure difference with in subunit

H_o = operating (average) pressure of the emitters

H_{min} = minimum pressure head.

Estimation of minimum pressure head

Usually emitter flow rates are best characterised by empirically determining flow rates as a function of operating pressure (Jensen, 1980)

$$q = K_e H^x \tag{76}$$

Where,

K_e = consists of orifice area, the flow coefficient and units transformation (so that q and H may take the technical units lph and m respectively)

x = empirical exponent which characterise the flow regime

From equations 74 and 76 the minimum pressure head in a subunit can be calculated as,

$$H_{min} = H_o \left[\frac{EU}{1 - \frac{1.27CV}{\sqrt{n}}} \right]^{1/x} \tag{77}$$

Lateral and manifold design

The lateral and manifold lines are designed as a function of emission uniformity (EU). The design process is to find the length and diameter of the respective pipe while keeping the summation of head loss both due to friction and elevation along the pipe within the maximum subunit allowable pressure variation. In this study, a predefined pipe network configuration is considered as shown in Fig. 3.2 to 3.4. Therefore, the design problem in case of single diameter pipe is reduced only to find the pipe diameter for the given layout. More specifically the aim is to select a pipe diameter form the commercially available pipe sizes and compare the summation of friction head loss calculated using equation 70 and elevation head difference with the allocated maximum allowable pressure variation of the pipe section. If more than one pipe sizes are suitable, then the pipe size which utilizes as nearly but not exceed as possible to the allowable head loss is selected. In case of tapered pipe the design is to find the lengths and diameters of the two consecutive pipe sizes, in which the pipe with larger diameter results in a too little pressure difference while the pipe with smaller diameter results in too high pressure variation as compared to the allocated maximum allowable pressure variation along the pipe. The length of the smaller size pipe section is determined as follows (Keller and Bliesner, 1990).

$$L_1 = L \left[\frac{h_{fa} - h_{f2}}{h_{f1} - h_{f2}} \right]^{1/m+1} \tag{78}$$

Where,

L_1 = length of the smaller pipe section (m)

L = total length of the pipe as determined from the given layout (m)

h_{fa} = maximum allowable pressure variation allocated to the pipe (m)

h_{f1} = friction loss calculated assuming the total length has diameter equal to smaller of the two sizes considered (m)

h_{f2} = friction loss calculated assuming the total length has diameter equal to the larger of the two sizes considered (m)

Equation 70 shows pressure head loss is proportional to volumetric flow rate. The hydraulic analysis of pressure head loss in a lateral and/or manifold (lines with multiple outlets) is more complex because it must account for the fact that water is removed at each emission point (in case of laterals) and at each lateral (in case of manifold) leading to a decreasing volumetric flow rate along the length of the line. To account for the decrease in flow along the line the pressure head loss calculated by equation 70 is multiplied by a factor called Christiansen friction factor (F). It is given by the following equation

When the first outlet is at full spacing from the supply line

$$F = \frac{1}{m+1} + \frac{1}{2N} + \frac{(m-1)^{0.5}}{6N^2} \tag{79}$$

When the first outlet is at half spacing from the supply line

$$F = \frac{2N}{2N-1}\left(\frac{1}{m+1} + \frac{(m-1)^{0.5}}{6N^2}\right) \tag{80}$$

Where,

N = number of outlets along the line

m = exponent on velocity related terms in friction head loss formula

3.2.6.2. Selection of main and submain sizes

The diameter of the main pipelines and submain are selected on the economic basis provided that the flow velocities are maintained between the required limits usually (0.2 and 2m/s). The main and submain lines carry water from the control head to the manifold or directly to the lateral lines. The basic system subunit includes the manifold with attached laterals. Pressure control or adjustment points are provided at the inlets to the manifold. Because of these pressure-control-point locations, pipe size selection for the main and submain lines is not affected by the pressure variation allowed for the subunit. Therefore, the pipe size should be selected primarily on the basis of economic trade-off between power costs and pipe installation costs.

CHAPTER - IV

RESULTS AND DISCUSSION

The aim of this study as explained previously is to develop a computer model for the design of drip irrigation system. The model analyses the design process by considering different

- combinations of the commonly available sizes of point source emitter and number of emitters per tree such that the required volume of water can be delivered within the available time for irrigation and...
- subunit size and number, where the total field is divided into a number of subunits which are multiples of the number of submains.

This chapter is to discuss the effect of emitter discharge and subunit size and dimension for the configurations of the system as explained in section 3.2.1

4.1 Model Description

4.1.1 Model inputs

After compiling the necessary farm data as explained in section 3.1.4, the following data with appropriate units should be identified and set as input for the developed model.

- Area of the field to be irrigated and its dimensions in the X and Y direction.
- Slope and water source location.
- Daily peak water us of the crop.
- Effective root zone depth at full maturity
- Moisture content of the soil at field capacity and permanent wilting point.
- Bulk density of the soil.
- Management allowed deficit.
- The emitter type and characteristics (Ke, x and CV).
- The plant spacing in both directions.
- Available time per day for irrigation and number of days without irrigation per irrigation cycle.
- Application efficiency and emission uniformity.
- A list of available diameters and pipe cost constants.

- Efficiency of pump, motor and pump cost constants.
- The head loss through filters, fertilizer units, valves and meters.
- Cost of all components

4.1.2 Assumption of the model

The model is based on the following assumptions:

- The field is rectangular with pre defined configuration as shown in Figs. 3.2 to 3.4.
- The field is flat or of uniform slope in both directions. Though, it is not a must in drip irrigation system, land leveling and grading for the purpose of efficient farm equipment operation is done.
- At least one subunit valve must be open on each submain per shift. This ensures that there is no submain left idle during any operation.
- Total numbers of subunits are equal to or a multiple of the number of subunits per shift. This ensures that the system load remains the same for each operation.
- Number and configuration of subunits working simultaneously under each submain are same. This ensures a balanced system load during each operation.

4.1.3 Main Program of the Model

To solve the model using complete enumeration method, computer code in C++ is written as shown in Appendix A and the main program is explained as follows.

Step 1: The irrigation requirements and irrigation interval are calculated from the soil, crop and climate data.

Step 2: The model calculates application time, and application rate for each combination of the commonly available size of point source emitters and number of emitters per tree. The combinations resulting, values of application time and application rate within the recommended range are considered as potential candidate for farther designing process.

Step 3: For each set of discharge per emitter, emitter per tree, application rate and application time calculated in **step 2**, the program then calculates all the design parameters for all suitable sizes of subunits, using their respective function/s developed in the program. The conceptual flow chart of the main program is presented in Fig.4.1.

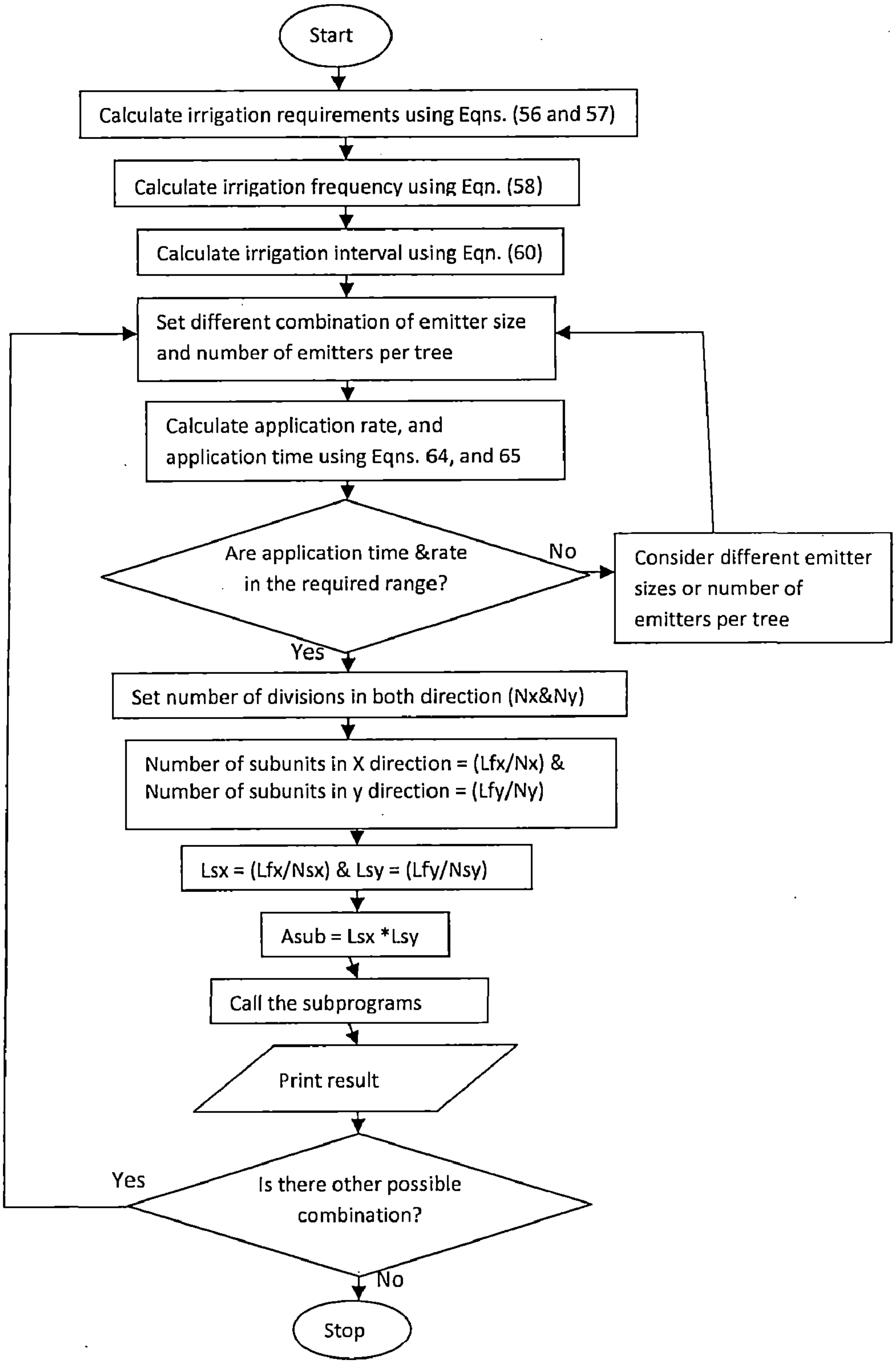

Fig. 4.1 Conceptual flowchart of the main program for design of drip irrigation system

4.1.4 Subprogram for subunit design

In designing subunit network, manifold and lateral are selected from commercially available pipe diameters which result; the total head variation within the allowable value. For most economic design the allowable subunit variation should be allocated 55 percent to lateral and 45 percent to manifold **Keller** and **Karmeli, (1974)**. The step by step design of lateral and manifold are explained using flow chart as shown in Fig.4.2 and Fig.4.3 respectively.

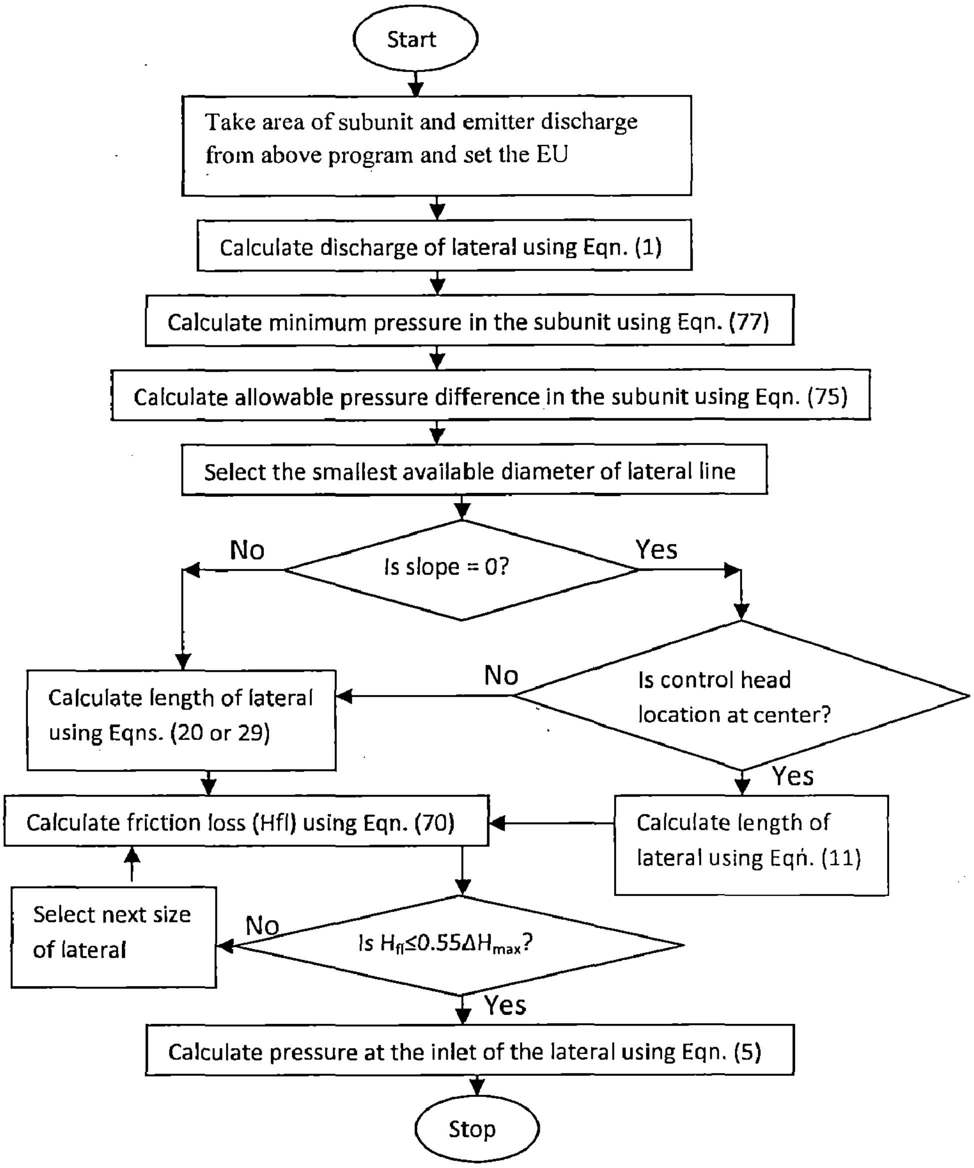

Fig. 4.2 Flowchart for subprogram of lateral line design of drip irrigation system

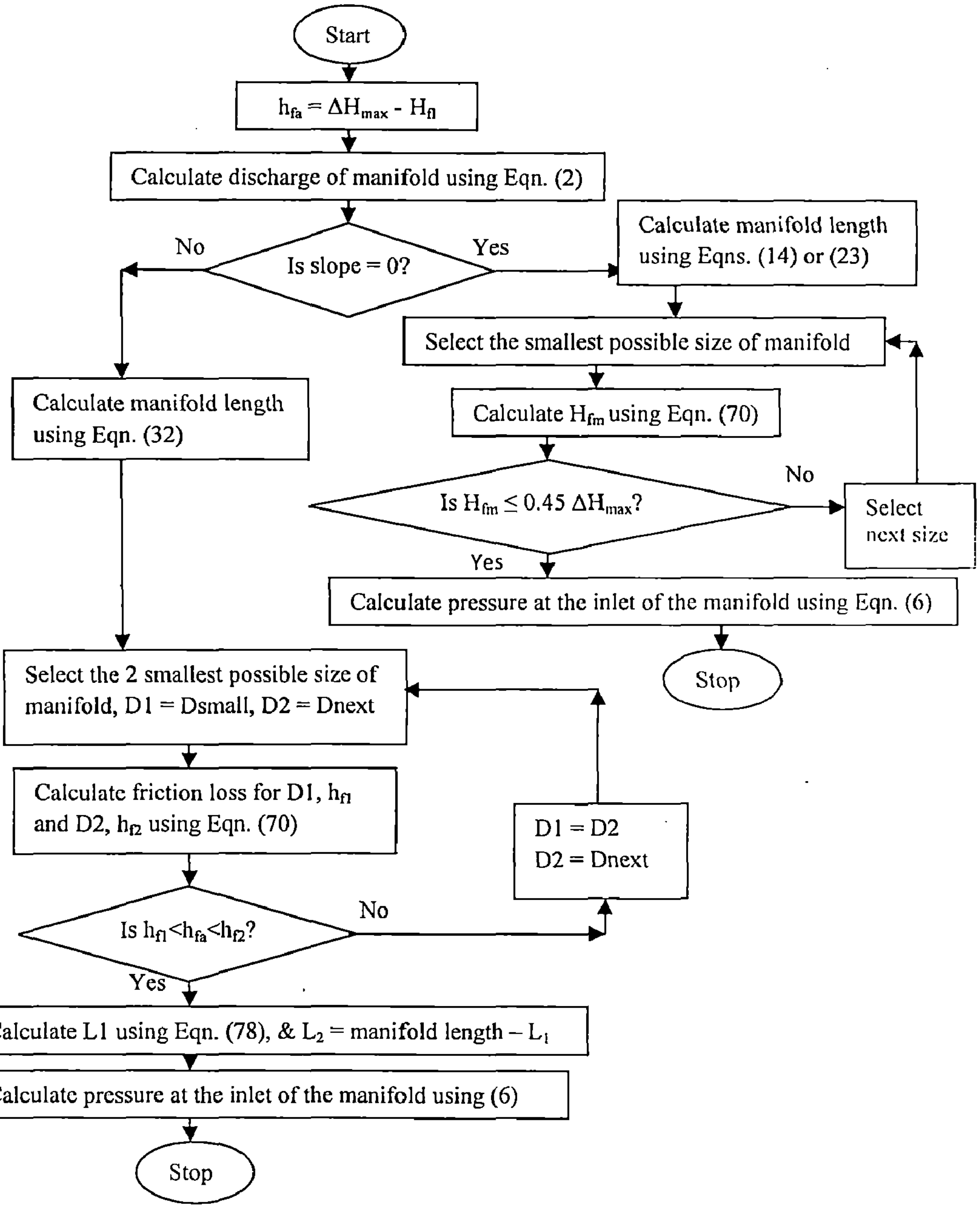

Fig. 4.3 Flowchart for subprogram of manifold line design of drip irrigation system

4.1.5 Subprogram for the design of main and submain line

This subprogram selects diameter of submain and main based on minimum cost of investment and operation. It calculates capital and operation cost by considering all feasible pipe sizes. Fig.4.4 depicts the selection process for the design of main and submain line.

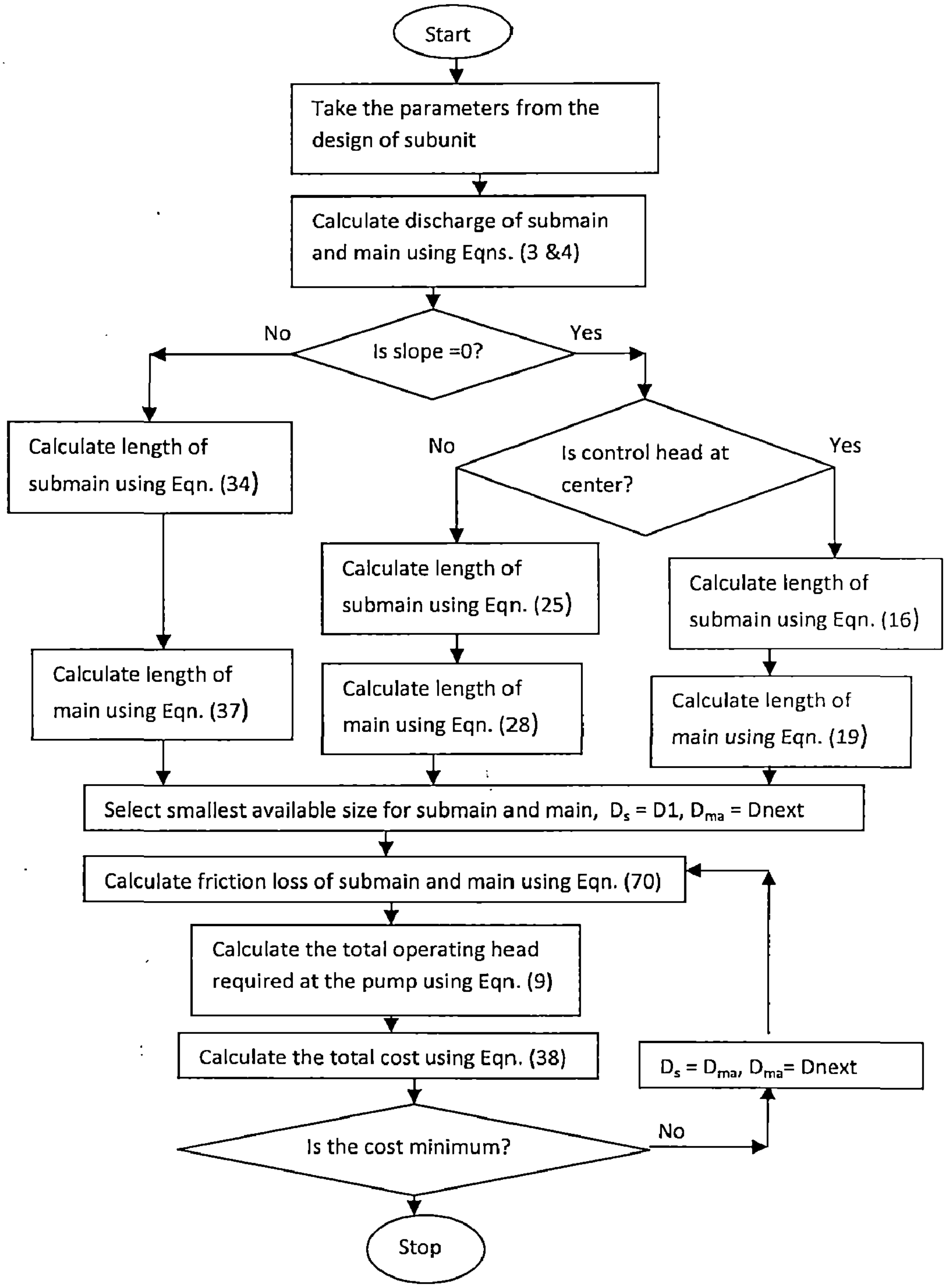

Fig.4.4 Flowchart for subprogram of selection of main and submain of drip irrigation system

4.2 Application of the model to published data (Hassanli and Dandy, 1995)

To test the capability of the model, it was used to design an irrigation system with the necessary input data as shown in Table 4.1. In this case the control head location is at the centre and the slope of the field is zero. The output of the model is shown in Tables 4.2 to 4.3

Table 4.1 Input data used to design a drip irrigation system

S.No.	Parameters	Unit	Value
1	Moisture content at field capacity	(%)	23
2	Moisture content at permanent wilting point	(%)	12
3	Bulk density of the soil	-	1.35
4	Effective root zone depth	m	1.0
5	Management allowed deficit	-	0.45
6	Wetted portion of the area	-	0.35
7	Application efficiency	-	0.85
8	Peak daily crop evapotranspiration	mm/day	4.6
9	Basic infiltration rate of the soil	mm/h	4.0
10	Number of days without irrigation	day	1
11	Available time for irrigation	h	22
12	Plant and emitter spacing	m	2 , 3
13	Dimensions of the field in the X and Y direction respectively	m	800 , 600
14	Area of the field	m^2	480000
15	Emission uniformity (EU)	-	0.90
16	Emitter discharge coefficient (Ke)	-	1.0
17	Emitter discharge exponent(x)	-	0.50
18	Emitters coefficient of variation (Cv)	-	0.04
19	Cost per emitter	$	0.09
20	The cost coefficients of the pipe		
	K_1	-	0.00096
	K_2	-	0.006
	K_3	-	0.18
21	The pump cost constants		
	K	-	1262
	V	-	0.2305
	W	-	0.9038
22	The cost of each control head components		
	A) main valve	$	180

	B) volumetric valve		$	200
	C) fertilizer unit		$	450
	D) screen filter		$	360
	E) media filter		$	400
	F) subunit valve		$	20
	G) subunit pressure regulator		$	25
	Cost of fittings for main and submain respectively		$	4, 2
	Cost of connectors of			
	Main		$	8
	Submain		$	6
	Manifold		$	4
23	Lateral		$	2
	Cost of end plugs of	Main	$	1.0
		Submain	$	0.75
		Manifold	$	0.50
		Lateral	$	0.075
25	Unit operating cost of the system		$/kwh	0.09
26	Annual irrigation requirement		mm	1000
27	Interest rate		-	0.10
28	Expected life of the components		year	12
29	Position of first outlet		-	0.50
30	Efficiency of the pump		-	0.72
31	Efficiency of the motor		-	0.95
32	Head loss in the suction pipe		m	3
33	Depth to water surface		m	20
34	Head loss of	A) main valve	m	0.70
		B) volumetric valve	m	1.50
		C) fertilizer unit	m	1.50
		D) screen filter	m	2.0
		E) media filter	m	4.0
		F) subunit valve	m	0.50

4.2.1 Emitter discharge and number of emitters per tree

In the design process of drip irrigation system, selection of emitter is subject to many subjective and objective criteria. However, one of the main idea introduced in this study is to identify the possible combination of emitter discharge and number of emitters per tree based on both the agronomic and time parameters. The system is then designed for each of the possible combination. Analysis of each design to identify the total minimum cost of the system is one of the features of the developed model. For the calculated gross irrigation requirement (27.06 mm), the irrigation frequency during the period of peak water use (4.6 mm/day) is 5 days. With 22 h and 4mm/h the maximum available time for irrigation and basic infiltration rate of the soil respectively, and one day without irrigation per cycle, the model identified 11 possible combinations of which seven are with one shift per day and four are with two shifts per day. These possible combinations with their corresponding preliminary design parameters and the optimal secondary design parameters are shown in Tables 4.2 to 4.12. For same emitter discharge, the total minimum cost increases with increase in number of emitters per tree. Apart from the additional cost involved, an increase in number of emitters per tree results higher discharge which needs larger pipe diameter leading to higher cost. On the other hand, an increase in number of emitters per tree lessens application time (operation time) which may reduce the operation cost. The minimum total cost in US Dollar for the first three combinations with equal emitter discharge of 2 lph but 4, 5, and 6 emitters per tree are 230041, 251887, and 266795 respectively. Fourth to seventh combination have equal emitter discharge of 4 lph but 2, 3, 4, and 5 emitters per tree resulting in minimum cost of 216937, 246256, 241080, and 269544 respectively. Similarly the minimum cost for the combinations with emitter discharge of 6 lph and 8 lph also increases with increase in number of emitters per tree. These results show that as the number of emitters per tree increase, its additional cost, for example due to the requirement of larger diameter is more than the cost saving due to the reduction in operating time. The local minimum ($230041) of the first combination (Tables 4.2a and 4.2b) is found at a subunit with dimension of 133.33m×75m. The resulting diameters are 12, 75, 160, and 180mm for lateral, manifold, submain and main respectively.

Table 4.2a: Preliminary design parameters (1st combination), flat topography

S.No	Parameters	Unit	Value
1	Gross irrigation requirement	mm	27.06
2	Irrigation interval	day	4
3	Discharge of emitter	lph	2
4	Number of emitters per plant	-	4
5	Application rate	mm/h	1.33
6	Application time	h	20.29
7	Total number of shifts	-	4
8	Discharge capacity of the system	lph	160000

Table 4.2b: Final design parameters (Lsx = 133.35 and Lsy = 75), flat topography

S.No	Parameter	Unit	Lateral	Manifold	Submain	Main
1	Length	m	36.00	132.33	262.50	266.67
2	Discharge	lph	96	12864	25728	80000
3	head loss	m	0.47	0.42	0.22	0.92
4	diameter	mm	12	75	160	180
5	Inlet pressure head	m	4.35	4.67	4.89	5.80
6	Total length	m	230400	6352	1575.00	533.33

As shown in Tables 4.3a and 4.3b, the second combination, number of emitters per tree is increased from 4 to 5. This increase resulted in reduced application time from 20.29 to 16.24 h, increased manifold and main diameters from 75 and 180mm to 90 and 200mm respectively and increase in total minimum cost from $230041 to $251887.

Table 4.3a: Preliminary design parameters (2^{nd} combination), flat topography

S.No	Parameters	Unit	Value
1	Gross irrigation requirement	mm	27.06
2	Irrigation interval	day	4
3	Discharge of emitter	lph	2
4	Number of emitters per plant	-	5
5	Application rate	mm/h	1.67
6	Application time	h	16.24
7	Total number of shifts	-	4
8	Discharge capacity of the system	lph	200000

Table 4.3b: Final design parameters (Lsx = 133.33 and Lsy = 75), flat topography

S.No	Parameter	Unit	Lateral	Manifold	Submain	Main
1	Length	m	36.00	132.33	262.50	266.67
2	Discharge	lph	120	16080	32160	100000
3	head loss	m	0.70	0.26	0.32	0.82
4	diameter	mm	12	90	160	200
5	Inlet pressure head	m	4.52	4.72	5.04	5.86
6	Total length	m	230400	6352	1575.00	533.33

However, farther increase in number of emitters per tree to 6, third combination as shown in Tables 4.4a and 4.4b resulted in shifting of the optimal subunit dimension from 133.33m×75m to 200m×50m. As a result the total length of manifold increased form 6352m to 9552m while the total length of lateral, submain and main decreased from 230400 to 225600, from1575 to 1100 and from 533.33m to 400 respectively. The diameter of submain is increased to 180mm with the other diameters same as in the second combination. The application time is farther reduced to 13.53 h. The overall effect is an increase in the total cost by $14908.

Table 4.4a: Preliminary design parameters (3rd combination), flat topography

S.No	Parameters	Unit	Value
1	Gross irrigation requirement	mm	27.06
2	Irrigation interval	day	4
3	Discharge of emitter	lph	2
4	Number of emitters per plant	-	6
5	Application rate	mm/h	2.00
6	Application time	h	13.53
7	Total number of shifts	-	4
8	Discharge capacity of the system	lph	240000

Table 4.4b: Final design parameters (Lsx = 200 and Lsy = 50), flat topography

S.No	Parameter	Unit	Lateral	Manifold	Submain	Main
1	Length	m	23.50	199.00	275.00	200.00
2	Discharge	lph	96	19200	57600	120000
3	head loss	m	0.32	0.54	0.53	0.85
4	diameter	mm	12	90	180	200
5	Inlet pressure head	m	4.24	4.64	5.17	6.02
6	Total length	m	225600	9552	1100.00	400.00

Unlike the previous combination with an emitter discharge of 2 lph, the following four combinations as shown in Tables 4.5 to 4.8 are all with emitter discharge of 4 lph, which is the most commonly available point source emitter according to **Keller** and **Bliesner, (1990)**. The difference within the following four combinations can be explained with the same reasoning as within the previous three combinations. To understand the effect of emitter discharge the first combination with 2 lph and 4 emitters per tree and fourth combination with 4 lph and 2 emitters per tree were compared. Owing to the same discharge per tree (16 lph) both the combinations have equal application time (20.29 h). The local minimum of the fourth combination equal to $216937 is found to be at a subunit with dimensions 200m×75m. The increase in subunit length from 133.33m in the first combination to 200m in the fourth combination resulted in an increase by 16m of manifold, decrease total length of submain and main by 525m and 133.33m respectively. The decrease in submain and main total length and number of emitters per tree are the main factors for the decrease in total minimum cost from $230041to $216937.

Table 4.5a: Preliminary design parameters (4th combination), flat topography

S.No	Parameters	Unit	Value
1	Gross irrigation requirement	mm	27.06
2	Irrigation interval	day	4
3	Discharge of emitter	lph	4
4	Number of emitters per plant	-	2
5	Application rate	mm/h	1.33
6	Application time	h	20.29
7	Total number of shifts	-	4
8	Discharge capacity of the system	lph	160000

Table 4.5b: Final design parameters (Lsx = 200m and Lsy = 75m), flat topography

S.No	Parameter	Unit	Lateral	Manifold	Submain	Main
1	Length	m	36.00	199.00	262.50	200.00
2	Discharge	lph	96	19200	38400	80000
3	head loss	m	0.47	1.28	0.44	0.69
4	diameter	mm	12	75	160	180
5	Inlet pressure head	m	16.35	17.31	17.75	18.43
6	Total length	m	230400	6368	1050.00	400.00

Table 4.6a: Preliminary design parameters (5th combination), flat topography

S.No	Parameters	Unit	Value
1	Gross irrigation requirement	mm	27.06
2	Irrigation interval	day	4
3	Discharge of emitter	lph	4
4	Number of emitters per plant	-	3
5	Application rate	mm/h	2.00
6	Application time	h	13.53
7	Total number of shifts	-	4
8	Discharge capacity of the system	lph	240000

Table 4.6b: Final design parameters (L_{sx} = 200 and Lsy = 75), flat topography

S.No	Parameter	Unit	Lateral	Manifold	Submain	Main
1	Length	m	36.00	199.00	262.50	200.00
2	Discharge	lph	144	28800	57600	120000
3	head loss	m	0.96	1.09	0.51	0.85
4	diameter	mm	12	90	180	200
5	Inlet pressure head	m	16.72	17.54	18.04	18.89
6	Total length	m	230400	6368	1050.00	400.00

Combinations 1st to 5th and as well as 8th and 10th have resulted single shift per day (irrigation interval equal to total number of shifts). With an increase in discharge per tree due to one or both of emitter discharge and number of emitters per tree, the time required to apply the gross irrigation requirement is reduced. If the total time available for irrigation per day is a whole number multiple of the application time, multiple shifts per day, equal to the whole number factor of the application time can be used. Combinations 6th, 7th, 9th, and 11th have got discharge per tree which limits the application time to less than half of the available time for irrigation per day. Hence, the use of two shifts per day is possible.

Table 4.7a: Preliminary design parameters (6th combination), flat topography

S.No	Parameters	Unit	Value
1	Gross irrigation requirement	mm	27.06
2	Irrigation interval	day	4
3	Discharge of emitter	lph	4
4	Number of emitters per plant	-	4
5	Application rate	mm/h	2.67
6	Application time	h	10.15
7	Total number of shifts	-	8
8	Discharge capacity of the system	lph	160000

Table 4.7b: Final design parameters (Lsx = 200 and Lsy = 75), flat topography

S.No	Parameter	Unit	Lateral	Manifold	Submain	Main
1	Length	m	36.00	199.00	262.50	200.00
2	Discharge	lph	192	38400	38400	80000
3	head loss	m	1.58	1.81	0.44	0.69
4	diameter	mm	12	90	160	180
5	Inlet pressure head	m	17.19	18.54	18.98	19.67
6	Total length	m	230400	6368	1050.00	400.00

Table 4.8a: Preliminary design parameters (7th combination), flat topography

S.No	Parameters	Unit	Value
1	Gross irrigation requirement	mm	27.06
2	Irrigation interval	day	4
3	Discharge of emitter	lph	4
4	Number of emitters per plant	-	5
5	Application rate	mm/h	3.33
6	Application time	h	8.12
7	Total number of shifts	-	8
8	Discharge capacity of the system	lph	200000

Table 4.8b: Final design parameters (Lsx = 133.33 and Lsy = 75), flat topography

S.No	Parameter	Unit	Lateral	Manifold	Submain	Main
1	Length	m	36.00	132.33	262.50	266.67
2	Discharge	lph	240	32160	32160	100000
3	head loss	m	2.34	0.88	0.32	0.82
4	diameter	mm	12	90	160	200
5	Inlet pressure head	m	17.76	18.42	18.74	19.56
6	Total length	m	230400	6352	1575.00	533.33

Table 4.9a: Preliminary design parameters (8^{th} combination), flat topography

S.No	Parameters	Unit	Value
1	Gross irrigation requirement	mm	27.06
2	Irrigation interval	day	4
3	Discharge of emitter	lph	6
4	Number of emitters per plant	-	2
5	Application rate	mm/h	2.00
6	Application time	h	13.53
7	Total number of shifts	-	4
8	Discharge capacity of the system	lph	240000

Table 4.9b: Final design parameters (Lsx = 200 and Lsy = 75), flat topography

S.No	Parameter	Unit	Lateral	Manifold	Submain	Main
1	Length	m	36.00	199.00	262.50	200.00
2	Discharge	lph	144	28800	57600	120000
3	head loss	m	0.96	2.60	0.51	0.85
4	diameter	mm	12	75	180	200
5	Inlet pressure head	m	36.72	38.67	39.17	40.02
6	Total length	m	230400	6368	1050.00	400.00

Table 4.10a: Preliminary design parameters (9th combination), flat topography

S.No	Parameters	Unit	Value
1	Gross irrigation requirement	mm	27.06
2	Irrigation interval	day	4
3	Discharge of emitter	lph	6
4	Number of emitters per plant	-	3
5	Application rate	mm/h	3.00
6	Application time	h	9.02
7	Total number of shifts	-	8
8	Discharge capacity of the system	lph	180000

Table 4.10b: Final design parameters (Lsx = 200 and Lsy = 75), flat topography

S.No	Parameter	Unit	Lateral	Manifold	Submain	Main
1	Length	m	36.00	199.00	262.50	200.00
2	Discharge	lph	216	43200	43200	90000
3	head loss	m	1.95	2.22	0.54	0.51
4	diameter	mm	12	90	160	200
5	Inlet pressure head	m	37.46	39.13	39.66	40.17
6	Total length	m	230400	6368	1050.00	400.00

Table 4.11a: Preliminary design parameters (10th combination), flat topography

S.No	Parameters	Unit	Value
1	Gross irrigation requirement	mm	27.06
2	Irrigation interval	day	4
3	Discharge of emitter	lph	8
4	Number of emitters per plant	-	1
5	Application rate	mm/h	1.33
6	Application time	h	20.29
7	Total number of shifts	-	4
8	Discharge capacity of the system	lph	160000

Table 4.11b: Final design parameters (Lsx = 400 and Lsy = 150), flat topography

S.No	Parameter	Unit	Lateral	Manifold	Submain	Main
1	Length	m	73.50	399.00	225.00	0.00
2	Discharge	lph	200	80000	80000	80000
3	head loss	m	3.39	5.03	0.77	0.00
4	diameter	mm	12	110	180	315
5	Inlet pressure head	m	66.54	70.32	71.09	71.09
6	Total length	m	235200	3192	450.00	0.00

Table 4.12a: Preliminary design parameters (11th combination), flat topography

S.No	Parameters	Unit	Value
1	Gross irrigation requirement	mm	27.06
2	Irrigation interval	day	4
3	Discharge of emitter	lph	8
4	Number of emitters per plant	-	2
5	Application rate	mm/h	2.67
6	Application time	h	10.15
7	Total number of shifts	-	8
8	Discharge capacity of the system	lph	160000

Table 4.12b: Final design parameters (Lsx = 200 and Lsy = 75), flat topography

S.No	Parameter	Unit	Lateral	Manifold	Submain	Main
1	Length	m	36.00	199.00	262.50	200.00
2	Discharge	lph	192	38400	38400	80000
3	head loss	m	1.58	4.30	0.44	0.69
4	diameter	mm	12	75	160	180
5	Inlet pressure head	m	65.19	68.41	68.85	69.53
6	Total length	m	230400	6368	1050.00	400.00

4.2.2 Subunit dimension and area

Considering the importance of dividing the field into subunits, one of the objectives of this study is to find optimal subunit dimension of drip irrigation system. For each possible combination of emitter discharge and number of emitters per tree, the model analyses the design process by dividing the field into subunits. The main thought here is, for a given pipe configuration of drip irrigation system, length of each type of pipe may change with change in subunit dimension. Consequently the total cost of the system, as shown in Table 4.14 for the fourth combination, is different for different subunit size for the same total size of the field. The minimum total cost in US Dollar for all the combinations of 1 to 11 are 230041, 251887, 266795, 216937, 246259, 241080, 269544, 256387, 265202, 253985 and 281315 respectively. The local optimum subunit dimension for all the combination in the same order are, (133.33×75), (133.33×75), (200×50), (200×75), (200×75), (200×75), (133.33×75), (200×75), (200×75), (400×150) and (200×75)m. The global minimum cost is $216937 with emitter discharge 4 lph and two emitters per tree. The optimal subunit area has dimensions of 200m × 75m.

Table 4.13: Subunit dimensions and their resulting costs (4th combination), flat topography

S. N	subunit number	subunit length	subunit width	emitters cost	lateral cost	manifold cost	main & submain cost	accessories &control head cost	operating cost	total system cost
1	8	400.00	150.00	10800	92038	47487	14564	1881	50905	234049
2	16	400.00	75.00	10800	67433	59639	16991	2187	50617	223956
3	24	400.00	50.00	10800	66029	61018	17800	2487	50706	225156
4	16	200.00	150.00	10800	92038	20288	36090	2188	51467	229409
5	32	200.00	75.00	10800	67433	28799	39947	2801	50810	216937
6	48	200.00	50.00	10800	66029	31294	41233	3401	50716	219792
7	24	133.33	150.00	10800	92038	14363	51977	2534	51187	239355
8	48	133.33	75.00	10800	67433	20810	57763	3453	50590	227132
9	72	133.33	50.00	10800	66029	20580	59692	4353	50706	228475
10	32	100.00	150.00	10800	92038	10379	65707	2887	51254	249540
11	64	100.00	75.00	10800	67433	13686	73422	4113	50865	236681
12	96	100.00	50.00	10800	66029	13942	75994	5313	51042	239532
13	40	80.00	150.00	10800	92038	10353	78574	3245	50752	262090
14	80	80.00	75.00	10800	67433	9271	88217	4777	51433	248458
15	120	80.00	50.00	10800	66029	13907	91432	6278	50440	255123
16	48	66.67	150.00	10800	92038	6808	91009	3606	51329	272087
17	96	66.67	75.00	10800	67433	9248	102581	5444	50896	262773
18	144	66.67	50.00	10800	66029	9610	106439	7245	51061	267601

The maximum total costs in US Dollar are 300620, 312998, 348990, 272087, 288239, 279203, 309872, 307262, 304978, 323475 and 327147 with subunit size of (400×50), (66.67×150), (400×150), (66.67×150), (66.67×150), (66.67×75), (400×75), , (66.67×150), (66.67×75), (66.67×50) and (66.67×75)m for the combinations 1 to 11 respectively. For this case study, the model show maximum saving in total cost of 70579, 61111, 82195, 55150, 41983, 38123, 40328, 50875, 39776, 69490 and 45832 for the combinations 1 to 11 respectively can be made by manipulating the subunit dimension. As the size of subunit dimension decreases the contribution from main and submain as well as from accessories and control head increases but the reverse is true for the contribution from lateral line. However the contribution from manifold increases with decrease in subunit dimension up to some level and then decreases with further decrease in subunit dimension as shown in Fig. 4.5.

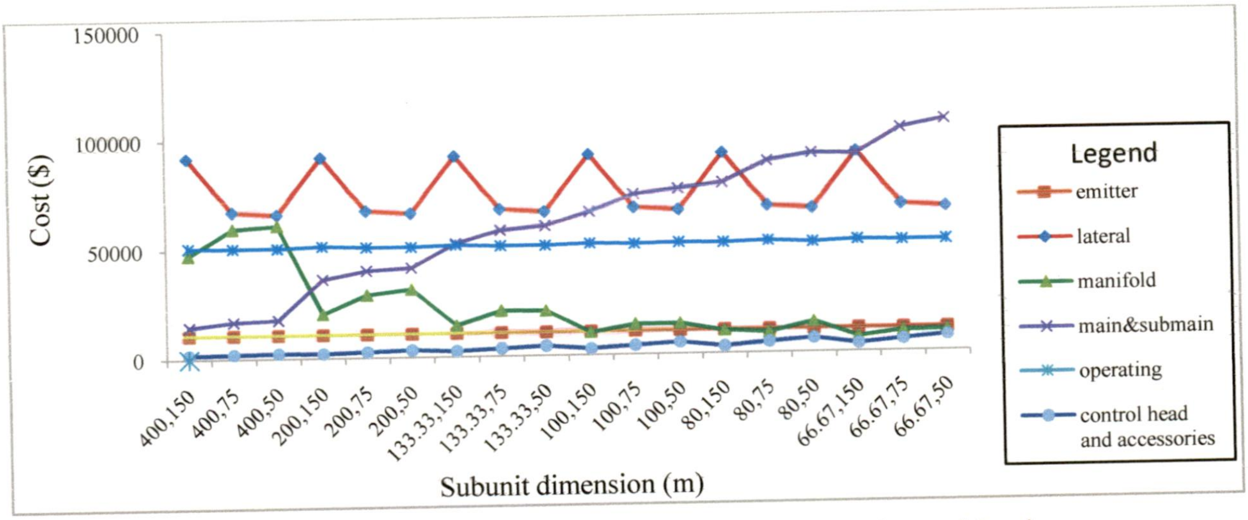

Figure 4.5 Cost of different components for the fourth combination

As shown in Fig. 4.6, the relationship between total cost and subunit area is not one-to-one. For example a subunit with an area of 10000 m^2 has total cost of $219792, $227132, and $272087 for the subunit dimensions of 200m×50m, 133.33m×75m, and 66.67m×150m respectively. However, Fig. 4.7 shows a one-to-one mapping of the total cost and subunit dimensions. Therefore, for a given area of field, significant savings in cost can be made by considering different combinations of the dimensions (length and width). This situation may be applicable in large fixed dimension fields where division into subunits is feasible, and in land consolidation where size of land holding of the farmer is fixed but field dimensions are yet to be fixed.

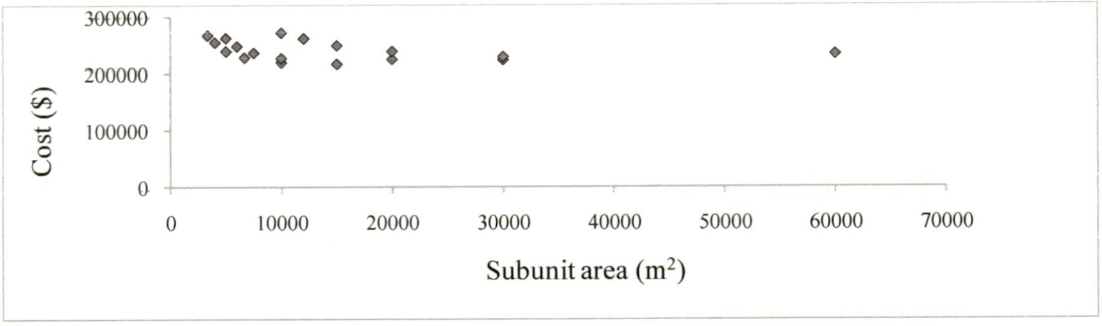

Figure 4.6 Total cost of the various subunit areas for the fourth combination

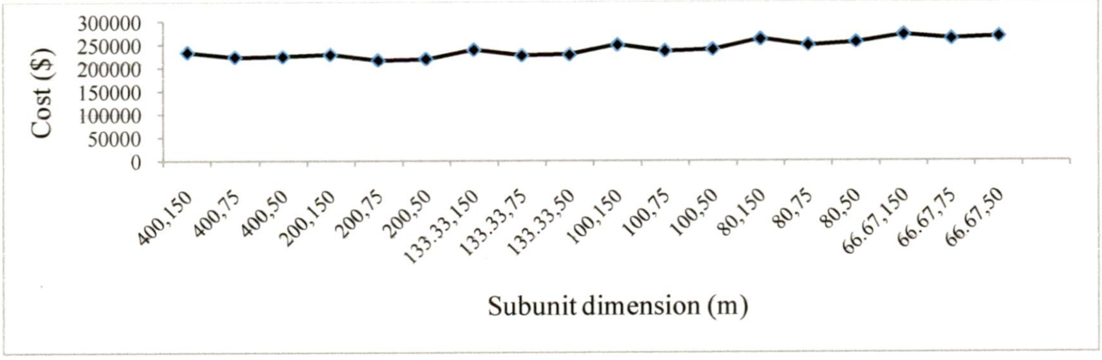

Figure 4.7 Total cost of subunit dimensions for the Fourth combination

4.3 Application of the Model to Designed Example (FAO, 2001)

In this case the model is applied to the design example presented in "FAO, (2001), "IRRIGATION MANUAL MODULE 9: localized irrigation systems: planning, design, operation and maintenance." The example is a field with dimensions of 150m by 300m to be divided equally to eight farmers. The field has 1% slope along the 300m length and the control head location is assumed at the center of the upper 150m long dimension. The input data for this is shown in Table 4.14. In order to identify the design with minimum cost, data related to different component type and costs are assumed to be same as in section 4.2.

Table 4.14 Input data used to design a drip irrigation system, uniform slope topography

S.No.	Parameters	Unit	Value
1	Moisture content at field capacity	(%)	22
2	Moisture content at permanent wilting point	(%)	12.4
3	Bulk density of the soil	-	1.25
4	Effective root zone depth	m	0.5
5	Management allowed deficit	-	0.20
6	Wetted portion of the area	-	1.0
7	Application efficiency	-	0.86
8	Peak daily crop evapotranspiration	mm/day	4.09
9	Basic infiltration rate of the soil	mm/h	4.0
10	The number of days without irrigation	day	0
11	The available time for irrigation	h	12
12	The plant and emitter spacing	m	1.8 , 0.6
13	Dimensions of the field in the X and Y direction respectively	m	150 , 300
14	Area of the field	m^2	45000
15	Emission uniformity (EU)	-	0.90

4.3.1 Emitter discharge and number of emitters per tree

For the calculated gross irrigation requirement 9.5mm, the irrigation frequency during the period of peak water use 4.09mm/day is 2 days. With 12 h and 4mm/h the maximum available time for irrigation and basic infiltration rate of the soil respectively the model identifies three possible combinations of which one is with two shifts per day and two are with four shifts per day. These possible combinations with their corresponding preliminary design parameters and the optimal final design parameters are shown in Tables 4.15 to 4.17. The minimum total costs in US Dollar for the first, second and third combinations are 31413, 35254 and 34783 respectively. Similar to the results in section 4.1, these results also show that as the number of emitters per tree increase, its additional cost, for example due to the requirement of larger diameter is more than the cost saving due to the reduction in operating time. The local minimum ($31413) of the first combination (Table 4.15a and 4.15b) is found to be at a subunit with dimension of 75m×150m.

Table 4.15a: Preliminary design parameters (1st combination), uniform slope topography

S.No	Parameters	Unit	Value
1	Gross irrigation requirement	mm	9.51
2	Irrigation interval	day	2
3	Discharge of emitter	lph	2
4	Number of emitters per plant	-	1
5	Application rate	mm/h	1.9
6	Application time	h	5.1
7	Total number of shifts	-	4
8	Discharge capacity of the system	lph	20833

Table 4.15b: Final design parameters (Lsx = 75and Lsy = 150), uniform slope topography

S.No	Parameter	Unit	Lateral	Manifold	Submain	Main
1	Length	m	37.20	148.1,1.0*	37.50	150.00
2	Discharge	lph	124	20832	20832	20833
3	head loss	m	0.16	-0.64	0.13	0.16
4	diameter	mm	16	75,90**	110	140
5	Inlet pressure head	m	4.12	2.23	2.35	1.01
6	Total length	m	24800	596	150.00	150.00

*length of smaller and larger diameter portion of the manifold

**diameters of the two diameter manifold line

The increase in number of emitters per tree from one in the first combination to 2 in the second combination resulted in the reduction of the application time from 5.1 h to 2.57 h which made the use of more (4 in this case) irrigation shifts per day possible. As a result the local minimum cost increased to $34783 which is found to be at a subunit with dimensions 37.5m×150m.

Table 4.16a: Preliminary design parameters (2^{nd} combination), uniform slope topography

S.No	Parameters	Unit	Value
1	Gross irrigation requirement	mm	9.51
2	Irrigation interval	day	2
3	Discharge of emitter	lph	2
4	Number of emitters per plant	-	2
5	Application rate	mm/h	3.70
6	Application time	h	2.57
7	Total number of shifts	-	8
8	Discharge capacity of the system	lph	20833

Table 4.16b: Final design parameters (Lsx = 37.5 and Lsy = 150), uniform slope topography

S.No	Parameter	Unit	Lateral	Manifold	Submain	Main
1	Length	m	18.45	31.66,117.44*	56.25	150.00
2	Discharge	lph	124	20832	20832	20833
3	head loss	m	0.37	-0.57	0.19	0.16
4	diameter	mm	12	63,75**	110	140
5	Inlet pressure head	m	4.28	2.42	2.61	1.27
6	Total length	m	24600	1193	225.00	150.00

*length of smaller and larger diameter portion of the manifold

**diameters of the two diameter manifold line

As shown in tables 4.17a the third combination is with 4 lph emitter discharge and one emitter per tree. This table also shows that, the combination has the same other preliminary design parameters and minimum cost subunit dimension, 37.5m×150m. However, they have different minimum costs which may be due to their differences in number of emitters and operating pressure with direct and indirect effect on the cost respectively.

Table 4.17a: Preliminary design parameters (3rd combination), uniform slope topography

S.No	Parameters	Unit	Value
1	Gross irrigation requirement	mm	9.51
2	Irrigation interval	day	2
3	Discharge of emitter	lph	4
4	Number of emitters per plant	-	1
5	Application rate	mm/h	3.70
6	Application time	h	2.57
7	Total number of shifts	-	8
8	Discharge capacity of the system	lph	20833

Table 4.17b: Final design parameters (Lsx = 37.5 and Lsy =150), uniform slope topography

S.No	Parameter	Unit	Lateral	Manifold	Submain	Main
1	Length	m	18.45	143.09,6.01*	56.25	150.00
2	Discharge	lph	124	20832	20832	20833
3	head loss	m	0.37	2.18	0.19	0.16
4	diameter	mm	12	63,75**	110	140
5	Inlet pressure head	m	16.28	16.16	16.35	15.01
6	Total length	m	24600	1193	225.00	150.00

*length of smaller and larger diameter portion of the manifold

**diameters of the two diameter manifold line

4.3.2 Subunit dimension and area

As explained in the problem, the field is owned by eight farmers. However, as shown in Table 4.18 the optimal design divides the field into four subunits with a minimum cost of \$31413. If each farmer is desired to have sole responsibility on his/her subunit components the second choice of 16 subunits (each farmer having two subunits) can be adopted with \$602 increase in the minimum cost. The maximum cost in this design which is equal to \$45294 is associated with the larger contribution from the cost of main and submain as well as cost of control head. As the number of subunits increases the length of main and submain and the number of control valves increases, and it may reach at a condition such that the associated increase in cost is higher than the saving in cost due to the decrease in lateral and manifold lengths.

Table 4.18: Subunit dimensions and their resulting costs (1st combination), uniform slope topography

S. N	subunit number	subunit length	subunit width	emitters cost	lateral cost	manifold cost	main & submain cost	accessories &control head cost	operating cost	total system cost
1	4	75.00	150.00	2812	9705	2705	4844	1555	2471	31413
2	16	18.75	150.00	2812	7083	4099	6245	2015	2462	32015
3	32	18.75	75.00	2812	7083	2524	11003	2615	2552	36125
4	48	18.75	50.00	2812	7083	1819	14768	3247	2581	39927
5	64	18.75	37.50	2812	7083	1426	14128	3886	2597	39589
6	80	18.75	30.00	2812	7083	1276	16507	4529	2606	42493
7	96	18.75	25.00	2812	7083	1082	18836	5172	2611	45294

As shown in the 2nd to 7th row of Table 4.18 lateral cost is constant ($7083) due to the constant subunit dimension along the lateral (18.75m). For the constant subunit length the manifold cost decrease from $4099 to $1082 due to the change in subunit width from 150m to 25m. The total system cost increased from $32015 to $45294, which is mainly due to the main and submain and control head costs. It can be seen in Fig. 3.4 the length of submain is half subunit length shorter than half of the field length while the length of main is a subunit width shorter than the field width. Therefore, as the subunit dimension decreases the length of main and submain increases for the same field dimension. Moreover smaller subunit dimension which means more subunits results in more submains and/or mains in the field. Hence, smaller subunit dimension have an increased effect in the total length of main and submain lines as well as in the number of valves and accessories. For example, as the size of subunit dimension decreased from 75m×150m to 18.75m×25m the cost of main and submain and control head increased from $4844 and $1555 to $18836 and $5172 respectively. The contribution from manifold increases with decrease in subunit dimension up to some level and then decreases with further decrease in subunit dimension as shown in Fig. 4.8.

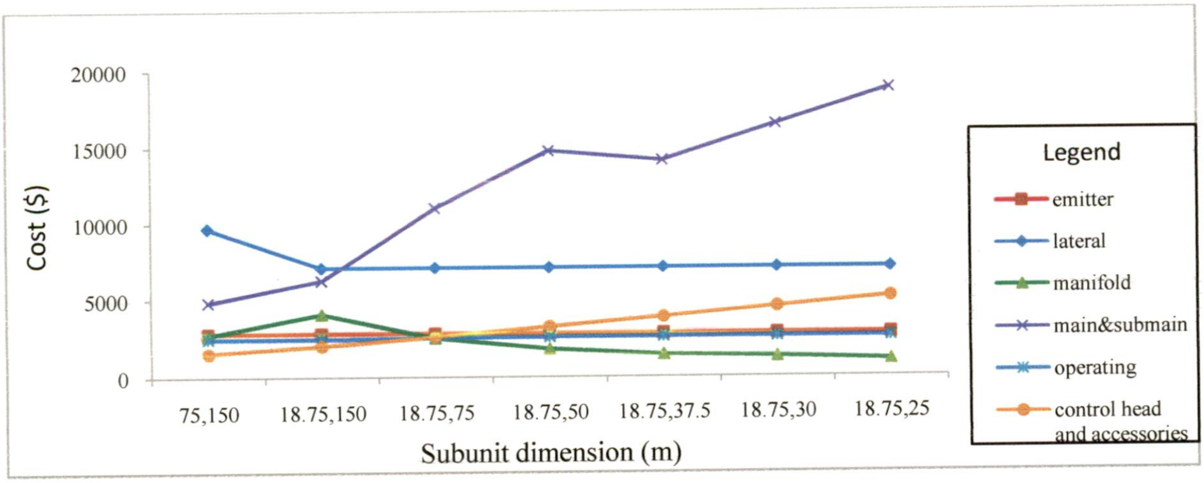

Fig. 4.8 Cost of different components for the 1st combination, uniform slope topography

As shown in Fig. 4.9 the total cost of the system increases with decrease in subunit area. Similarly Fig. 4.10 shows an increasing trend of the total cost as the subunit dimension decreases. In both cases the increase in cost due to main and submain and accessories and control heads overweighed the decrease in cost due to laterals and manifolds.

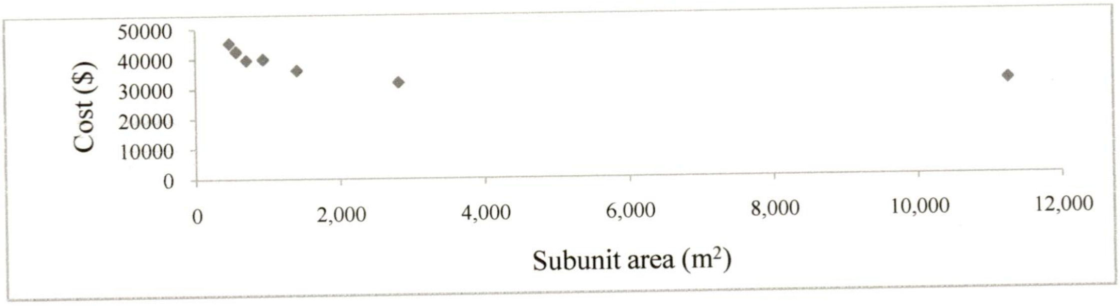

Fig. 4.9 Total cost of subunit areas for the 1st combination, uniform slope topography

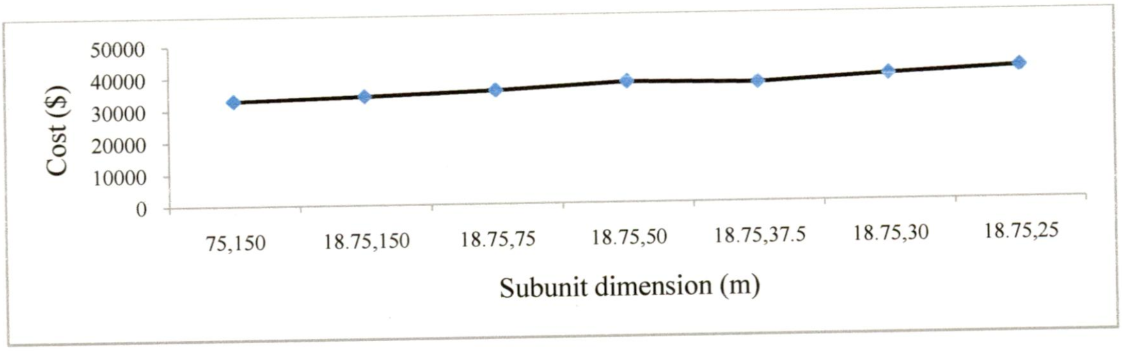

Fig. 4.10 Total cost of subunit dimensions for the 1st combination, uniform slope topography

CHAPTER V

SUMMARY AND CONCLUSION

As its name implies drip irrigation system is applying water drop by drop. When it is properly designed, maintained and operated it can result in more crop per drop. Moreover drip irrigation system may assure sustainable irrigated agriculture by maximizing water and nutrient uptake by the crop and minimizing the leaching of nutrients and chemicals out of the root zone. Owing to all its relative merits area under drip irrigation system increased from 56,000 ha in 1970 to 6 million ha in 2006. Despite the fast adoption in countries like Israel, USA and Australia, the system is expanding at a slow pace in developing countries, with one of the myriad reasons being its high initial investment cost. Hence, modeling and optimization of drip irrigation system to make a major saving in the capital cost while achieving the desirable level of distribution uniformity of water application is crucial.

This study was planned with specific objective to develop a non linear optimization model, which minimizes the total cost of drip irrigation system. Depending on the appropriate agronomic, management and hydraulic constraints modeling and optimization of drip irrigation system design was dealt with a main focus in the effect of:-

1. Combination of emitter discharge and number of emitters per plant, where the commonly available point source emitter sizes of 2, 4, 6 and 8 lph with a maximum of six emitters per tree were considered, and
2. Subunit dimension and area, where the field was divided into different even number subunits.

To ease the computational effort and to provide quicker sensitivity analysis, the model was written in computer code in C++ language. To test the capability of the model it was applied to two situations, where the first is flat topography and the second is uniform slope topography.

The model's output summary and the conclusions drawn for the design example with flat topography field are:

1. To apply the required amount of water per tree within the available time for irrigation the model identified the following combinations:
    - 2 lph with number of emitters per tree 4, 5, and 6.
    - 4 lph with number of emitters per tree 2, 3, 4 and 5.
    - 6 lph with number of emitters per tree 2 and 3.
    - 8 lph with number of emitters per tree 1 and 2.
2. Combinations with 16 lph or greater discharge per tree produced two shifts per day. Whereas those with discharge per tree less than 16 lph has one shift per day.
3. The optimal design (minimum cost) is found corresponding to emitter discharge of 4 lph and two emitters per tree. The preliminary design parameters; application time, irrigation shifts and system capacity were 20.29 h, 1, and 160000 lph respectively. The diameter (mm) and length (m) of lateral, manifold, submain and main pipes were 12 and 36, 75 and 199, 160 and 262.5 and 180 and 200 respectively.
4. For same field size, total system cost was changing with change in subunit dimension and the minimum total cost was found with subunit dimension of 200m×75m.
5. The cost was one to one function to subunit dimension but it was not the case to subunit area, for example a subunit with an area of 10000m^2 has total cost of \$219792, \$227132, and \$272087for subunit dimensions of 200m×50m, 133.33m×75m, and 66.67m×150m respectively.

The model's output summary and the conclusions drawn for the design example with uniform slope topography field are:

1. To apply the required amount of water per tree within the available time for irrigation the model identified the following combinations:
    - 2 lph with number of emitters per tree 1, and 2.
    - 4 lph with number of emitters per tree 1
2. The alternative with 2 lph and one emitter per tree produce one irrigation shift per day whereas the alternatives with 2 lph and two emitters per tree as well as 4 lph and one emitter per tree produce two irrigation shifts per day.

3. The optimal design (minimum cost) was found corresponding to emitter discharge of 2 lph and one emitter per tree. The preliminary design parameters; application time, irrigation shifts and system capacity were 5.1 h, 1, and 20833 lph respectively. The diameter (mm) and length (m) of lateral, manifold, submain and main pipes were 16 and 37.2, 75 and 149.1, 110 and 37.5 and 140 and 150 respectively.
4. For the same field size, the total system cost was changing with change in subunit dimension and the minimum total cost was found with subunit dimension of 75m×150m.
5. Smaller subunit dimension have an increased effect in the total length of main and submain lines as well as in the number of valves and accessories.

REFERENCES

Barragan, J. and Wu, I. P. (2005), "Simple pressure parameters for micro-irrigation design," Biosystems Engineering, 90(4), 463–475.

Barragan,J., Bralts V. F., and Wu, I. P.(2005),"Assessment of Emission Uniformity for Micro-irrigation Design," Biosystems Engineering 93 (1), 89–97.

Cuenca, R.H., (1989), "Irrigation system design: an engineering approach," Prentice hall, New Jersey.

FAO, (2001), "IRRIGATION MANUAL MODULE 9: localized irrigation systems: planning, design, operation and maintenance", FAO, SAFR/AGLW/DOC/005, Harare.

Finkel, H.J., (1982), "CRC Handbook of Irrigation Technology," Vol.I, CRC Press, Florida.

Hassanli, A.M., and Dandy, G.C., (1996), "Application of genetic algorithms to the optimum design and layout of drip irrigation system," Department of Civil and Environmental Engineering, The University of Adelaide Research report No.R.134.

Hassanli, A.M., and Dandy, G.C., (1995), "Optimum design and operation of multiple subunit drip irrigation systems," Department of Civil and Environmental Engineering, The University of Adelaide Research report No.R.130.

Hassanli, A.M., and Dandy, G.C., (1993), "Optimization of drip irrigation system " Department of Civil and Environmental Engineering, The University of Adelaide Research report No.R.106.

Hanson, B.R., Sˇ Imunek, J., and Hopmans, J.W., (2006). Evaluation of urea–ammonium–nitrate fertigation with drip irrigation using numerical modelling. Agric. Water Manage. 86 (1–2), 102–113.

Holzapfel, E.A., Marino, M.A. and Valenzuela, A., (1990), "Drip irrigation non-linear optimization model", Journal of Irrigation and Drainage Engineering, ASCE, 116(4), 479-496.

INCID, (1994), "Drip Irrigation in India" Jolly Reprographics, New Delhi.

Wu, I. P., (1997), "An assessment of hydraulic design of micro-irrigation systems" agricultural water management, 32, 275-284.

Jain, S.K., Singh, K.K. and Singh, R.P, (2002), " Microirrigation lateral design using lateral discharge equation", Journal of irrigation and Drainage Engineering, ASCE, 128, (2), 125-128

James, L.G., (1988), "Principles of farm irrigation system design", John Wiley & Sons, New York.

Jensen, M.E., (1980), "Design and operation of farm irrigation systems", ASAE, Michigan

Juana, L., Sinobas, L.R., Sanchez, R. and Losada, A., (2005), "Analytical Expressions for hydraulic Calculation of Trapezoidal Drip Irrigation Units", Journal of irrigation and Drainage Engineering, ASCE, 131(5), 420-432.

Juana, L., Losada, A.,Sinobas, L.R., and Sanchez, R., (2004), "Analytical relationship for designing drip Irrigation Units", Journal of irrigation and Drainage Engineering, ASCE, 130(1), 47-59.

Kang, Y., and Nishiyama, S., (1997), "An improved method for designing microirrigation submain units", irrigation science, 17, 183-193.

Kang, Y., Nishiyama, S. and Chen, H., (1996), "Design of microirrigation laterals on non-uniform slopes", irrigation science, 17, 3-14.

Karmeli, D., Peri, G. and Todes, M., (1985) , "Irrigation systems : design and operation," Oxford University Press, Capt Town.

Keller, J., and Bliesner, R. D., (1990), "Sprinkler and trickle irrigation." Van Nostrand Reinhold, New York, N.Y.

Keller, J., and Karmeli, D., (1974), "Trickle irrigation design parameters." Trans. ASAE, 17(4). 678-784.

Khemaies, Z. and Moncef, H., (2009), "Design of level ground lateral in trickle irrigation systems" Journal of irrigation and Drainage Engineering, ASCE, 135,(5), 620-625.

Lakhdar, Z. and Dalila, S., (2006), "Analysis and design of a microirrigation lateral", Journal of Central European Agriculture, 7(1), 57-62.

Monserrat, J., (2009), "Allocation of flow to plots in pressurized irrigation distribution networks: analysis of the Clement and Galand method and a new proposal", Journal of Irrigation and Drainage Engineering, ASCE, 135(1), 1-6.

Oron, G., (1982), "Technical and economic consideration in the design of closed conduit irrigation systems: a case of study." Agricultural Water Management, 5(1), 15-17.

Oron, G., and Karmeli, D., (1979). "Procedure for the economical evaluation of water networks parameters." Water Resour. Bull., 15(4), 1050-1059.

Pedras, C. M. G., Pereira, L. S., and Goncalves. J. M., (2008), "MIRRIG: a decision support system for design and evaluation of microirrigation systems", Agricultural water management, (96), 691-701.

Pedras, C. M. G., Pereira, L. S., and Goncalves. J. M., (2001), "A simulation model for design and evaluation of micro-irrigation systems", Irrig. and Drain. 50, 323-334.

Perez, R., Martinez, F., and Vela, A., (1993), "Improved design of branched network by using pressure reducing valve." Journal of Irrigation and Drainage Engineering, ASCE, 119(2), 164-180

Pitts, D., Peterson, K., Gilbert, G., and Fastenau, R., (1993). Field assessment of irrigation system performance, Applied Engineering in Agriculture 12(3): 307–313.

Saad, J.C.C. and Frizzone, A., (1996), "Design and management optimization of trickle irrigation system using non-linear programming", Journal of agricultural engineering research, 64, 109-118.

Saad, J.C.C. and Marino, M.A., (2002), "Optimum design of microirrigation system in sloping lands", Journal of Irrigation and Drainage Engineering, ASCE, 128(2),116-124.

Valiantzas, J.D., (2002), "Hydraulic analysis and optimum design of multi diameter irrigation laterals". Journal of Irrigation and Drainage Engineering, ASCE, 128(2), 78-86.

Wu, I. P. and Gitlin, H. M., (1974). Drip irrigation design based on uniformity. Transactions of the ASAE, 17(3), 157–168

www.docstoc.com/docs/16462631/Drip-irrigation, April, 10, 2010

www.livinghistoryfarm.org/farminginthe50s/water_02.html, April, 05, 2010.

APPENDIX A: C++ FOR OPTIMUM DESIGN OF DRIP IRRIGATION SYSTEM

```
//***********************************************************************
#include <iostream>
#include <cmath>
#include <iomanip>
using namespace std;
//***********************************************************************
class drip {
   public:
                             /* functions */
      void setIWR (int,int,float,char);
      float NIR(){return (FC-PWP)*Bd*Rz*Wa*MAD*10;}
      int irrigationfrequency() {return NIR()/ETc;}
      float adjustedNIR(){ return irrigationfrequency()*ETc;}
      float GIR(){return adjustedNIR()/Ae;}
      int irrigationinterval(){return (irrigationfrequency()-toff);}
      float QRsystem() {return GIR()*Lfx*Lfy/(irrigationinterval()*Tav);}
      float applicationrate(){return Ia;}
      int emitterspertree(){return Ne;}
      float selectedemitterdischarge(){return qe;}
      float applicationtime(){return Ta;}
      float operatingpressure (float, float);
      int totalshifts(){return (int)A/Ash;}
      int Nofsubunits (){return Nsx*Nsy;}
      float LXofsubunit (){return (Lfx/Nsx);}
      float LYofsubunit (){return(Lfy/Nsy);}
      float areaofsubunit (){return LXofsubunit()*LYofsubunit();}
      float Nsis (){return (Ash/areaofsubunit());}
      double Qsystem () {return Ash*applicationrate();}
      float lengthoflateral (float,char);
      float lateraloutlets(){return ceil(lengthoflateral(slope, LCH)/(Se));}
      double lateraldischarge(){returnlateraloutlets()*
                       selectedemitterdischarge()*emitterspertree();}
      float subunitvariation(float,float,float);
      float Cfactor (float);
      float lateralheadloss();
      float lateraldia();
      float inletlateralhead (){return (operatingpressure(X,Ke)+0.75*
                              lateralheadloss());}
```

```
float allowablemanifoldvariation (){return(subunitvariation(EU,CV,X)-
                                        lateralheadloss());}
float manifoldoutlets(char);
double manifolddischarge(){return 2*lateraldischarge()*
                                 manifoldoutlets(LCH);}
float cfactormanifold ();
float manifoldlength(float,char);
double manifolddia();
float manifoldheadloss(float);
double manifolddia2();
double manifold_L1();
float manifold_L2(){return manifoldlength(slope,LCH)- manifold_L1();}
float manifoldinlethead ();
double Hf1();
double Hf2();
int Nsubmains(float,char);
double submaindischarge (){return (ceil
              (Nsis()/Nsubmains(slope,LCH)))*manifolddischarge();}
double maindischarge(char);
float submainlength (char);
float mainlength(char);
int Temitters (){return floor(A*emitterspertree()/(Sl*Se));}
float Tlengthoflaterals(float,char);
float Tlengthofmanifolds(char);
float Tlengthofsubmains(float,char);
float Tlengthofmain(char);
float emittercost (){return Temitters ()*Cpe*0.75 ;}
float lateralcost(){return 0.75*((K1*lateraldia()*lateraldia()+K2*
                   lateraldia()+K3)*Tlengthoflaterals(slope,LCH));}
float manifoldcost (float);
double submaindia ();
double maindia ();
float submainheadloss(){return 0.4654*submainlength(LCH)*pow(
                     submaindischarge(),1.75)/pow(submaindia (),4.75);}
float submaininlethead(){return
                         manifoldinlethead()+submainheadloss();}
float mainheadloss(){return 0.4654*(mainlength(LCH)*pow(
                   maindischarge(LCH),1.75))/pow(maindia (),4.75);}
float maininlethead(){return(submaininlethead()+mainheadloss()-
                              mainlength ( LCH)*slope/100);}
```

```
     float mainsubmaincost(){return (K1*submaindia()*submaindia()+K2*
            submaindia()+K3)*Tlengthofsubmains(slope, LCH)+(K1*maindia()*
             maindia()+K2*maindia ()+K3)*Tlengthofmain( LCH);}
     float costofcontrolhead(){return
                   0.75*(Cmv+Cvv+Cft+Csf+Cmf+(Csv+Csp)*Nofsubunits ());}
     float costofaccessories ();
     float costofch_as(){return costofaccessories()+costofcontrolhead();}
     float operatingcost();
     float totalcost ();
     void printprimary();//prints the primary design parameters
     void readdata();//input data
     void printcosts();//prints the cost of different components
     void printsecondary();//prints the final design parameters
                                  /* end of functions */
      int Tav,Ne;
      float qe,Ia,Se,Sl,Ta,A,Ash,Is;
  private:
  float FC,PWP,Bd,Rz,Wa,MAD,Ae,ETc,Lfx,Lfy,slope,EU,CV,X,Ke,Ep,Cpe,K1,K2,
  K3,Sh,Hwt,Epo,Em,AIR,K,Co,IR,Ny,Hmv,Hvv,Hft,Hsf,Hmf,Hsv,Hsp,Cmv,Cvv,Cft,
  Csf,Cmf,Csv,Csp,Cfma,Cfs,Cfm,Cfl,Ccma,Ccs,Ccm,Ccl,Cedma,Ceds,Cedm,Cedl;
        int Nsx,Nsy, toff;
        char  LCH;
        double V,W;         };
//*****************************************************************************
                                  /* functions body */
//*****************************************************************************
 void drip::setIWR (int nsx,int nsy,float s, char  lch)
 { Nsx=nsx;Nsy=nsy;slope=s;  LCH= lch; }
//*****************************************************************************
float drip::lengthoflateral(float slope,char  LCH)
{float Ll;
      if ( LCH=='C') Ll = 0.5*(LYofsubunit()-se);
        else Ll = 0.5*(LXofsubunit()-se);
        return Ll; }
//*****************************************************************************
float drip :: operatingpressure(float X, float Ke)
{  double y = selectedemitterdischarge()/Ke;
      double z = 1/X;
      float Ho = pow(y,z);
      return Ho;    }
```

```
//**********************************************************************
float drip:: subunitvariation(float EU,float CV,float X)
{      double Y = (EU/(1-(1.27*CV/sqrt(emitterspertree()))));
       double Z = 1/X;
       float Hm = operatingpressure(X, Ke)* (pow(Y, Z));
          return  2.5*(operatingpressure(X, Ke)-Hm);          }
//**********************************************************************
float drip::Cfactor(float Epo)
{float F; //
       if (Epo==1)F = (1/2.75) +(1/(2*lateraloutlets())) + (sqrt(0.75))/(6*
lateraloutlets()*lateraloutlets());
   if (Epo==0.5) F = (2*lateraloutlets()/(2*lateraloutlets()-1))*((1/2.75)+
   (sqrt(0.75)/(6*lateraloutlets()*lateraloutlets())));
   return F;  }
//**********************************************************************
float drip::lateralheadloss ()
{double Dl[10]={9.3,12.8,16.2,20.6,26.6,33.6,42.2,53.5,63.9,76.6};
float hfl=0,hf;
for (int i = 0; i<10; i++)
{hf = Cfactor(Epo)*0.4654*lengthoflateral(slope,
                         LCH)*pow(lateraldischarge(),1.75)/pow(Dl[i],4.75);
if (hf<=0.55*subunitvariation(EU,CV,X)) hfl=(hfl>hf)?hfl:hf;}
   return hfl; }
//**********************************************************************
float drip::lateraldia()
{float  D,dia, dial;
dia= pow(Cfactor(Epo)*0.4654*lengthoflateral(slope, LCH)*
                pow(lateraldischarge(),1.75)/lateralheadloss (),1/4.75)
  dial =(15*(dia+1.1)/13);
  if (dial - int(15*(dia+1.1)/13)>0.5) D = ceil (dial);
  if (dial - int(15*(dia+1.1)/13) < 0.5) D = int(dial);
    return D;     }
//*******************************************************************
float drip::manifoldoutlets(char  LCH)
{float F;
            if ( LCH=='C')F = ceil(LXofsubunit()/Sl);
            else if ( LCH=='B')F = ceil(LYofsubunit()/Sl);
            return F;    }
//*******************************************************************
float drip::cfactormanifold()
```

```
{ float F;
 if (Epo==1)F = (1/2.75) +(1/(2*manifoldoutlets( LCH))) + (sqrt(0.75))/(6
*manifoldoutlets( LCH)*manifoldoutlets( LCH));
   if (Epo==0.5) F = (2*manifoldoutlets( LCH)/(2*manifoldoutlets(LCH)-1))*(
   (1/2.83)+(sqrt(0.75)/(6*manifoldoutlets( LCH)*manifoldoutlets(LCH))));
   return F;    }
//*************************************************************************
float drip::manifoldlength(float slope,char  LCH)
{      if (slope==0&& LCH=='C') return LXofsubunit()-0.5*Sl;
            else  return LYofsubunit()-0.5*Sl;    }
//*************************************************************************
double drip::manifolddia()
{ float hfm=0,hf,dia,hf1,hf2,diam,D,hfa;
 double Dm[18]={12.8,16.2,20.6,26.6,33.6,42.2,53.5,63.9,76.6,94.2,120.2,
        137.6,154.9,172.2,193.9,215.6, 241.6,271.9};
 hfa = allowablemanifoldvariation ()+ slope*manifoldlength(slope, LCH)/100;
if (slope==0){
    for (int i = 0; i<18; i++){
          hf = cfactormanifold()*0.4654*manifoldlength(slope, LCH)*
          pow(manifolddischarge(),1.75)/pow(Dm[i],4.75);
          if (hf<=allowablemanifoldvariation ()) hfm=(hfm>hf)?hfm:hf;
          }dia=pow(cfactormanifold()*0.4654*manifoldlength(slope, LCH)*
          pow(manifolddischarge(),1.75)/hfm,1/4.75);          }
else {
    for(int i=0;i<18;i++) {
            hf1 = cfactormanifold()*.4654*manifoldlength(slope, LCH)*
            pow(manifolddischarge(),1.75)/pow(Dm[i],4.75);
            hf2 = cfactormanifold()*.4654*manifoldlength(slope, LCH)*
            pow(manifolddischarge(),1.75)/pow(Dm[i+1],4.75);
           if (hf1 > hfa && hf2 < hfa){
              dia = Dm[i]; break;}
}}
dia = (dia<271.9)? dia : 271.9;
diam =(15*(dia+1.1)/13);
  if (diam - int(15*(dia+1.1)/13)>0.5) D = ceil (diam);
  if (diam - int(15*(dia+1.1)/13) < 0.5) D = int(diam);
 return D;  }
//*************************************************************************
double drip::manifolddia2()
 { float hfm,dm,hf1,hf2,diam,D,hfa;
```

```
 Double Dm[18]={12.8,16.2,20.6,26.6,33.6,42.2,53.5,63.9,76.6,94.2,
        120.2,137.6,154.9,172.2,193.9,215.6, 241.6,271.9 },d2;
 hfa = allowablemanifoldvariation ()+ slope*manifoldlength(slope, LCH)/100;
if (slope==0){
    for (int i = 0; i<18; i++){
          hfm = cfactormanifold()*0.4654*manifoldlength(slope, LCH)*
          pow(manifolddischarge(),1.75)/pow(Dm[i],4.75);dm=Dm[i];
          if (hfm>=0.45*subunitvariation(EU,CV,X)&&
          hfm<=allowablemanifoldvariation ()) break;   }   }
else {
    for(int i=0;i<18;i++) {
         hf1 = cfactormanifold()*.4654*manifoldlength(slope, LCH)*
         pow(manifolddischarge(),1.75)/pow(Dm[i],4.75);
         hf2 = cfactormanifold()*.4654*manifoldlength(slope, LCH)*
         pow(manifolddischarge(),1.75)/pow(Dm[i+1],4.75);
      if (hf1 > hfa && hf2 < hfa){
                d2 = Dm[i+1]; break;}
}}
diam = (15*(d2+1.1)/13);
        if (diam - int(15*(d2+1.1)/13)>0.5) D = ceil (diam);
        if (diam - int(15*(d2+1.1)/13) < 0.5) D = int(diam);
        return D;}
//*******************************************************************
double drip::manifold_L1()
 { double hfm,dm,hf1,hf2,diam,hfa, L1;
 double Dm[18]={12.8,16.2,20.6,26.6,33.6,42.2,53.5,63.9,76.6,94.2,
     120.2,137.6,154.9,172.2,193.9,215.6, 241.6,271.9 };
 hfa = allowablemanifoldvariation ()+ slope*manifoldlength(slope, LCH)/100;
if (slope==0){
    for (int i = 0; i<18; i++){
          hfm = cfactormanifold()*0.4654*manifoldlength(slope, LCH)*
          pow(manifolddischarge(),1.75)/pow(Dm[i],4.75);dm=Dm[i];
          if (hfm>=0.45*subunitvariation(EU,CV,X)&&
          hfm<=allowablemanifoldvariation ()) break;   }  }
else {
    for(int i=0;i<18;i++) {
         hf1 = cfactormanifold()*.4654*manifoldlength(slope, LCH)*
         pow(manifolddischarge(),1.75)/pow(Dm[i],4.75);
         hf2 = cfactormanifold()*.4654*manifoldlength(slope, LCH)*
         pow(manifolddischarge(),1.75)/pow(Dm[i+1],4.75);
```

```
      if (hf1 > hfa && hf2 < hfa)    break;   }
}
    L1 =manifoldlength(slope, LCH)*pow((hfa- hf2)/(hf1-hf2),(1/2.75));
return L1; }
//**********************************************************************
double drip::Hf1()
{ double hf1;
    hf1 = cfactormanifold()*.4654*manifoldlength(slope, LCH)*
              pow(manifolddischarge(),1.75)/pow(manifolddia(),4.75);
return hf1;}
//**********************************************************************
double drip::Hf2()
{ double hf2;
hf2 = cfactormanifold()*.4654*manifoldlength(slope, LCH)*
pow(manifolddischarge(),1.75)/pow(manifolddia2(),4.75);
return hf2;}
//**********************************************************************
float drip :: manifoldheadloss(float slope)
{float h;
   if (slope ==0 ||manifolddia()==manifolddia2())
         h = cfactormanifold()*0.4654*manifoldlength(slope, LCH)*
          pow(manifolddischarge(),1.75)/pow(manifolddia(),4.75);
   else
   h = allowablemanifoldvariation()-slope*manifoldlength(slope, LCH)/100;
   return h;}
//**********************************************************************
float drip :: manifoldinlethead ()
{float hm;
 if (slope == 0 ||manifolddia()== manifolddia2())
   hm = inletlateralhead ()+ 0.75*manifoldheadloss(slope)-
                       manifoldlength(slope, LCH)*slope/100;
 else
  hm = inletlateralhead ()+ 0.63*manifoldheadloss(slope)-
                       manifoldlength(slope, LCH)*slope/100;
  return hm;  }
//**********************************************************************
int drip::Nsubmains(float slope,char  LCH)
{float Ns;
      if ( LCH=='C') Ns = Lfx/LXofsubunit();
        else {if (slope==0) Ns = Lfy/LYofsubunit();
```

```
           else Ns =2* Lfy/LYofsubunit();}
        return int(Ns);      }
//************************************************************************
float drip::submainlength(char  LCH)
{float L;
if ( LCH=='C') L = 0.5*(Lfy-LYofsubunit());
else if ( LCH=='B') L = 0.5*(Lfx-LXofsubunit());
return L; }
//************************************************************************
double drip::maindischarge(char  LCH)
{double Q;
if ( LCH=='C') Q = (Qsystem ())/2;
else if ( LCH=='B') Q = Qsystem ();
return Q;      }
//************************************************************************
float drip::mainlength(char  LCH)
{float L;
if ( LCH=='C') L = (Lfx-2*LXofsubunit())/2;
else if ( LCH=='B') L = (Lfy-LYofsubunit());
return L;  }
//************************************************************************
float drip:: Tlengthoflaterals(float slope)
{float L;
      if (slope==0&&LCH=='C')
                 L = (A*(1-se/LYofsubunit())/Sl);
      else
                 L = (A*(1-se/LXofsubunit())/Sl);
            return L;}
//************************************************************************
 float drip:: Tlengthofmanifolds(char LCH)
 {float L;
      if (slope==0&&LCH =='C')
               L = (A*(1-Sl/(2*LXofsubunit()))/LYofsubunit());
      else
               L = (A*(1-Sl/(2*LYofsubunit()))/LXofsubunit());
      return L; }
//************************************************************************
float drip :: manifoldcost (float slope)
{float C;
  if (slope == 0)
```

```
      C = 0.75*((K1*manifolddia()*manifolddia()+K2*manifolddia()+K3)*
                                                    Tlengthofmanifolds( LCH));
  else C = 0.75*(((K1*manifolddia()*manifolddia()+K2*manifolddia()+K3)*
     Tlengthofmanifolds( LCH)* manifold_L1()/manifoldlength(slope, LCH))+
     ((K1*manifolddia2()*manifolddia2()+K2*manifolddia2()+K3)*
     Tlengthofmanifolds( LCH)*(manifoldlength(slope, LCH)-
     manifold_L1())/manifoldlength(slope, LCH)));
  return C;}
//**********************************************************************
float drip:: Tlengthofsubmains(float slope,char  LCH)
{float L;
      if (slope==0&& LCH=='C')
      L = (0.5*(Lfy-LYofsubunit())*Lfx/LXofsubunit());
      else if (slope==0&& LCH=='B')
      L = (0.5*(Lfx-LXofsubunit())*Lfy/LYofsubunit());
      else if(slope!=0&& LCH=='B')
      L = ((Lfx-LXofsubunit())*Lfy/LYofsubunit());
      return L;      }
//**********************************************************************
float drip::Tlengthofmain(char  LCH)
{float L;
if ( LCH=='C') L = (Lfx-2*LXofsubunit());
else L = (Lfy-LYofsubunit());
return L;   }
//**********************************************************************
double drip::submaindia()
{double D[16]={20.6,26.6,33.6,42.2,53.5,63.9,76.6,94.2,120.2,137.6,
154.9,172.2,193.9,215.6, 241.6,271.9},
d2,d1,hfs,hfma,hft,Hpu,Pm,Aen,Ct,C1,C2=298.593e+012,temp,D11,dias,Dias;
for (int i=0;i<16;i++) {
    for (int j=0;j<16;j++){
                d1=D[i];
                d2=D[j];
            if (d1>d2) continue;
            else {
hfs= 0.4654*submainlength( LCH)*pow(submaindischarge(),1.75)/pow(d1,4.75);
hfma=0.4654*(mainlength( LCH)*pow(maindischarge( LCH),1.75))/pow(d2,4.75);
hft=hfs+hfma;
Hpu=hft+manifoldinlethead ()+Sh+Hwt+Hmv +Hvv+Hft+Hsf+Hmf+Hsv+Hsp;
Pm=0.0000027*Qsystem ()*Hpu/(Ep*Em);
```

```
Aen=Pm*AIR*(Lfx*Lfy)/(EU*Qsystem ());
Ct=(K*pow((0.00000028*Qsystem()),V)*pow(Hpu,W))+ emittercost()+
    lateralcost()+ manifoldcost(slope)+(K1*d1*d1 +K2*d1+K3)*
    Tlengthofsubmains(slope, LCH)+(K1*d2*d2 +K2*d2+K3)*Tlengthofmain( LCH)+
    Aen*Co*((1-pow((1+IR),(-1*Ny)))/IR);
                  temp=C2;
                  C2=Ct;
                  C1=temp;
                  if(C1-C2<0)
D11= pow(0.4654*submainlength( LCH)*pow(submaindischarge()
                               ,1.75)/hfs,1/4.75); break; }
            if(C1-C2<0) break;}
            if(C1-C2<0) break;}
                              D11 = (D11<271.9)? D11 : 271.9;
                              dias =(15*(D11+1.1)/13);
  if (dias - int(15*(D11+1.1)/13)>0.5) Dias = ceil (dias);
  if (dias - int(15*(D11+1.1)/13) < 0.5) Dias = int(dias);
      Dias =(manifolddia()>Dias)?manifolddia():Dias;
                 return Dias;                   }
//**************************************************************************
double drip::maindia()
{double D[16]={20.6,26.6,33.6,42.2,53.5,63.9,76.6,94.2,120.2,137.6,
154.9,172.2,193.9,215.6, 241.6,271.9},
d2,d1,hfs,hfma,hft,Hpu,Pm,Aen,Ct,C1,C2=298.593e+012,temp,D21, diama,Diama;
for (int i=0;i<16;i++) {
    for (int j=0;j<16;j++){
                d1=D[i];
                d2=D[j];
            if (d1>d2) continue;
            else {
hfs=.4654*submainlength( LCH)*pow(submaindischarge()
                               ,1.75)/pow(d1,4.75);
hfma=0.4654*(mainlength( LCH)*pow(maindischarge( LCH),1.75))/pow(d2,4.75);
hft=hfs+hfma;
Hpu=hft+manifoldinlethead ()+Sh+Hwt+Hmv +Hvv+Hft+Hsf+Hmf+Hsv+Hsp;
Pm=0.0000027*Qsystem ()*Hpu/(Ep*Em);
Aen=Pm*AIR*(Lfx*Lfy)/(EU*Qsystem ());
Ct=(K*pow((0.00000028*Qsystem ()),V)*pow(Hpu,W))+ emittercost()+
lateralcost()+ manifoldcost(slope)+(K1*d1*d1 +K2*d1+K3)*Tlengthofsubmains
(slope, LCH)+(K1*d2*d2 +K2*d2+K3)*Tlengthofmain( LCH)+Aen*Co*((1-pow((1+IR),
```

```
(-1*Ny)))/IR);
                    temp=C2;
                    C2=Ct;
                    C1=temp;
                    if(C1-C2<0)
D21= pow(0.4654*mainlength( LCH)*pow(maindischarge( LCH)
                              ,1.75)/hfma,1/4.75);
            }if(C1-C2<0) break;}if(C1-C2<0) break;}
                         D21 = (D21<271.9)? D21 : 271.9;
                              diama =(15*(D21+1.1)/13);
  if (diama - int(15*(D21+1.1)/13)>0.5) Diama = ceil (diama);
  if (diama - int(15*(D21+1.1)/13) < 0.5) Diama = int(diama);
             Diama =(submaindia()<Diama)? Diama :submaindia();
             return Diama;                  }
//*************************************************************************
float drip :: costofaccessories ()
{ float Cfi,Cco, Ced,Ca;
Cfi = Cfma*Tlengthofmain( LCH)/12 +
                        Cfs*submainlength( LCH)*Nsubmains(slope, LCH)/12;
Cco = Ccma + Ccs*Nsubmains(slope, LCH) + Ccm *Nofsubunits() +
                                Ccl*manifoldoutlets( LCH);
Ced = Cedma + Ceds*Nsubmains(slope, LCH)+ Cedm *Nofsubunits() +
                                        Cedl*manifoldoutlets( LCH);
if ( LCH=='C') Ca=0.75*(Ccma + Cedma +Cfi +Cco + Ced);
else Ca = 0.75*(Cfi + Cco + Ced);
return Ca; }
//*************************************************************************
float drip::operatingcost()
{float Cop,Hpu,Pm,Aen;
Hpu=submainheadloss()+mainheadloss()+manifoldinlethead ()+Sh+Hwt+Hmv
                     +Hvv+Hft+Hsf+Hmf+Hsv+Hsp;
Pm=9.8*Hpu/(Ep*Em);
Aen=0.00000028*Pm*AIR*(Lfx*Lfy)/(EU);
Cop= 0.75*Aen*Co*((1-pow((1+IR),(-1*Ny)))/IR);
                              return Cop;              }
//*************************************************************************
float drip::totalcost()
{  double Hpu,Ct;
Hpu=submainheadloss()+mainheadloss()+manifoldinlethead ()+Sh+Hwt+Hmv
                     +Hvv+Hft+Hsf+Hmf+Hsv+Hsp;
```

```
Ct=0.75*(K*pow((0.00000028*Qsystem ()),V)*pow(Hpu,W))+ emittercost()+
   lateralcost()+ manifoldcost(slope)+ mainsubmaincost()+
   costofcontrolhead()+costofaccessories ()+operatingcost();
                              return Ct; }
//**************************************************************************
void drip::readdata()
{   cout<<"\n WELCOME TO THE DESIGN OF DRIP IRRIGATION SYSTEM";
    cout<<"\n Please Enter The Following Data with the indicated unit";
    cout<<"\n moisture content at field capacity (%)= ";cin>>FC;
    cout<<"\n permanent wilting point(%)= ";cin>>PWP;
    cout<<"\n bulk density of the soil = "; cin>>Bd;
    cout<<"\n effective root zone depth (in m) = ";cin>>Rz;
    cout<<"\n management allowed deficit  = ";cin>>MAD;
    cout<<"\n wetted portion of the area ( in decimal)= ";cin>>Wa;
    cout<<"\n application efficiency( in decimal) = ";cin>>Ae;
    cout<<"\n peak daily crop evapotranspiration (in mm/day) = ";cin>>ETc;
    cout<<"\n number of days without irrigation (day) = ";cin>>toff;
    cout<<"\n available time for irrigation per day (h) = ";cin>>Tav;
    cout<<"\n basic infiltration rate of the soil (mm/h) ="; cin>>Is;
    cout<<"\n plant and emitter spaceing = ";cin>>Sl>>Se;
    cout<<"\n dimensions of the field in the X and Y direction
              respectively = ";cin>>Lfx>>Lfy;
    cout<<"\n area of the field";cin>>A;
    cout<<"\n the required emission uniformity (EU) = "; cin>>EU;
    cout<<"\n emitters discharge coefficeint(Ke) = ";cin>>Ke;
    cout<<"\n emitter discharge exponent(x) = "; cin>>X;
    cout<<"\n emitters coefficient of variation (Cv) = ";cin>>CV;
    cout<<"\n cost per emitter = ";cin>>Cpe;
    cout<<"\n the cost coefficients of the pipe ";
              cout<<"\n K1 = ";cin>>K1;
              cout<<"\n K2 = ";cin>>K2;
              cout<<"\n K3 = ";cin>>K3;
    cout<<"\n the pump cost constants  ";
              cout<<"\n K = ";cin>>K;
              cout<<"\n V = ";cin>>V;
              cout<<"\n W = ";cin>>W;
    cout<<"\n the cost of each control head components ";
    cout<<"\n a) main valve = ";cin>>Cmv;
    cout<<"\n b) volumetric valve = "; cin>>Cvv;
    cout<<"\n c) fertilizer unit = ";cin>>Cft;
```

```
    cout<<"\n d) screen filter = "; cin>>Csf;
    cout<<"\n e) media filter = "; cin>>Cmf;
    cout<<"\n f) subunit valve = "; cin>>Csv;
    cout<<"\n g) subunit pressure regulator = "; cin>>Csp;
    cout<<"\n cost of fittings for main and submain respectively
              =";cin>>Cfma>>Cfs;
    cout<<"\n cost of connectors of  ";
           cout<<"\n main = "; cin>>Ccma;
           cout<<"\n submain = ";cin>>Ccs;
           cout<<"\n manifold = "; cin>>Ccm;
           cout<<"\n lateral = "; cin>>Ccl;
    cout<<"\n cost of ends for  ";
           cout<<"\n main = "; cin>>Cedma;
           cout<<"\n submain = ";cin>>Ceds;
           cout<<"\n manifold = "; cin>>Cedm;
           cout<<"\n lateral = "; cin>>Cedl;
    cout<<"\n unit operating cost of the system = ";cin>>Co;
    cout<<"\n annual irrigation requirement = ";cin>>AIR;
    cout<<"\n interest rate & expected life of components =";cin>>IR>>Ny;
    cout<<"\n position of first outlet along lateral or manifold= ";cin>>Epo;
    cout<<"\n efficiencies of pump and motor respectively=";cin>>Ep>>Em;
    cout<<"\n head loss in the suction pipe and depth to water surface
          respectively = ";cin>>Sh>>Hwt;
    cout<<"\n head loss in each control head components ";
    cout<<"\n a) main valve = ";cin>>Hmv;
    cout<<"\n b) volumetric valve = "; cin>>Hvv;
    cout<<"\n c) fertilizer unit = ";cin>>Hft;
    cout<<"\n d) screen filter = "; cin>>Hsf;
    cout<<"\n e) media filter = "; cin>>Hmf;
    cout<<"\n f) subunit valve = "; cin>>Hsv;
    cout<<"\n g) subunit pressure regulator = "; cin>>Hsp;    }
//**********************************************************************
void drip::printprimary()//primary design parameters
{cout<<"\n Preliminry design parameters              "<<","<<"Value";
cout<<"\n------------------------------------------------------ ";
cout<<"\n Gross irrigation requirement"<<","<<setprecision(2)<<GIR();
cout<<"\n Irrigation interval"<<","<<irrigationinterval();
cout<<"\nDischarge of emitter
              "<<","<<setprecision(0)<<selectedemitterdischarge();
cout<<"\n Number of emitters per plant      "<<","<<emitterspertree();
```

```
cout<<"\n Application rate "<<","<<setprecision(2)<<applicationrate();
cout<<"\n Application time "<<","<<setprecision(2)<<applicationtime();
cout<<"\n Total number of shifts          "<<","<<totalshifts();
cout<<"\n Discharge capacity of the system (l/h)
"<<","<<setprecision(0)<<setiosflags(ios::fixed )<<Qsystem();
cout<<"\n---------------------------------------------------------- ";  }
//***************************************************************************
void drip::printsecondary()//secondary design parameters
{cout<<"\n Final design parameters   (Lsx = "<<LXofsubunit()<<" and Lsy =
"<<LYofsubunit()<<")";
cout<<"\n-----------------------------------------------------------------";
cout<<"\n"<<setiosflags(ios::left)<<setw(20)<<"Parameter"<<","<<setw(15)<<
"Lateral"<<","<<setw(15) <<"Manifold"<<","<<setw(15)<<"Submain"<<","<<
setw(10)<<"Main";
cout<<"\------------------------------------------------------------------";
   if (slope==0)
cout<<"\n"<<setiosflags(ios::left)<<setw(20)<<"Length"<<","<<setw(15)<<setpre
cision(2)<<setiosflags(ios::fixed)<<lengthoflateral(slope, LCH)<<","<<
setw(15)<<setprecision(2)<<setiosflags(ios::fixed)<<manifoldlength(slope,
LCH)<<","<<setw(15)<<setprecision(2)<<setiosflags(ios::fixed)<<submainlength(
LCH)<<","<<setw(10)<<setprecision(2)<<setiosflags(ios::fixed)<<
mainlength( LCH);
 else if (slope!=0)
cout<<"\n"<<setiosflags(ios::left)<<setw(20)<<"Length"<<","<<setw(15)<<
setprecision(2)<<lengthoflateral(slope,
LCH)<<","<<setprecision(2)<<manifold_L1()<<","<<setw(12)<<manifold_L2()<<","<
<setw(15)<<setprecision(2)
<<submainlength( LCH)<<","<<setw(10)<<setprecision(2)<<mainlength( LCH);
cout<<"\n"<<setiosflags(ios::left)<<setw(20)<<"Discharge (l/h)"<<","<<setw
(15)<<setprecision(0)<<lateraldischarge()<<","<<setw(15)<<setprecision(0)<<ma
nifolddischarge()<<","<<setw(15)<<setprecision(0)<<submaindischarge()<<","<<s
etw(10)<<setprecision(0)<<maindischarge( LCH);
cout<<"\n"<<setiosflags(ios::left)<<setw(20)<<"Headloss"<<","<<setw(15)<<setp
recision(2)<<setiosflags(ios::fixed)<<lateralheadloss()<<","<<setw(15)<<setpr
ecision(2)<<setiosflags(ios::fixed)<<manifoldheadloss(slope)<<","<<setw(15)<<
setprecision(2)<<setiosflags(ios::fixed)<<submainheadloss()<<","<<setw(10)
<<setprecision(2)<<setiosflags(ios::fixed)<<mainheadloss();
 if (slope==0)
cout<<"\n"<<setiosflags(ios::left)<<setw(20)<<"Diameter"<<","<<setw(15)<<setp
recision(0)<<lateraldia()<<","<<setw(15)<<setprecision(0)<<manifolddia()<<","
```

```
<<setw(15)<<setprecision(0)<<submaindia()<<","<<setw(10)<<setprecision(0)<<ma
india();
else if (slope!=0)
cout<<"\n"<<setiosflags(ios::left)<<setw(20)<<"Diameter"<<","<<setw(15)<<setp
recision(0)<<lateraldia()<<","<<setprecision(0)<<manifolddia()<<","<<setw(12)
<<manifolddia2()<<","<<setw(15)<<setprecision(0)<<submaindia()<<","<<setw(10)
<<setprecision(0)<<maindia();
cout<<"\n"<<setiosflags(ios::left)<<setw(20)<<"Inletpressure"<<","<<setw(15)<
<setprecision(2)<<setiosflags(ios::fixed)<<inletlateralhead()<<","<<setw(15)<
<setprecision(2)<<setiosflags(ios::fixed)<<manifoldinlethead()<<","<<setw(15)
<<setprecision(2)<<setiosflags(ios::fixed)<<submaininlethead()<<","<<setw(10)
<<setprecision(2)<<setiosflags(ios::fixed)<<maininlethead();
cout<<"\n"<<setiosflags(ios::left)<<setw(20)<<"Totallength"<<","<<setw(15)<<s
etprecision(0)<<Tlengthoflaterals(slope,
LCH)<<","<<setw(15)<<setprecision(0)<<Tlengthofmanifolds(
LCH)<<","<<setw(15)<<setprecision(2)<<Tlengthofsubmains(slope,
LCH)<<","<<setw(10)<<setprecision(2)<<Tlengthofmain(LCH);
 cout<<"\n------------------------------------------------------------"; }
//***********************************************************************
void drip:: printcosts()
{cout<<"\n"<<setiosflags(ios::left)<<setw(3)<<Nofsubunits()<<","<<setw(8)<<se
tprecision(2)<<LXofsubunit()<<","<<setw(8)<<setprecision(2)<<LYofsubunit()<<"
,"<<setw(8)<<setprecision(0)<<emittercost()<<","<<setw(7)<<setprecision(0)<<l
ateralcost()<<","<<setw(7)<<setprecision(0)<<manifoldcost(slope)<<","<<setw(7
)<<setprecision(0)<<mainsubmaincost()<<","<<setw(7)<<setprecision(0)<<costofc
h_as()<<","<<setw(7)<<setprecision(0)<<operatingcost()<<","<<setw(7)<<setprec
ision(0)<<totalcost();}
//***********************************************************************
                              /* Main program */
int main ()
{ float s, I,T, q[4]={2,4,6,8};
double min = 1e+12;
int nsx,nsy,n,Nsx[6]={2,4,6,8,10,12},Nsy[6]={2,4,6,8,10,12},N[6]=
{1,2,3,4,5,6};
    drip x;
    x.readdata();
    char output, lch;
cout<<"\n enter slope of field & location of control head = ";cin>>s>> lch;
cout<<"\nspecify the output(p parameters,c costs & m minimum)";cin>>output;
    while (output){
```

```
     for (int i=0;i<4;i++){
        for (int j=0;j<6;j++){
           I=(q[i]*N[j])/(x.se*x.Sl);
           T=x.GIR ()/I;
           if (I>=x.Is || T>x.Tav) continue;
             else {n = (int)x.Tav/T;
                    x.Ash = x.A/(n*x.irrigationinterval());
                            x.Ia = I;
                            x.Ta = T;
                            x.qe = q[i];
                            x.Ne = N[j];
       x.printprimary();
       for (int i = 0;i<6;i++)  {
          for (int j=0;j<6;j++)  {
                 nsx=Nsx[i];   nsy=Nsy[j];
        x.setIWR (nsx,nsy,s, lch);
if(x.lateraldischarge()>x.manifolddischarge()||x.manifolddischarge()
     >x.submaindischarge()||x.submaindischarge()>x.maindischarge( LCH))
      continue;
      else if((int(x.Nsis())%x.Nsubmains(s,
LCH)==0||x.Nofsubunits()==x.totalshifts()))
      min = (min<x.totalcost())? min : x.totalcost();}}
       if (output == 'c')
{cout<<"\n"<<setiosflags(ios::left)<<setw(3)<<"Nsu"<<","<<setw(8)<<"Lsx"<<","
<<setw(8)<<"Lsy"<<","<<setw(8)<<"Ce"<<","<<setw(7)<<"Cl"<<","<<setw(7)
<<"Cm"<<","<<setw(7)<<"Cs&Cma"<<"," <<setw(7)<<"ch&ac"<<","<<setw(7)
<<"Co"<<","<<setw(7)<<"Ct";
 cout<<"\n--------------------------------------------------------------";}
      for (int i = 0;i<6;i++)  {
          for (int j=0;j<6;j++)  {
                 nsx=Nsx[i];
                 nsy=Nsy[j];
        x.setIWR (nsx,nsy,s, lch);
if(x.lateraldischarge()>x.manifolddischarge()||x.manifolddischarge()>x.sub
maindischarge()||x.submaindischarge()>x.maindischarge( LCH)) continue;
     else if((int(x.Nsis())%x.Nsubmains(s,
LCH)==0||x.Nofsubunits()==x.totalshifts()))
       if(output=='p') {
                          x.printsecondary();cout<<endl;           }
       else if (output=='c')   {
```

```
                      x.printcosts();cout<<endl;               }
       else if (output=='m'){ // local minimum
            if (x.totalcost() == min) {
                              x.printsecondary();cout<<endl;
           else continue;
            }  }   }  }   }     }
     cout<<"\n do you want to see the other output"; cin>>output;
cout<<endl;
system ("pause");
return 0;}
//***************************************************************************
```

Appendix B: Output of the Program for the Combinations with the Optimal Subunit

Output for the design example (Flat topography field)

```
 Preliminry design parameters                   Value
------------------------------------------------------
 Gross irrigation requirement (mm)                27.06
 Irrigation interval(day)                         4
 Discharge of emitter (l/h)                       4
 Number of emitters per plant                     2
 Application rate (mm/h)                          1.33
 Application time (h)                             20.29
 Total number of shifts                           4
 Discharge capacity of the system (l/h)           160000
------------------------------------------------------

 Final design parameters    (Lsx = 400 and Lsy = 150)
-----------------------------------------------------------------------
Parameter           Lateral        Manifold       Submain        Main
-----------------------------------------------------------------------
Length (m)          73.50          399.00         225.00         0.00
Discharge (l/h)     200            80000          80000          80000
Headloss (m)        0.74           1.60           0.77           0.00
Diameter (mm)       16             140            180            315
Inlet pressure (m)  16.56          17.76          18.53          18.53
Total length (m)    235200         3192           450.00         0.00
-----------------------------------------------------------------------

 Final design parameters    (Lsx = 400.00 and Lsy = 75.00)
-----------------------------------------------------------------------
Parameter           Lateral        Manifold       Submain        Main
-----------------------------------------------------------------------
Length (m)          36.00          399.00         262.50         0.00
Discharge (l/h)     96             38400          76800          80000
Headloss (m)        0.47           1.39           0.84           0.00
Diameter (mm)       12             110            180            315
Inlet pressure (m)  16.35          17.40          18.24          18.24
Total length (m)    230400         6384           525.00         0.00
-----------------------------------------------------------------------

 Final design parameters    (Lsx = 400.00 and Lsy = 50.00)
-----------------------------------------------------------------------
Parameter           Lateral        Manifold       Submain        Main
-----------------------------------------------------------------------
Length (m)          23.50          399.00         275.00         0.00
Discharge (l/h)     64             25600          76800          80000
Headloss (m)        0.16           1.78           0.88           0.00
Diameter (mm)       12             90             180            315
Inlet pressure (m)  16.12          17.45          18.33          18.33
Total length (m)    225600         9576           550.00         0.00
-----------------------------------------------------------------------

 Final design parameters    (Lsx = 200.00 and Lsy = 150.00)
-----------------------------------------------------------------------
Parameter           Lateral        Manifold       Submain        Main
-----------------------------------------------------------------------
Length (m)          73.50          199.00         225.00         200.00
Discharge (l/h)     200            40000          40000          80000
Headloss (m)        0.74           1.94           0.40           0.69
Diameter (mm)       16             90             160            180
Inlet pressure (m)  16.56          18.01          18.42          19.10
Total length (m)    235200         3184           900.00         400.00
-----------------------------------------------------------------------
```

```
 Final design parameters    (Lsx = 200.00 and Lsy = 75.00)
----------------------------------------------------------------------
Parameter            Lateral        Manifold       Submain        Main
----------------------------------------------------------------------
Length (m)           36.00          199.00         262.50         200.00
Discharge (l/h)      96             19200          38400          80000
Headloss (m)         0.47           1.28           0.44           0.69
Diameter (mm)        12             75             160            180
Inlet pressure (m)   16.35          17.31          17.75          18.43
Total length (m)     230400         6368           1050.00        400.00
----------------------------------------------------------------------

 Final design parameters    (Lsx = 200.00 and Lsy = 50.00)
----------------------------------------------------------------------
Parameter            Lateral        Manifold       Submain        Main
----------------------------------------------------------------------
Length (m)           23.50          199.00         275.00         200.00
Discharge (l/h)      64             12800          38400          80000
Headloss (m)         0.16           1.44           0.46           0.69
Diameter (mm)        12             63             160            180
Inlet pressure (m)   16.12          17.20          17.65          18.34
Total length (m)     225600         9552           1100.00        400.00
----------------------------------------------------------------------

 Final design parameters    (Lsx = 133.33 and Lsy = 150.00)
----------------------------------------------------------------------
Parameter            Lateral        Manifold       Submain        Main
----------------------------------------------------------------------
Length (m)           73.50          132.33         225.00         266.67
Discharge (l/h)      200            26800          26800          80000
Headloss (m)         0.74           1.53           0.20           0.92
Diameter (mm)        16             75             160            180
Inlet pressure (m)   16.56          17.70          17.90          18.82
Total length (m)     235200         3176           1350.00        533.33
----------------------------------------------------------------------

 Final design parameters    (Lsx = 133.33 and Lsy = 75.00)
----------------------------------------------------------------------
Parameter            Lateral        Manifold       Submain        Main
----------------------------------------------------------------------
Length (m)           36.00          132.33         262.50         266.67
Discharge (l/h)      96             12864          25728          80000
Headloss (m)         0.47           0.97           0.22           0.92
Diameter (mm)        12             63             160            180
Inlet pressure (m)   16.35          17.08          17.30          18.21
Total length (m)     230400         6352           1575.00        533.33
----------------------------------------------------------------------

 Final design parameters    (Lsx = 133.33 and Lsy = 50.00)
----------------------------------------------------------------------
Parameter            Lateral        Manifold       Submain        Main
----------------------------------------------------------------------
Length (m)           23.50          132.33         275.00         266.67
Discharge (l/h)      64             8576           25728          80000
Headloss (m)         0.16           1.43           0.23           0.92
Diameter (mm)        12             50             160            180
Inlet pressure (m)   16.12          17.19          17.41          18.33
Total length (m)     225600         9528           1650.00        533.33
----------------------------------------------------------------------

 Final design parameters    (Lsx = 100.00 and Lsy = 150.00)
----------------------------------------------------------------------
Parameter            Lateral        Manifold       Submain        Main
----------------------------------------------------------------------
Length (m)           73.50          99.00          225.00         300.00
Discharge (l/h)      200            20000          20000          80000
```

```
Headloss (m)       0.74          1.57          0.12           1.03
Diameter (mm)      16            63            160            180
Inlet pressure (m) 16.56         17.74         17.86          18.89
Total length (m)   235200        3168          1800.00        600.00
-------------------------------------------------------------------

 Final design parameters   (Lsx = 100.00 and Lsy = 75.00)
-------------------------------------------------------------------
Parameter          Lateral       Manifold      Submain        Main
-------------------------------------------------------------------
Length (m)         36.00         99.00         262.50         300.00
Discharge (l/h)    96            9600          19200          80000
Headloss (m)       0.47          1.30          0.13           1.03
Diameter (mm)      12            50            160            180
Inlet pressure (m) 16.35         17.33         17.46          18.49
Total length (m)   230400        6336          2100.00        600.00
-------------------------------------------------------------------

 Final design parameters   (Lsx = 100.00 and Lsy = 50.00)
-------------------------------------------------------------------
Parameter          Lateral       Manifold      Submain        Main
-------------------------------------------------------------------
Length (m)         23.50         99.00         275.00         300.00
Discharge (l/h)    64            6400          19200          80000
Headloss (m)       0.16          1.85          0.14           1.03
Diameter (mm)      12            40            160            180
Inlet pressure (m) 16.12         17.50         17.64          18.67
Total length (m)   225600        9504          2200.00        600.00
-------------------------------------------------------------------

 Final design parameters   (Lsx = 80.00 and Lsy = 150.00)
-------------------------------------------------------------------
Parameter          Lateral       Manifold      Submain        Main
-------------------------------------------------------------------
Length (m)         73.50         79.00         225.00         320.00
Discharge (l/h)    200           16000         16000          80000
Headloss (m)       0.74          0.85          0.08           1.10
Diameter (mm)      16            63            160            180
Inlet pressure (m) 16.56         17.20         17.28          18.37
Total length (m)   235200        3160          2250.00        640.00
-------------------------------------------------------------------

 Final design parameters   (Lsx = 80.00 and Lsy = 75.00)
-------------------------------------------------------------------
Parameter          Lateral       Manifold      Submain        Main
-------------------------------------------------------------------
Length (m)         36.00         79.00         262.50         320.00
Discharge (l/h)    96            7680          15360          80000
Headloss (m)       0.47          2.04          0.09           1.10
Diameter (mm)      12            40            160            180
Inlet pressure (m) 16.35         17.88         17.97          19.07
Total length (m)   230400        6320          2625.00        640.00
-------------------------------------------------------------------

 Final design parameters   (Lsx = 80.00 and Lsy = 50.00)
-------------------------------------------------------------------
Parameter          Lateral       Manifold      Submain        Main
-------------------------------------------------------------------
Length (m)         23.50         79.00         275.00         320.00
Discharge (l/h)    64            5120          15360          80000
Headloss (m)       0.16          1.00          0.09           1.10
Diameter (mm)      12            40            160            180
Inlet pressure (m) 16.12         16.87         16.96          18.06
Total length (m)   225600        9480          2750.00        640.00
-------------------------------------------------------------------
```

```
 Final design parameters   (Lsx = 66.67 and Lsy = 150.00)
-----------------------------------------------------------------------
Parameter                Lateral        Manifold       Submain        Main
-----------------------------------------------------------------------
Length (m)               73.50          65.67          225.00         333.33
Discharge (l/h)          200            13600          13600          80000
Headloss (m)             0.74           1.60           0.06           1.14
Diameter (mm)            16             50             160            180
Inlet pressure (m)       16.56          17.76          17.82          18.96
Total length (m)         235200         3152           2700.00        666.67
-----------------------------------------------------------------------
```

```
 Final design parameters   (Lsx = 66.67 and Lsy = 75.00)
-----------------------------------------------------------------------
Parameter                Lateral        Manifold       Submain        Main
-----------------------------------------------------------------------
Length (m)               36.00          65.67          262.50         333.33
Discharge (l/h)          96             6528           13056          80000
Headloss (m)             0.47           1.28           0.07           1.14
Diameter (mm)            12             40             160            180
Inlet pressure (m)       16.35          17.31          17.38          18.52
Total length (m)         230400         6304           3150.00        666.67
-----------------------------------------------------------------------
```

```
 Final design parameters   (Lsx = 66.67 and Lsy = 50.00)
-----------------------------------------------------------------------
Parameter                Lateral        Manifold       Submain        Main
-----------------------------------------------------------------------
Length (m)               23.50          65.67          275.00         333.33
Discharge (l/h)          64             4352           13056          80000
Headloss (m)             0.16           1.81           0.07           1.14
Diameter (mm)            12             32             160            180
Inlet pressure (m)       16.12          17.48          17.54          18.69
Total length (m)         225600         9456           3300.00        666.67
-----------------------------------------------------------------------
```

```
Subunit and their resulting costs (4th Combination)

Nsu  Lsx      Lsy      Ce      Cl      Cm      Cs&Cma  Ch&ac   Co      Ct
------------------------------------------------------------------------------
8    400.00   150.00   10800   92038   47487   14564   1881    50905   234049

16   400.00   75.00    10800   67433   59639   16991   2187    50617   223956

24   400.00   50.00    10800   66029   61018   17800   2487    50706   225156

16   200.00   150.00   10800   92038   20288   36090   2188    51467   229409

32   200.00   75.00    10800   67433   28799   39947   2801    50810   216937

48   200.00   50.00    10800   66029   31294   41233   3401    50716   219792

24   133.33   150.00   10800   92038   14363   51977   2534    51187   239355

48   133.33   75.00    10800   67433   20810   57763   3453    50590   227132

72   133.33   50.00    10800   66029   20580   59692   4353    50706   228475

32   100.00   150.00   10800   92038   10379   65707   2887    51254   249540

64   100.00   75.00    10800   67433   13686   73422   4113    50865   236681

96   100.00   50.00    10800   66029   13942   75994   5313    51042   239532

40   80.00    150.00   10800   92038   10353   78574   3245    50752   262090

80   80.00    75.00    10800   67433   9271    88217   4777    51433   248458

120  80.00    50.00    10800   66029   13907   91432   6278    50440   255123
```

```
48  66.67   150.00  10800   92038  6808    91009  3606    51329  272087

96  66.67   75.00   10800   67433  9248    102581 5444    50896  262773

144 66.67   50.00   10800   66029  9610    106439 7245    51061  267601
----------------------------------------------------------------------
```

Output for the design example (uniform slope topography field)

```
 Preliminry design parameters                   Value
------------------------------------------------------
 Gross irrigation requirement (mm)                9.5
 Irrigation interval(day)                         2
 Discharge of emitter (l/h)                       2
 Number of emitters per plant                     1
 Application rate (mm/h)                          1.9
 Application time (h)                             5.1
 Total number of shifts                           4
 Discharge capacity of the system (l/h)           20833
-------------------------------------------------------
```

```
 Final design parameters   (Lsx = 75 and Lsy = 150)
-----------------------------------------------------------------------
Parameter             Lateral        Manifold       Submain        Main
-----------------------------------------------------------------------
Length (m)            37.20          148.10,1.00    37.50          150.00
Discharge (l/h)       124            20832          20832          20833
Headloss (m)          0.16           -0.64          0.13           0.16
Diameter (mm)         16             75,90          110            140
Inlet pressure (m)    4.12           2.23           2.35           1.01
Total length (m)      24800          596            150.00         150.00
-----------------------------------------------------------------------
```

```
 Final design parameters   (Lsx = 18.75 and Lsy = 150.00)
-----------------------------------------------------------------------
Parameter             Lateral        Manifold       Submain        Main
-----------------------------------------------------------------------
Length (m)            9.07           95.07,54.03    65.63          150.00
Discharge (l/h)       32             5376           5376           20833
Headloss (m)          0.02           -0.50          0.02           0.16
Diameter (mm)         12             40,50          110            140
Inlet pressure (m)    4.01           2.21           2.23           0.89
Total length (m)      24200          2386           262.50         150.00
-----------------------------------------------------------------------
```

```
 Final design parameters   (Lsx = 18.75 and Lsy = 75.00)
-----------------------------------------------------------------------
Parameter             Lateral        Manifold       Submain        Main
-----------------------------------------------------------------------
Length (m)            9.07           66.20,7.90     65.63          225.00
Discharge (l/h)       32             2688           2688           20833
Headloss (m)          0.02           0.25           0.01           0.24
Diameter (mm)         12             32,40          110            140
Inlet pressure (m)    4.01           3.43           3.44           1.43
Total length (m)      24200          2371           525.00         225.00
-----------------------------------------------------------------------
```

```
 Final design parameters   (Lsx = 18.75 and Lsy = 50.00)
-----------------------------------------------------------------------
Parameter             Lateral        Manifold       Submain        Main
-----------------------------------------------------------------------
Length (m)            9.07           37.68,11.42    65.63          250.00
Discharge (l/h)       32             1792           1792           20833
Headloss (m)          0.02           0.50           0.00           0.27
```

```
Diameter (mm)        12              25,32          110            140
Inlet pressure (m)   4.01            3.84           3.84           1.61
Total length (m)     24200           2357           787.50         250.00
-----------------------------------------------------------------------


 Final design parameters    (Lsx = 18.75 and Lsy = 37.50)
-----------------------------------------------------------------------
Parameter            Lateral         Manifold       Submain        Main
-----------------------------------------------------------------------
Length (m)           9.07            17.61,18.99    65.63          262.50
Discharge (l/h)      32              1344           1344           20833
Headloss (m)         0.02            0.63           0.00           0.28
Diameter (mm)        12              20,25          90             140
Inlet pressure (m)   4.01            4.04           4.05           1.70
Total length (m)     24200           2342           1050.00        262.50
-----------------------------------------------------------------------


 Final design parameters    (Lsx = 18.75 and Lsy = 30.00)
-----------------------------------------------------------------------
Parameter            Lateral         Manifold       Submain        Main
-----------------------------------------------------------------------
Length (m)           9.07            23.59,5.51     65.63          270.00
Discharge (l/h)      32              1088           1088           20833
Headloss (m)         0.02            0.70           0.00           0.29
Diameter (mm)        12              20,25          90             140
Inlet pressure (m)   4.01            4.16           4.17           1.76
Total length (m)     24200           2328           1312.50        270.00
-----------------------------------------------------------------------


 Final design parameters    (Lsx = 18.75 and Lsy = 25.00)
-----------------------------------------------------------------------
Parameter            Lateral         Manifold       Submain        Main
-----------------------------------------------------------------------
Length (m)           9.07            8.95,15.15     65.63          275.00
Discharge (l/h)      32              896            896            20833
Headloss (m)         0.02            0.75           0.00           0.30
Diameter (mm)        12              16,20          90             140
Inlet pressure (m)   4.01            4.25           4.25           1.79
Total length (m)     24200           2314           1575.00        275.00
-----------------------------------------------------------------------
Not that, these design assumes two diameter manifold hence two values of
length and diameter are indicated in each of the above tables.


Subunit and their resulting costs (4th Combination)

Nsu  Lsx     Lsy     Ce     Cl     Cm     Cs&Cma ch&ac  Co     Ct
---------------------------------------------------------------------
4    75.00   150.00  2812   9705   2705   4844   1555   2471   31413

16   18.75   150.00  2812   7083   4099   6245   2015   2462   32015

32   18.75   75.00   2812   7083   2524   11003  2615   2552   36125

48   18.75   50.00   2812   7083   1819   14768  3247   2581   39927

64   18.75   37.50   2812   7083   1426   14128  3886   2597   39589

80   18.75   30.00   2812   7083   1276   16507  4529   2606   42493

96   18.75   25.00   2812   7083   1082   18836  5172   2611   45294
---------------------------------------------------------------------
```