MODELING OF OPTIMAL DESIGN AND MANAGEMENT OF MICRO-IRRIGATION SYSTEM

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ABSTRACT

A nonlinear optimization model for design and management of micro-irrigation system is proposed. The model divides the field into subunits. The decision variables are pipes lengths and diameters (lateral, riser, manifold, auxiliary, submain and main), the total number of subunits, number of sets or shifts operating simultaneously, irrigation time per set, system average operating pressure, pressure at the control head (pump), pump power, emitter average flow rate and total capital cost. The Microsoft Excel Solver tool that applies the Generalized Reduced Gradient (GRG2) nonlinear optimization code was used to solve the optimization problem. The objective function is minimizing the system total cost. Results showed that the cost per unit area increased by increasing the total irrigated area: Meanwhile the total costs increased by increasing the total area in case of irrigating the whole area at once (one shift). The rate of increasing cost depends on the number of shifts, number of sets and number of subunit per set that operate simultaneously. The total costs were affected by the emission uniformity. Results indicated that total cost increased at higher uniformity. This effect increased by decreasing number of shifts.

Keywords: *Modeling, Optimization, Micro-irrigation, Management*

INTRODUCTION

A major challenge of today's society is to increase food production and conserve water resources to accommodate tomorrow's needs. Micro-irrigation is an application system supplying filtered water directly to a plant through an emitter and complex distribution network. The distribution net work is typically subdivided into subunits, each having laterals, manifold, auxiliary, and control unit. The distribution network is divided into subunits for several reasons; increase flexibility in

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irrigation practices, better uniformity of water application to the soil and smaller pipe sizes can be selected throughout the system to reduce the initial investment. The required number and size of subunits depends on, field geometry, application rate, irrigation interval, available system capacity, and the desired operating schedule. **Keller and Karmeli (1975)** stated that a major challenge in system design is to select the optimum size and number of subunits that will achieve economical and efficient operation. **Sharaf (1996)** developed an interactive model to select the most economical design for trickle irrigation submain unit Efficient micro-irrigation systems must meet peak ET requirements, wet enough portion of the root zone and eliminate runoff. All these criteria affect the initial design and are affected by water availability and quality, energy operational costs, and initial component costs.

Raju and Kumar (2004) applied Genetic Algorithms for irrigation planning. The method used to evolve efficient cropping pattern for maximization benefits for irrigation in India. Their results compared with linear programming solution and found to be reasonably close.

Dandy *et al.* (1993) outlined the following main optimization techniques which have been applied to water distribution networks as, Partial enumeration (**Loubser and Gessler 1990**), nonlinear programming (**EI-Bahrawy and Smith** (**1985**)), linear programming (**Quindry *et at.*** (**1981**)) and Genetic algorithms (**Hassanli and Dandy** (**1995**)).

A few studies have been reported on the optimization of pressurized irrigation systems considering the field geometry and subunit sizes. **Oron and Karmeli** (**1979**) applied the combined Generalized Gradient Pressure (GGP) and Branch & Bound (B&B) procedures to an irrigation system to find the optimum values for the number of laterals on a manifold, number of sprinklers on laterals, diameters of manifold and laterals, and the discharges of laterals and sprinklers. Their analysis was limited to minimizing the capital cost for a fixed layout of a sprinkler irrigation system.

Oron and Walker (**1981**) presented an optimization model for sprinkler irrigation systems. Their model was based on the work of **Oron and Karmeli** (**1979**), but extended to various field sizes with various dimensions. The main aims of this work were to compute the number of subunits in both directions of the field, the optimum size of subunits, and the associated diameter of the system components. The system cost, which consists of capital and operating costs, was examined as a function of field geometry, consumptive use and pressure head at the water source. They showed that the optimum division of the field into subunits is greatly affected by the field geometry. It depends not only on the area of the field, but also on its width/length ratio and most economical size of the subunit is the square type.

Oron (**1982**) suggested that fields to be irrigated with permanent pressurized systems should be divided into subunits. The subunit array permits one to irrigate part of the field at a time, achieve a more uniform emitter discharge, increase flexibility in irrigation practices, select smaller pipe sizes throughout the system, and allow one to use an increasing number of emitters per plant during the growing stages of orchards. **Holzapfel *et al.* 1990** found small cost differences among subunit sizes for a specific field size.

Dandy and Hassanli (**1996**), proposed a nonlinear model for optimum design and operation of drip irrigation system on flat terrain. Their optimization model procedure involves complete enumeration approach, which minimizes the sum of the capital cost of the system and the present value of operating cost. In the model, the field was divided to subunits with an assumed layout and configuration of piping system.

Water flow in an irrigation distribution network is a nonlinear process; **Geohring** (**1976**). Friction head losses determined by Darcy-Weisbach formula vary nonlinearly with changes in discharge and/or pipe diameter. Many existing models are restricted to linear problems in which the optimization of a linear objective function is subject to linear constraints in determining optimal distribution networks, utilized linear programming theory. The nonlinearity of the water flow was linearized by prior assumption of network configuration and by assuming that the discharge and pressure head were known at all points within the network except the source. Since the exact network configuration and pressure distribution are not known in the problem of this study, this approach could not be applied.

Saad and Marino (**2002**) developed a linear optimization model to design micro irrigation system with tapered downhill lines, minimizing the annual cost of the hydraulic network and maximizing the uniformity to subunit. Their model proved to be efficient in designing irrigation system in terms of emission uniformity.

Morimorto *et. al*., (**2007**) investigated an optimization water scheduling that improve the quality of Satsuma mandarins using neural networks and Genetic Algorithms. The dynamic changes of sugar and citric content were identified using neural network. An optimal water scheduling was to maximize the sugar contents. Their approach was successful to faithful their objective.

The purpose of this study is to develop an optimization model for design, planning and management of micro irrigation system. The model maintains efficient operation of the system and minimize the total investments cost of the distribution network.

OPTIMIZATION PROBLEM DEVELOPMENT

An optimum irrigation system must not only be capable of supplying maximum water requirement of a crop, but also supplying these requirements in amounts that reduce plant stress without exceeding infiltration rates or saturating the root zone. These requirements mean that water must be distributed uniformly over the entire irrigated area. Operating policies must be reasonable so that initial investments are minimal.

Approximately 70 to 80 percent of trickle irrigation system cost is attributable to the distribution network components (**Dandy and Hassanli, 1996**). Therefore, minimization of their costs becomes an important step. Since the number of components and pipe lengths is generally fixed for a given row spacing and field size, it is necessary to select the size and number of subunits which minimize the initial investment cost of the distribution network. Consequently, the optimization problem is to define the costs of all distribution network components and formulate them along with annual operation cost into an objective function. The problem constrained by relationships that insure proper operation of the system of distributing enough and uniform water to meet ET requirements efficiently as described by soil, water, and plant interrelationships.

Current prices for each element were used to determine a continuous function of the cost. The components are assumed to be; hydraulically compatible within the distribution network; easily assembled to each other and the expected life of all components is nearly the same. The cost function of pipes and tees were limited to power function. The correlation coefficients generated by the regression analysis varied from 0.94 to 1.0 indicating that satisfactory functions were developed. The prices of pipes and tees are related to the diameter and type of material. For polyethylene (PE) and polyvinyl chloride pipes (PVC), the costs of unit length (m) are:

$$CP_{PE} = n1\, D_1{}^{m1} \qquad (1)$$

$$CP_{PVC} = n2\, D_2{}^{m2} \qquad (2)$$

Where:

CP_{PE} = cost in L.E. per unit length (m) of polyethylene (PE) pipe.
CP_{PVC} = cost in L.E. per unit length (m) of polyvinyl chloride (PVC) pipe.
D_1 = inside diameter of lateral or riser pipes, (mm).
D_2 = inside diameter of manifold, auxiliary, submain and main pipes, (mm)
$n1,m1$ = constants for PE pipe cost function
$n2,m2$ = constants for PVC pipe cost function

The cost of tees as a function of diameter and type of material are:

$$CT_{PE} = n3\, D_1{}^{m3} \qquad (3)$$

$$CT_{PVC} = n4\, D_2{}^{m4} \qquad (4)$$

Where:

CT_{PE} = cost in L.E. per unit of polyethylene (PE) tee.
CT_{PVC} = cost in L.E. per unit of polyvinyl chloride (PVC) tee.
D_1 = inside diameter of polyethylene tee, (mm).
D_2 = inside diameter of polyvinyl chloride tee, (mm).
$n3,m3$ = constants for PE tee cost function
$n4,m4$ = constants for PVC tee cost function

The cost of control head including filters, flow meters, pressure gages, valves and injection pump as a function of discharge was estimated according to **Holzapfel *et al.*** (**1990**), by the following:

$$C_{CH} = C1\,[kH^x * ne * nl * 2Nsx * S] - C2 \qquad (5)$$

Where:

C_{CH} = cost in L.E. of the control head.
kH^x = emitter flow rate m^3/h as a function of H, operating pressure and x, k
ne = No. of emitters along the lateral, including both sides of the manifold

nl = No. of laterals along both sides of the manifold.
Nsx = No. of submains, each serving two subunits parallel to the main line
S = No. of sets working simultaneously.
C1,C2 = Constants of control head cost function

The cost of pumping system, as a function of power required to operate the system, was estimated by:

$$C_P = C3\left[\frac{(kH^x.ne.nl\,.2Nsx\,.\;S)\,.TDH}{270\,.P_E}\right] \qquad (6)$$

Where:

C_p = cost of pumping station in L.E.
TDH = total dynamic head, m (summation of operating pressure , friction losses, elevation differences and pump suction left)
P_E = pumping efficiency including pump and motor (decimal).
C3 = Constant of pumping cost function

Cost of energy is a function of the pump power and operating time during the irrigation season assuming the source of power is electricity:

$$C_E = 0.746\left[\frac{(kH^x.ne.nl\,.2Nsx\,.\;S)\,.TDH}{270\,.P_E}\right].\frac{Nsy}{S}\;.LIS.C_{KWH}.T_r \qquad (7)$$

Where:

C_E = cost of energy L.E.
LIS = No. of irrigation days per season or growing season / irrigation interval.
Nsy = System total No. of sets or No. of subunit parallel to the submain line.
Nsy/S = No. of shifts
C_{KWH} = price of kilowatt hour
T_r = maximum irrigation hours per shift per day (h/day)

SYSTEM HYDRAULIC LOSSES

Darcy-Weisbach formula was applied to determine the friction head loss within the piping system, as well as the Blassius equation:

$$Hf(i) = 79844.75\,.L(i)\,.\;Q(i)^{1.75}D(i)^{-4.75}F(i) \qquad (8)$$

Where:

i =subscript the pipe
Hf = friction loss along the pipe, (m)
F = reduction factor of the pipe as a function of outlets.
L = pipe length (m)
Q = pipe discharge (m^3/h)

D = pipe diameter (mm)

Definitions of system piping (i), system length (L), discharge (Q), and number of outlets (no) are given in Table (1).

Table (1): Definitions of system piping components and variables

Pipe (i)	L, (m)	Q, (m^3/h)	Outlet No. no
Lateral	$0.5(ne-1)\,.se$	$0.5\,ne\,.kH^x$	INT. $(0.5\,ne)$
Manifold	$0.5(nl-1)\,.sl$	$0.5\,(nl\,.ne).kH^x$	INT. $(0.5\,nl)$
Riser	0.6	$ne\,.kH^x$	-
Auxiliary	$0.5(ne\,.se)$	$(nl\,.ne).kH^x$	-
Submain	$Ly-0.5(nl\,.sl)$	$2\,.S.(nl\,.ne).kH^x$	$2\,.S$
Main	$Lx-(ne\,.se)$	$2\,.S.\ Nsx\,.(nl\,.ne).kH^x$	Nsx

Where:

Lx = field length in x direction, (m)

Ly = field length in y direction, (m)

se = spacing between emitters (m)

sl = spacing between laterals (m)

INT = integer number

The pipe outlets reduction factor for the Darcy Weisbach equation was estimated by the following equation:

$$F(i) = 0.33 + \frac{1}{2no} + \frac{1}{6\,ne^2} \qquad (9)$$

Minor loss due to emitter connection barb on lateral was estimated by additional length method according to **SCS, 1984** by:

$$f_e = 1 + \frac{18.91}{se\,.\ Dl^{1.87}} \qquad (10)$$

Then lateral length (L) changed by (L . $\frac{se+fe}{se}$) where D is lateral diameter, (mm).

Tee head loss due to connecting the network pipes was estimated according to **Keller and Bliesner**, (**1990**) by:

$$Hf_T = K_T\frac{V^2}{2g} \quad or \quad 6375.5\,K_T.Q_T{}^2\,.D_T{}^{-4} \qquad (11)$$

Where:

V = water velocity (m/s)

g = acceleration of gravity (m/s^2)

K_T = tee resistance coefficient (1.2 from line to branch flow and 0.8 from branch to line flow)

D_T = diameter of the tee, (mm)
Q_T = discharge across the tee (m^3/h)

In large areas where the field is divided into subunit it is essential to use pressure regulator to assure greater uniformity in water application. Friction loss on it is a function of diameter and discharge. Friction loss at pressure regulator (HF_{PR}) was approximated by an empirical equation according to **Geohrin**, (**1976**) by the following, assuming an average diameter 40 mm of the auxiliary:

$$Hf_{PR} = 0.01336\,(\,kH^x ne\,.nl)^2 + 0.66795(kH^x ne\,.nl) + 1.56941 \qquad (12)$$

Head loss at control head (Hf_{CH}), including filter, counter and valves is a function of discharge, and approximated according to **Holzapfel *et al.* 1990** by:

$$Hf_{CH} = .02\,(2\,.S.\ Nsx\,.(nl\,.ne).kH^x)^{1.474} \qquad (13)$$

MODELING OF THE FIELD GEOMETRY

The problem of optimizing subunit size and the corresponding piping, fittings, and accessories involves a mixture of integer variables describing the subunit and continuous variables describing the hydraulics and costs. A rectangular or square area will be the assumed field geometry as this is the most common shape of agricultural fields. Variables of the field geometry define integer parameters. A summary of these variables and various constants is illustrated in Fig. (1) and (2). The field geometry in Fig. (2) includes three submain lines (Nsx = 3), three subunit parallel to the submain line (Nsy =3) in Y direction and three sets (S=3) each have 6 subunits.

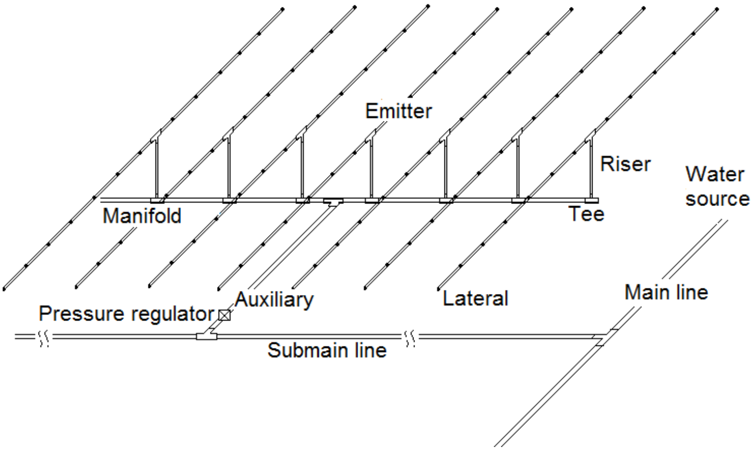


Fig. (1) Schematic diagram of subunit components.

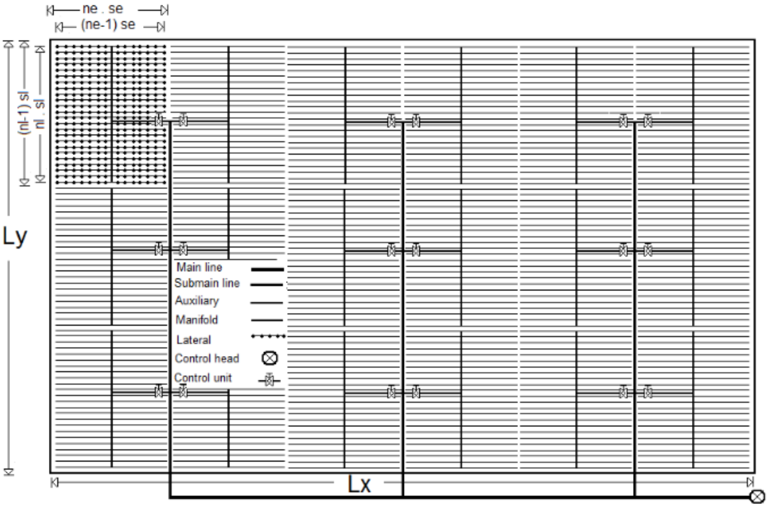


Fig. (2) Field geometry of multiple- subunit trickle irrigation system and parameters description.

The integer variables are *ne, nl, Nsx* and *Nsy* and the constants are *Lx, Ly, se* and *sl*. The number and/or length of all the field components in the distribution network can be expressed with the above variables and constants as given in Table (2).

Table (2): Field components as a function of constants and variables

Total No of emitter on the system TNE	$Lx * Ly\left[\frac{1}{se * sl}\right]$
Total lateral lengths on the system TLL	$Lx * Ly\left[\frac{ne - 1}{sl * ne}\right]$
Total length of riser (hr) on the system TRL	$Lx * Ly\left[\frac{hr}{ne * se * sl)}\right]$
Total length of Manifolds pipes TML	$Lx * Ly\left[\frac{nl - 1}{ne * se * nl}\right]$
Auxiliary pipe lengths TAL	$Lx * Ly\left[\frac{0.5}{nl * sl}\right]$
Submain total length TSUL	$Nsx\left[Ly - \frac{nl * sl}{2}\right]$
Main line total length TMIL	$Lx - (ne * se)$
Total No. of end plugs for laterals	$(2 * nl) * \frac{Lx * Ly}{(ne * se) * (nl * sl)}$
Tees connecting manifold to auxiliary TMA	$\frac{Lx * Ly}{(ne * se) * (nl * sl)}$
Tees connecting riser to manifold TRM Tees connecting lateral to riser TRL	$(nl) * \frac{Lx * Ly}{(ne * se) * (nl * sl)}$
Tees connecting auxiliary to submain TAS	$\frac{Lx * Ly}{(ne * se) * (nl * sl)}$
Tees connecting submain to main TSM	Nsx
Total No. of subunit on the system Ns Total No. of subunit valve TNV Total No. of subunit pressure regulator TNP	$\frac{Lx * Ly}{(ne * se) * (nl * sl)}$

THE OBJECTIVE FUNCTION

The objective is to minimize the total cost of the distribution network components plus the annual operating costs. The annual operating costs are included because they are interrelated with the selection of optimum subunit size and number, and thereby, the size and number of the components. Furthermore, operating costs are directly related to the cost of energy (assumed electrical). The mathematical form of the **objective function** is:

$$minimize \qquad X_O = \left\{ \sum_{i=1}^{i=n} C(i).\ Y(i) \right\} + C_{OP} \qquad (14)$$

Where:

X_O = total cost of the micro- irrigation system, (L.E.)

$C(i)$ = cost function of the i^{th} component in the network, (L.E.).

n = number of different components in the distribution network

Y = total length of pipe (m) or integer number of components.

C_{OP} = annual operating energy cost as function of discharge and head,(L.E.)

Subject to:

1 - The hydraulic constraint from the distal emitter to the source:

$$\frac{He \pm \Delta E + \sum_i^n Hf(i)}{Hs} \leq 1 \qquad (15)$$

Where:

He = emitter average pressure head (m)

i = subscript i^{th} component in the distribution system.

Hs = pressure head at the source (pump)

n = No. of component on the system; lateral riser, manifold, auxiliary, submain, main, tee connecting pipes, pressure regulator and control head.

ΔE = elevation difference between the highest outlet point and pump level

2- The hydraulic constraint to achieve acceptable emission uniformity on the subunit:

An acceptable value of emission uniformity can be obtained by limiting the variation of pressure of the emitter within the subunit that include lateral and tee connecting riser to lateral, riser and tee connecting manifold to riser, auxiliary and tee connecting auxiliary to manifold. Emission uniformity according to **Keller and Karmeli** (**1975**) was defined as:

$$EU = \left[1 - 1.27\frac{v}{\sqrt{np}}\right]\frac{q_{min}}{q_{ave}} \qquad (16)$$

Where:

EU = emission uniformity

v = emitter coefficient of manufacturing variation

np = No. of emitter per plant

q_{min} = minimum emitter flow rate (m^3/h)

q_{ave} = average emitter flow rate (m^3/h)

The relationship between emitter type and pressure could be written as:

$$\frac{H_{min}}{H_{ave}} = \left[\frac{q_{min}}{q_{ave}}\right]^{1/x} \quad or \quad H_{min} = H_{ave}\left[\frac{EU}{1 - 1.27\frac{V}{\sqrt{np}}}\right]^{1/x} \qquad (17)$$

Consider the H_{ave} is the emitter nominal operating pressure H_n, therefore the H_{max} and H_{min} could be changed to:

$$H_{max} = 2H_n - H_{min} \quad and \quad H_{min} = H_n\left[\frac{EU}{1 - 1.27\frac{V}{\sqrt{np}}}\right]^{\frac{1}{x}} \qquad (18)$$

Therefore, the pressure on emitter in the subunit should be bounded to the following constraint:

$$H_{min} \le H_e \le H_{max} \qquad (19)$$

In addition to, the allowable pressure variation within the subunit should not exceed the difference between H_{max} and H_{min} and could be limited to the following constraint:

$$\sum_{j=1}^{j=m} Hf(j) \pm \Delta e \le H_{max} - H_{min} \qquad (20)$$

Where:

m = No. of components within the subunit; lateral, riser, manifold, auxiliary and tees, j subscript the component

Hf = friction loss on component j

3- Equality constraints relating the number of subunits in the field as a function of the total area. The number of subunits parallel to the submain is governed by the following constraint as:

$$Nsy = \frac{Ly}{nl * sl} \quad or \quad \frac{Nsy * nl * sl}{Ly} = 1 \qquad (21)$$

Where:

Nsy = No. of subunit along the submain in Y direction
Ly = Field length parallel to the manifold in Y direction
*n*l = Integer number of laterals along the manifold.
sl = Spacing between two adjacent laterals

The number of subunits parallel to the main line has to be some multiple of two for the field geometry that is specified. For this reason, *Nsx,* is defined to be the number of submains which can supply two subunits, and the number of subunits actually becomes 2* *Ns*x, realizing this fact, this equality constraint becomes:

$$2 * Nsx = \frac{Lx}{ne * se} \quad or \quad \frac{2 * Nsx * ne * se}{Lx} = 1 \qquad (22)$$

4- Suitability of emitter flow rate to soil type and crop. The rate of application from an emitter is a function of pressure head and should satisfy the percentage of wetted area (wr), leaching requirements (LR) and the crop evapotranspiration during the irrigation cycle and should not exceed the infiltration capacity of the soil. This could be achieved by the following constraints:

$$\frac{1000 \, . kH^x}{I \, .wr \, .se \, . \, sl} \leq 1 \qquad (23)$$

Where:

I = soil infiltration rate, (mm/h)
wr = ratio of wetted area (decimal)

$$\frac{1000 \, . kH^X . T_r \, .Ea \, .(1 - LR)}{se \, .sl \, .ET_o . \; kc. \; Kr} = 1 \qquad (24)$$

Where:

T_r = irrigation time per shift per day, (h/day)
Ea = irrigation system efficiency (decimal)
ET_o = reference evapotranspiration, (mm/day)
kc = crop coefficient
Kr = trickle irrigation reduction factor
LR = leaching requirements

5- Main and submain line diameters selection criteria. The head losses on the submains and main lines were restricted to two constraints. The first was that friction loss in both of them not exceeds 15% of the emitter average pressure operating head as:

$$\frac{Hf(sub) + Hf(m)}{0.15\,He} \leq 1 \qquad (25)$$

The second was that the water velocity not exceeds 1.5 m/s:

$$354\,\frac{Q}{D} \leq 1.5 \qquad (26)$$

Where:

Q = discharge of submain or main lines, (m^3/h)

D = diameter of submain or main lines, (mm)

6- The irrigated area by the system must cover the total area:

$$\frac{(se\,.ne).(sl\,.nl).(2\,.Nsx).Nsy}{Lx\,.Ly} = 1 \qquad (27)$$

7- Management aspects required limiting both lateral and manifold lengths to insure uniformity of water application, therefore, it was suggested the following bounds, as shown in Table (3):

Table (3): Constraints limited lateral and manifold in vegetable and Orchard crops

	orchard	Vegetables or closed spacing
Lateral	$30 \leq \frac{(ne-1)se}{2} \leq 75$	$25 \leq \frac{(ne-1)se}{2} \leq 50$
Manifold	$30 \leq \frac{(nl-1)sl}{2} \leq 75$	$25 \leq \frac{(nl-1)sl}{2} \leq 50$

8- The operating policy would not adequately be described without indication of actual operating time of the system. For any given interval, the total irrigation time has to cover the specified operation time within that interval. This constraint takes the form:

$$T_r \leq T_{max} \quad and \quad \frac{T_r\,.Nsy\,.}{S\,.T_{max}\,.\;F} \leq 1 \qquad (28)$$

Where:

T_r = irrigation time per shift per day (h/day)

T_{max} = maximum irrigation hours per day (h/day).

F = irrigation interval, (days)

9- The number of sets that can operate simultaneously is limited by water availability, the constraint to account for this becomes:

$$\frac{S\,.\,2\,Nsx\,.\,ne\,.\,nl\,.\,KH^{x}}{Qs} \leq 1 \qquad (29)$$

Where:

Qs = water discharge available at the source, (m^3/h)

10- It is logical that the most economical operating policy is to operate one subunit along each submain line that leads to reduce the submain diameter, but sometimes the optimum integer number of the subunit working simultaneously is difficult to be distributed equally on the submain lines to cover the irrigation time over the irrigation interval. To avoid this problem, it was suggested to use an optimum integer number of sets instead of number of subunits working simultaneously. To insure that at least two subunits attached to each submain line working simultaneously. Therefore, the minimum number of sets (S) which could be applied is one containing 2Nsx subunits and then the number of shifts equals Nsy/S. Then operating policy constraint of number of shifts becomes:

$$\frac{Nsy}{S} = integer \qquad (30)$$

ALOGRITHM AND METHOD USED

The optimization model was run using the Microsoft Excel Solver tool that applies the Generalized Reduced Gradient (GRG2) nonlinear optimization code. Integer problems use the simplex method with bounds on the variables, and the branch-and-bound method.

The model is carried out by complete enumeration of all alternatives. The basic inputs are:

- Dimensions of the field, (LX), and (LY).
- The spacing between emitters, (se), and laterals, (sl).
- No of irrigation days per season (LIS), and hours available per day for irrigation (Tr).
- Soil field capacity (FC %), welting point (Wp %), wetted area (Wr %), root depth (Rd) and depletion ratio (dr).

- Plant evapotranspiration (ETo), crop coefficient (Kc), reduction factor (Kr) and soil infiltration rate (Ir).
- Emitter constant (x, k), price (Ce), coefficient of flow variation (cv), No of emitter per plant (n) and nominal operating pressure (Ho)
- System application efficiency (Ea) and emission uniformity (EU)
- Source available flow rate (Qs)
- The energy cost (C-kWh)
- The cost functions of the system component.
- Efficiencies for the electric motor (ηm) and pump (ηp)

Assumptions:

In the optimization model, the general configurations of the conveyance piping system within the field (main and submain lines) and within the subunits (lateral, riser, manifold and auxiliary) are fixed. However, the area and the dimensions of the subunits in both X and Y direction change in each run, the lengths and size of all pipes change as well. The model was developed for a field with given area and known dimensions for which the water source is located at any one of the four corners. However, the model can be easily applied to any size and dimensions of field.

RESULTS AND DISCUSSION

The main objective of the study is to identify an optimum design and planning of micro-irrigation system based on multiple subunit system. The model enables an examination of the influence of subunit sizes and shifts on the system total cost and find an optimum solution among various operating conditions. A number of effects were evaluated and discussed among case studies.

Case Study

A numerical example presented as case study to identify the model utility. Assume we need to optimally design and plan a micro irrigation system for a farm of 43.12 Fed. The input data presented in Table(4). The objective function target cell and formulation of constraints showed in solver screen as shown in Fig. (3). The constraints and their values for the case study were presented in Table (5). When solver found solution and all constraints are satisfied, a massage appeared as shown in Fig. (4)

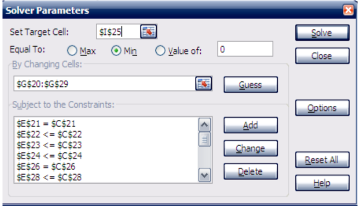
Table. (4): Constants and input data for the case studies.

Variable	value	unit	Variable	value	unit	Variable	value
Se	5	m	X	0.5	-	n1	0.4325
Sl	5	m	Ce	7	LE.	m1	1.0970
LSI	180	day	CV	0.05	-	n2	0.0063
Tr	20	hr	n	1	-	m2	1.6250
FC	20	%	Ho	20	m	n3	0.2010
WP	10	%	Ea	90	%	m3	1.0950
Wr	50	%	EU	90	%	n4	0.0120
Rd	1	m	Qs	1000	m3/hr	m4	1.1960
dr	50	%	PE	60	%	C1	345.0
Ir	12.4	mm/hr	C-kWh	0.4	LE./kwh	C2	275.0
ETcrop	8	mm/day	C-EP	0.5	LE.	C3	350.0
K	0.008	-	C-PR	100	-		

Table (5):Results of satisfaction the hydraulic and management constrains

Parameters	Limit	Actual output
1- For total system to find the pressure at source	≤1	1.00000000
2 - To insure the uniformity at subunit	≤1	1.00000000
3- Constrain friction loss of main and submain	≤1	1.00000000
4- Irrigation available time	≤1	0.26762956
5- Limiting ETcrop	≤1	1.00000000
6- Operating subunits less than total	≤1	0.01666666
7- Average pressure higher than Hmin	≥1	1.19959458
8 - Limiting Run Off	≤1	0.24106502
9- Limiting water velocity on submain	≤1	1.00000000
10 - Limiting water velocity on main	≤1	1.00000000
11-Operating one subunit along each submain	=1	1.00000000
12- Limiting No of Shifts	≥1	6.00000000
13- limiting irrigation frequency	≤1	0.53525910
14 - average pressure less than Hmax	≤1	1.00000000
15- limiting No. of subunit parallel to submain	=1	1.00000000
16- Limiting No. of subunit parallel to main	=1	1.00000000
17- Constrained irrigation area	=1	1.00000000
18- Limiting lateral length 1	≥25	25.0000000
19- Limiting lateral length 2	≤80	25.0000000
20- Limiting manifold length 1	≥25	25.0000000
21- Limiting manifold length 2	≤80	25.0000000
22- Enough water available at the source	≥1	1.00000000

Typical results of the model for total costs of 43.12 Fed. were illustrated in Table (6). The results indicated that the total area divided into 60 subunits. The system has 5 submain lines and each set contain 10 subunits and lateral length is 50 m and the manifold have the same length. The minimum total cost was 2955 LE./Fed. this value was due to operating the system in 6 shifts where 10 subunits operated simultaneously. The other parameters of design, operation and cost analyses are illustrated in Table (6). Material and equipment list shown in Table (7). The configuration and planning of the system according to this design criteria is shown in Fig(5).



Set Target Cell: $I$25

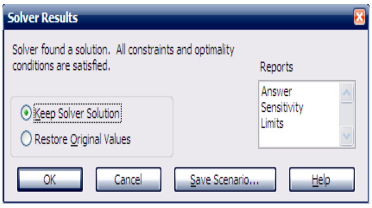
Equal To: ○ Max ● Min ○ Value of: 0

By Changing Cells: $G$20:$G$29

Subject to the Constraints:

```
$E$21 = $C$21
$E$22 <= $C$22
$E$23 <= $C$23
$E$24 <= $C$24
$E$26 = $C$26
$E$28 <= $C$28
```

Fig. (3) : typical solver screan for options and formulating the consraints



Solver found a solution. All constraints and optimality conditions are satisfied.

● Keep Solver Solution
○ Restore Original Values

Fig. (4): massage of solver when constraints are satisfied and solver found solution

Table (6): Results of minimum capital cost for 43.21 Fed. applied six shifts.

Area(Fed.)	43.21428571	Materials	Cost%
SX (m)	550	Lateral	12.07444
SY (m)	330	Riser	0.119442
DX (m)	5	Manifold	2.000142
DY (m)	5	Auxiliary	3.137806
NS	60	Submain	5.610544
Nsx	5	Main	6.360669
Nsy	6	emitters	39.79164
NX	11	Total	69.09468
NY	11		
No. of shifts	6	Accessories.	5.708934
Irr. Time hr	5.352591324	C. head	4.019887
DL (mm)	13.54650287	Pumping	4.146466
DR (mm)	16.96886285	Energy	17.03003
DM (mm	22.27792837	Total	100
DA (mm)	46.03139626		
DSU (mm)	59.28177668	T. cost (L.E.)	127715.3
DMI (mm)	131.4850527	Cost/Fed. (L.E)	2955.395
He (m)	21.81483064		
H source (m)	43.21428571		
Emitter (m^3/h)	0.037365079		
System Q	45.21174611	T friction loss (m)	12.39982
head at pump	54.21465555	Subunit FL (m)	3.629662
Pump(HP)	15.13048915	FL of M+S (m)	3.357103
Pump (KW)	11.28734491	subunit size (m^2)	3025

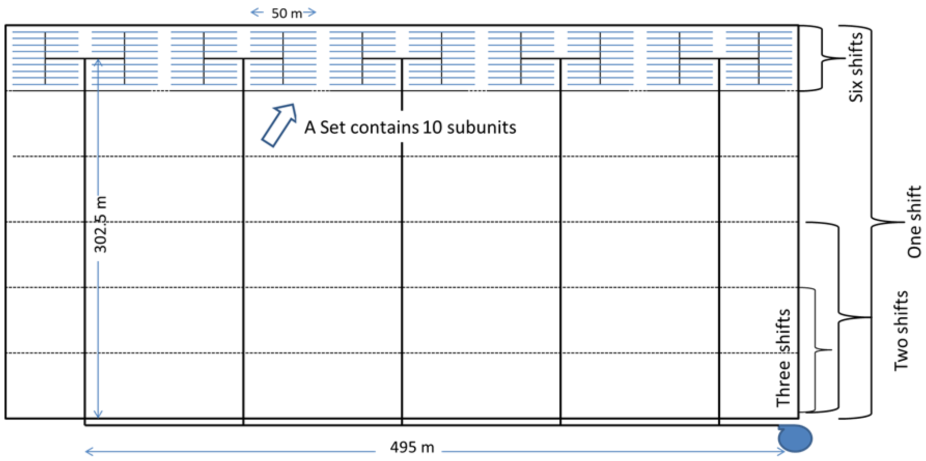


Fig.(5): schematic diagram of 43.21 Fed. and possible options of operating the system in one, two, three or four shifts that get the minimum cost.

Table (7): Result of material and equipment for list for 43.21 Fed.

Variable	Quantity	Unit
Total No of emitter on the system TNE	7260	piece
Total lateral lengths on the system TLL	33000	m
End plugs for laterals TLEP	1320	piece
Total Tees connecting lateral to riser TRL	660	piece
Total length of riser on the system TRL	396	m
Tees connecting riser to manifold TRM	660	piece
Total length of Manifolds pipes TML	3000	m
Tees connecting manifold to auxiliary TMA	60	piece
Auxiliary pipe lengths TAL	1650	m
Submain total length TSUL	1512.5	m
Tees connecting auxiliary to submain TAS	60	piece
Main line total length TMIL	495	m
Tees connecting submain to main TSM or NXM	5	piece
Total No of subunit on the system	60	No.
Total No of subunit valve TNV	60	No.
Total No of subunit pressure regulator TNP	60	No.

ANALYSIS OF THE MODEL

The micro-irrigation optimization model was analyzed for runs using data given in Table (4). This represents irrigation of Orchard crop (plant spacing 5 m x 5 m) field areas as 15.32 Fed. (390 m x165 m), 22.29 Fad.

(390 m x 240 m), 43.21 Fed. (550 m x 330 m) and 91.93 Fed. (780 m x 495 m). The results are presented in Table (8). The upper part of the Table (8) shows the configuration and the layout of the system. The lower part of the table shows management options in case of operating the system for minimum capital cost where the numbers of shifts were 9, 6, 4, 3 respectively and the maximum capital costs when the system operates in one shift and the operational variables related to each operation option.

Irrigating a set of subunits instead of irrigating the whole system simultaneously along with decreasing the total capital and operation cost increases the flexibility and the reliability of the system. Applying partial irrigation to the whole land requires mostly higher emitter flow rate and pressure operating head, which may overcome clogging problems and provide greater wetted area. It is also more flexible in relation to sharing irrigation water for specified set of subunits when available water is either provided from different sources or the field belongs to different owners. It was observed that by increasing the number of shifts, the network, pumping, control head, costs are decreased while energy and emitter costs are increased

Effect of total area and number of shifts on total capital cost:.

The total capital cost of different areas, 91.93, 43.21, 22.29 and 15.32 Fed. irrigated according to the design planned and management criteria resulted in 2917 LE./Fed (9 shifts were applied), 2955 LE./Fed. (6 shifts were applied), 3184 L.E./Fed. (4 shifts were applied) and 3262 L.E./Fed. (3 shifts were applied) respectively. The total capital cost of the previous configurations applying one shift (The whole area is irrigated once in time) showed different results as 6108, 5286, 4817 and 4691 L.E./Fed, respectively. The results indicated in Fig.(6).

In case of applying the system for minimum capital cost, where number of subunit working simultaneously is in one set (higher number of shifts), it is clear that minimum total cost is decreased by different ratios depends on total area, number of shifts and number of subunit per set. The total cost in these cases followed power function as:

$$Xo = 3864\, area^{-0.62} \qquad R^2 = 0.99 \qquad (31)$$

The total cost per unit area (Xo) increased by increasing the irrigated total area in one shift policy as shown in Fig. (6). The relationship showed also power function as:

$$Xo = 3085 \ area^{0.48} \qquad R^2 = 0.98 \qquad (32)$$

Where:

$92 \geq$ area ≥ 15 Fed

Another option of management is to decrease the number of shifts (increasing the number of sets operating simultaneously), this leads to decrease the irrigation time but increase the total capital cost per unit area, the results in Table (9) indicated that the use of higher number of irrigation shifts or decreasing the number of sets operate simultaneously is more economic.

The effect of uniformity on total cost

Effect of uniformity on total cost was investigated for the system total area 43.12 Fed., where the system operated in one and six shifts. The results presented in Fig. (7). The trend was exponential. The effect was higher in case of operating the system in one shift where the total cost increased from 5075 to 5500 L.E./Fed to improve the uniformity from 0.8 to 0.9 . The same trend was found in case of operating the system in 6 shifts (minimum capital cost) where the cost increased from 2863 to 2965 L.E./ Fed. to improve the uniformity for the same range.

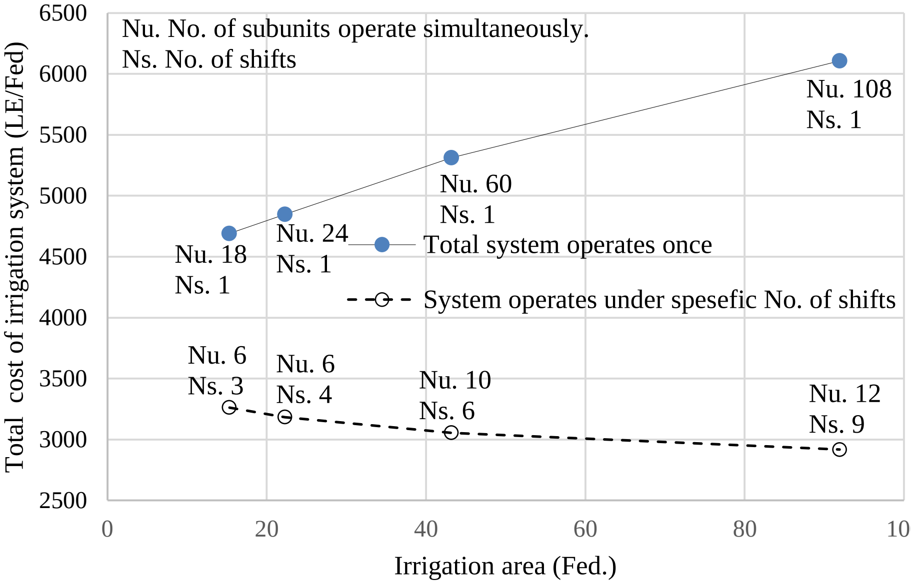


Fig. (6): Effect of total area and No. of shifts on total cost.

Table (8):Results of design, management and minimizing cost of some micro-irrigation areas.

Variables	Total area fed.							
	91.93		43.21		22.29		15.32	
Length Lx(m)	780		550		390		390	
Width Ly (m)	495		330		240		165	
No. of submain lines Nsx	6		5		3		3	
No. of subunit on Y direction (Nsy)	9		6		4		3	
No. of emitters on lateral (ne)	13		11		13		13	
No. of laterals on manifold (nl)	11		11		12		11	
Total No. of subunits (Ns)	108		60		24		18	
Lateral length Ll (m)	60		50		60		60	
Manifold length (Lm) m	50		50		55		50	
Auxiliary length (La)m	32.5		27.5		32.5		32.5	
Submain length (Lsub) m	467.5		302.5		210		137.5	
Length of main line (Lmain) m	715		495		325		325	
No. of Shifts	1	9	1	6	1	4	1	3
Emitter flow rate (q) m^3/h	0.0353	0.0374	.0354	.0374	.0355	.0373	.0350	.0367
Average operating pressure head He (m)	19.48	21.81	19.60	21.82	19.72	21.75	19.34	21.14
Pressure head at pump (Hs) (m)	48.95	35.32	34.15	34.22	31.05	33.13	29.22	32.49
Total dynamic head TDH(m)	68.94	55.32	54.15	54.22	51.05	53.13	49.22	52.49
System water capacity (m^3/h)	545.30	64.12	257.12	45.21	133.00	34.93	90.56	31.56
Pump power(KW)	173.13	16.31	64.12	11.29	31.27	8.55	20.53	7.63
Irrigation time (hr/shift)	5.66	5.35	5.65	5.35	5.63	5.36	5.68	5.44
Total Cost/.fed. (L.E).	6107	2913	5285	2955	4817	3184	4691	3262
Cost of Piping %	42.12	31.59	38.0	29.30	35.37	32.16	34.21	30.29
Cost of Accessories%	2.46	4.94	3.3	5.71	2.86	4.21	3.15	4.44
Cost of Emitter %	19.26	40.31	22.25	39.79	24.27	36.93	25.07	36.05
Cost of Pumping %	14.47	2.85	13.17	4.15	13.58	5.65	13.40	7.16
Cost of control Head %	11.21	2.73	12.97	4.02	14.15	5.56	14.44	7.12
Cost of Energy %	10.68	17.58	9.51	17.03	7.78	15.49	9.74	14.94

Table (9): Total cost related to No. of shifts and No. of subunits operate simultaneously related to the total area.

Area		No. of shifts*								
		1	2	3	4	5	6	7	8	9
15.32	Cost LE./Fed.	4691	-	3262	-	-	-	-	-	-
	No. of subunits*	18		6	-	-	-	-	-	-
22.29	Cost LE./Fed.	4847	3697	-	3184	-	-	-	-	-
	No. of subunits*	24	12	-	6	-	-	-	-	-
43.21	Cost LE./Fed.	5286	3910	3439	-	-	2955	-	-	-
	No. of subunits*	60	30	20	-	-	10	-	-	-
91.93	Cost LE./Fed.	6107	-	3708	-	-	-	-	-	2917
	No. of subunits*	108	-	36	-	-	-	-	-	12

* No. of subunit per set is the subunit No. at the higher No. of shifts.

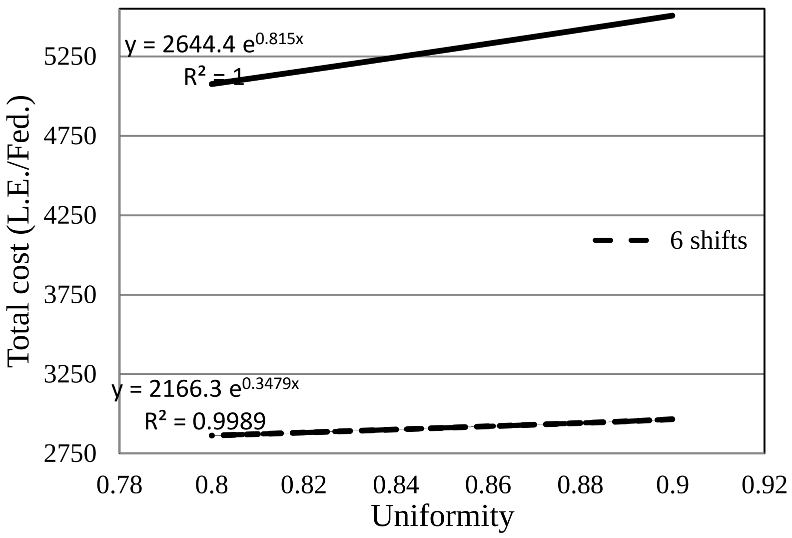


Fig. (7): Effect of uniformity on total cost in case of operating the system for minimum cost (6 shifts) and maximum cost (one shift)

SUMMARY AND CONCLUSIONS

An optimization model for micro irrigation system design, planning and cost estimation was developed. The model divided the field into subunits with an assumed land layout and configuration of piping system. The model selects among different layouts, number of shifts, number of sets and number of subunit per set with minimum total cost. The model was developed using the Microsoft Excel Solver tool that applies the Generalized Reduced Gradient (GRG2) nonlinear optimization code. The model can be applied to rectangular field with water source at any of its corners. The model can be applied to various field sizes, crops, soil types, and regions. This can be achieved by specifying the input data such as field dimensions, emitter function, lateral and manifold spacing, crop coefficient, evapotranspiration and irrigation requirements and soil hydraulic properties. When applied a case study the results indicated that minimum cost is decreased by increasing the total area to be irrigated when just one set of subunit operates simultaneously. Meanwhile the total costs increased by increasing the total area in case of irrigate the whole area once in time (one shift). The rate of increase depends on number of shifts, number of sets and number of subunit per set operate simultaneously. The total costs were affected the emission uniformity. Results indicated that the total cost increased at higher uniformity. This effect increased by decreasing the number of shifts.

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الملخص العربي

نمذجة التصميم والإدارة الأمثلين لنظم الري المصغرة

جمال شرف[١] ، عزة حسن[٢] ، هاشم محمود[٣]

الهدف من هذا البحث هو خفض التكاليف الكلية لوحدات الري المصغر من خلال تطوير نموذج للتخطيط والتصميم والإدارة الأمثلين وتقليل التكاليف، وقد تم استخدام بحوث العمليات كتطبيق لحل هذه المشكلة وذلك من خلال تحديد دالة الهدف وهي تقليل التكاليف الكلية والتي تشتمل تكاليف المعدات والأجهزة وتكاليف التشغيل السنوية نتيجة لمجموعة من القيود التي تنظم عمليات التخطيط والتصميم والتشغيل. وقد تم الاستعانة بوسيلة حل نماذج بحوث العمليات الغير خطية الملحقة ببرنامج إكسيل، وقد تم التوصل للحلول المختلفة لدالة الهدف وتحقيق القيود المحددة بكفاءة عالية ونسبة خطأ منخفضة ($1x\ 10^{-6}$). ونموذج التخطيط يعتمد على أن مصدر المياه عند أي من أركان نظام الري يمتد من الخط الرئيسي ليغذي مجموعة من الخطوط التحت رئيسية العمودية عليه يقوم كل منها بتغذية وحدتين ري على الجانبين وبذلك يكون عدد وحدات الري الموازية للخط الرئيسي مساوي ضعف عدد الخطوط التحت رئيسية وتعمل هذه المجموعة كوحدة تتكرر هذه الوحدات على طول الخطوط التحت رئيسية ومن تقاسيم هذه الوحدات يتم تحديد عدد المناوبات. وبناء على هذا التخطيط يتم التصميم الهيدروليكي للنظام حيث يتم تحديد أطوال الخطوط الفرعية والموزعات وبالتالي التصرفات ومن انتظام توزيع المياه المطلوب يتم تحديد أقصى واقل ضغط داخل وحدات الري يتم توزيع هذا الفاقد في تصميم أقطار الأنابيب سواء للتوزيع أو التوصيل داخل وحدة الري. أما أقطار الخطوط التحت رئيسية والخط الرئيسي يتم تصميمهما على أساس فواقد مقدارها ١٥% من ضغط التشغيل الأسمى للمنقطات وعلى التصرف المستخدم طبقا لعدد وحدات الري التي تعمل معا وعلى المناوبات المختلفة. الخطوة التالية يتم حساب قدرة المضخة بناء على الضاغط الديناميكي الكلى وتصرف عدد وحدات الري التي تعمل معا.

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وبعد ذلك يتم حساب التكاليف مع التقيد بالشروط التي تحقق دالة الهدف في حساب اقل التكاليف الذي يستوفى الشروط الخاصة بالتشغيل والتصميم والتخطيط. ومع تحقيق دالة الهدف تظهر رسالة مفادها تحقيق كل القيود والوصول إلى حل وهو اقل تكلفة كلية ومقدارها مع متغيرات النظام الأخرى من تخطيط (عدد وحدات الري ومساحتها، عدد الخطوط التحت رئيسية وعدد خطوط الري وعدد الموزعات هذا بالإضافة إلى أطوال وأقطار كل هذه الأنابيب) وإجمالي المعدات المطلوبة وكمياتها ونسبتها المئوية من التكلفة الكلية وعدد وحدات الري التي تعمل معا وعدد المناوبات وتصرف المنقطات المتوسط وضغط التشغيل المتوسط واعلي واقل ضغط على وحدات الري وقدرة المضخة المطلوبة وتكلفة الطاقة اللازمة لتشغيل النظام والسعة الكلية للنظام. ومن خلال دراسة حالة، تم تقدير اقل تكاليف كلية لتشغيل نظم الري المصغر لمساحات تتراوح من ١٥ إلى ٩٢ فدان حسب قيود وشروط مسبقة وتم استنتاج أن اقل تكلفة كلية لوحدة المساحة (فدان) حوالي ٢٩١٧، ٢٩٥٥، ٣١٨٤، ٣٢٦٢ جنيه/فدان للمساحات التالية على الترتيب ٩٢، ٤٣، ٢٢، ١٥ فدان، وهذه التكلفة عند تشغيل ٩، ٦، ٤، ٣ مناوبات على الترتيب للمساحات السابقة. أي أن التكلفة الكلية تقل بشكل عكسي بالنسبة لزيادة المساحة مع تطبيق نظام المناوبات. تختلف النتائج وبشكل جذري عند تطبيق نظام المناوبة الواحدة (تروى المساحة الكلية دفعة واحدة) إذ بلغت التكلفة الكلية ٦١٠٨، ٥٢٨٦، ٤٨٧٣، ٤٦٩١ جنيه/فدان وذلك لنفس ترتيب المساحات السابقة. ومن خلال هذا البحث تم دراسة تأثر انتظام توزيع المياه على التكلفة الكلية، حيث اظهرت النتائج ارتفاع التكلفة مع زيادة انتظام توزيع المياه. ومن خلال النتائج المستنتجة من هذا البحث نوصى بتطبيق الأمثلة في تصميم نظم الري الحديث وذلك لخفض تكاليف الإنشاء والتشغيل.