OPTIMIZATION OF DEVELOPED IRRIGATION SYSTEM NETWORK USING GENETIC ALGORITHMS

أمثلة شبكة نظام الري المطور باستخدام الخوارزميات الجينية

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ملخص البحث

يهدف البحث إلى الوصول إلى التصميم الأمثل لشبكات الري المطور باستخدام الخوارزميات الجينية. ونتيجة لذلك يمكن الوصول إلى الاستخدام الأمثل لمصادر المياه المستخدمة لري المزارع. حيث ستحصل كل مزرعة على كمية المياه المطلوبة عند الضغط الصحيح في أثناء الوقت المحدد لها خلال فترة توصيل المياه، حيث سيتم تصميم وإنشاء المواسير الصحيحة ذات الأقطار المختلفة بأقل تكلفة. ان تقنية الخوارزميات الجينية أكثر مناسبة لأمثلة أنظمة الري المطور حيث يمكن الوصول إلى أفضل خطط للري، شبكات الري المثلى، وتخفيض وقت الري وبالتالي الوصول إلى أقل تكلفة وأقل استهلاك للطاقة. ومن خلال هذا البحث تتبين الجدوى الاقتصادية من تحويل الري السطحي إلى ري مطور. حيث أنه باستخدام الري المطور يتم توفير 40-50% من كمية المياه المستخدمة في الري السطحي وكذلك الوصول إلى أقصى إنتاج للمحاصيل. تم استخدام طريقة الخوارزميات الجينية لمزرعة ذات مساحة ألف فدان مزروعة بالمحاصيل وأشجار الفاكهة حيث تم الوصول إلى توفير 41% من تكلفة شبكة نظام الري مقارنة بطريقة التصميم اليدوي للشبكة.

ABSTRACT

The main objective of this research is to reach the optimum design for the developed irrigation system network using genetic algorithms, GA. As result, optimum use of water sources at the irrigation farms is reached. Each farm will obtain the required water discharge with the correct pressure within the available duration time and water delivery period, where the right combination of various pipe sizes with minimum cost are designed and constructed. The GA technique is most appropriate for optimization of developed irrigation plan, optimum networks, reduction of necessary time of watering plan, and consequently minimum cost and minimum energy can be reached. Within this research it is shown that it is economically profitable to convert from surface irrigation system to developed irrigation systems. The use of developed irrigation systems leads to water saving by 40-50% compared to surface irrigation, together with reaching maximum yield of plants. The use of GA optimization method for the studied case of 1000 feddan cultivated by crops and trees safes 41% of the irrigation system network cost compared to the manual design method.

Keywords: Genetic algorithms, Developed irrigation systems, Optimization, Water cycle

1. INTRODUCTION

Water is most important liquid for living, where the agriculture sector in Egypt consumes over 83% of water for irrigation, [1]. The dramatic increase of population in Egypt with limited water resources and limited cultivated area represents very big problems which limit the development. Egypt decision makers are always under pressure to produce more food, which requires both vertical and horizontal expansion of agriculture. As a result, the productivity per feddan is increased and

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the total cultivated land must be also increased. Considering the available data of the cultivated area in Egypt and used irrigation methods, the developed irrigation is used for 13.58% of the total cultivated area of 8.1 x 10^6 feddan, [2].

By 2025, the annual per capita water supply will be approximately 500 m^3/cap/year, [3]. With such limited water resources and the need for horizontal expansion of agriculture, the developed irrigation must expand to replace surface irrigation. Providing the crops with correct amount of water is essential for producing high yields. Proper irrigation is important at each stage of crop growth from establishment to ending. Many factors must be taken into account, such as local climate, soil type and elevation. Developed irrigation systems apply right water amount, at right time and right place with minimum waste, [4].

The water delivery method to irrigation farms depends on discharge required for the farm with the required pressure, duration time and water delivery period for each crop.

The profitability of converting from surface irrigation system to developed irrigations using genetic algorithm technique is included in the work of Bagher and Payman [5], where they reached the best irrigation schedule. Their results indicate that the genetic algorithm method is useful for water distribution problem in irrigation channels, that can optimize some different objectives and the maximum time for irrigation fulfillment obtained during agricultural season for all products.

Hoesein and Limantara [6] studied the optimization of water supply for irrigation of 1236 ha at Jatimlerek of east Java, Indonesia, using linear programming model, where 312 constrains and 450 variables were considered. They determined the minimum and maximum water requirements.

Nasab et al. [7] studied the suitability of different irrigation systems in an area of 4688 ha in Bonah Basht plain – Iran. The results showed that sprinkle and drip irrigation methods are more suitable than surface irrigation for all tested land.

Rodrigues et al. [8] developed a seasonal model for irrigation management optimization at farm level in the Mediterranean region. In this study three irrigation scenarios for maize were used. Considering the three scenarios, the more suitable solution was the one based in medium levels of irrigation modernization.

The aim of this study is to reach the optimum use of water sources at the irrigation farms which is satisfied by using genetic algorithm method. As a result, each farm will obtain the required quantity of water with the correct pressure with choosing the right combination of various pipe sizes with minimum cost.

2. TYPES OF DEVELOPED IRRIGATION SYSTEMS

Developed irrigation systems are categorized in two basic types: sprinkler, and drip irrigation, Fig. 1.

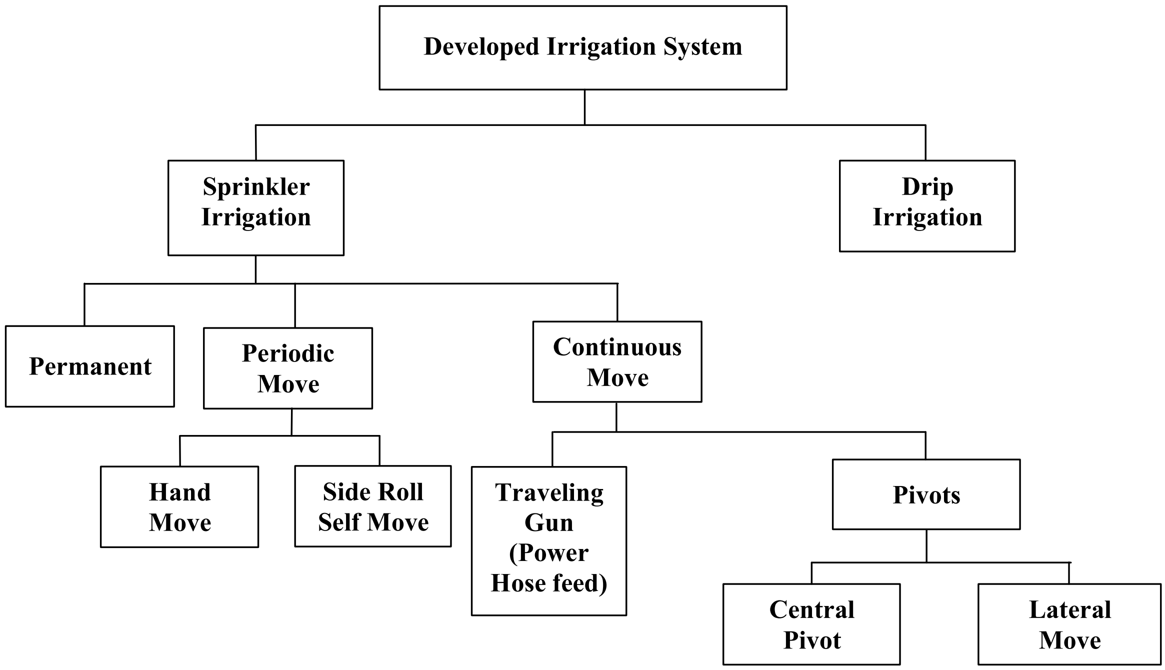


Fig. 1 Types of developed irrigation systems

Sprinkler irrigation is the application of water in the farm of spray formed from the flow of water under pressure through small orifices or nozzles. Sprinkler irrigation systems can be divided into three general categories: permanent, periodic move and continuous move. The periodic move systems include hand move and side roll self move. While the continuous move systems include traveling gun and pivots. The pivots have two types: center pivot and lateral move system.

Drip irrigation is a system for supplying filtered water directly into the soil. It eliminates spraying or running water down and allows water to dissipate under low pressure in an exact pattern. The drip system consists of: control head, main, sub main and laterals which include emitters. The emitters are classified into on line emitters and in line emitters.

3. EVALUATION OF DIFFERENT IRRIGATION SYSTEMS

Many factors affect the choice of developed irrigation systems. These factors include: slope limitation, soil limitation, water holding capacity, water quality, climate factors, potential for automation, type of crops and system cost. All these factors affect on the performance characteristics of irrigation systems which include basically the water uniformity and application efficiency. Table 1 shows a comparison between performance characteristics of different irrigation systems, [9,10].

Table 1 Uniformity and application efficiency comparison, [9,10]

Irrigation System	Uniformity	Application Efficiency, %
Surface	35-70	35-50
Sprinkler Pivot	90-95	85-95
Drip	80-90	81-86

As a conclusion, the conversions of surface irrigation to developed system conserves water, improve return on investment in time, labor, fertilizer and chemicals, reduces runoff plus the benefit of uniformly applying the correct amount of water at right time. As a result, the developed irrigation systems give less water use, less waste, lower energy costs, lower labor costs, fewer maintenance and less stress on the environment. On the base of Table 1, the use of developed irrigation systems leads to water saving by 40-50% compared to surface irrigation. Figure 2 shows the irrigation water cycle diagram. The different steps of the cycle are: ET_O, potential evapotranspiration defined as the rate of evapotranspiration from reference crop (grass or alfalfa) with height (30-40 cm) planted in a fixed area where soil is under well water conditions and it is expressed as depth of water per unit time (mm/day).

K_C, Crop factor which depends on the type of crop.

ET_C, Crop water consumptive use defined by Eq. (1), [11].

$$ET_C = ET_O \,.\, K_C \text{ (mm/day)} \tag{1}$$

W_r, water requirements, [12].

$$W_r = \frac{ET_C \cdot C}{\eta} \tag{2}$$

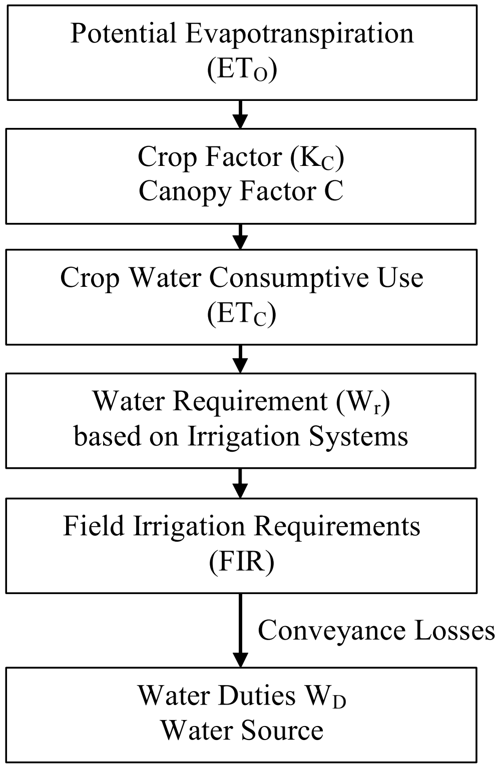


Fig. 2 Irrigation water cycle diagram

C, Canopy factor which depends on the crop phase growth.

η, Irrigation efficiency or application efficiency that depends on the used irrigation system.

FIR, Field irrigation requirements. It is the sum of crop water consumptive use plus water required for flashing salt from soil minus sum of water gained by capillary and precipitation.

CL, Conveyance losses along rivers and canals.

W_D, Water duties. It is the sum of field irrigation requirements and conveyance losses, [13].

$$W_D = FIR + CL \tag{3}$$

4. OPTIMIZATION OF IRRIGATION NETWORKS

4.1 Governing Equations

Consider a typical network system, Fig. 3, where there are one supply source, one pump station and four of demands: c, f, i and j which requires flow rates Q_c, Q_f, Q_i and Q_j, respectively. All are connected by net of pressurized pipe lines and ended by developed irrigation systems (pivots & drip) to fulfill the demands.

The problem is to reach one optimum design of the whole pipe line system that will satisfy the irrigation demands with correct pressure supply, i.e. choose the right combination of various pipe sizes (lengths of specified diameters) to minimize the cost of main and submain pipelines.

The friction losses of head, Δh, per meter length of pipe is calculated using the Hazen-Williams formula, [14]:

$$\Delta h = \frac{H_L}{L} = 10.675\left(\frac{Q}{C_f}\right)^{1.852}\frac{1}{D^{4.87}} \qquad (4)$$

where,

H_L, head loss (m).

L, pipe length (m).

C_f, friction factor, $C_f = 150$ for very smooth PVC pipe.

D, pipe internal diameter (m).

As head loss in a given constant diameter pipe varies linearly with the length, thus optimization of developed irrigation system network using genetic algorithm seems appropriate.

Taking the considered irrigation model, Fig. 3, the following information has been specified and must be met by the design. They are:

- Pump head at source.
- Minimum head required at each demand.
- Flow requirement at each demand for the selected developed irrigation system.

By knowing the pump head at source of supply and head required at each demand point and neglecting the local losses (relatively long pipe lines), the total allowable friction head loss can be computed as:

$$H = H_p - H_d \qquad (5)$$

where,

H, total allowable friction loss in the main and submain pipes.

H_p, pump head.

H_d, minimum head required at demand point.

Friction head loss should not exceed H, which represents the first set of restriction, as follows:

$$\sum_{j=1}^{n}\sum_{i=1}^{m}\Delta h_{ij}\,L_{ij} \le H \qquad (6)$$

where,

Δh_{ij}, friction head losses per meter length of pipe line i, with diameter j.

L_{ij}, length of pipe section in line i having diameter j.

A second set of restrictions is that the physical layout of each path should be as specified (length of each line in any path should be as given), which is represented mathematically as:

$\sum_{j=1}^{n} L_{ij} = L_i$ for each i line, i =1,2, …m (7)

Any path may have one or more lines, and a line may consist of one or more pipe sections with different diameters. The cost of pipe is higher for larger diameters. The optimization of the irrigation network is reached by choosing the minimum cost combination of pipe diameters and lengths in each line, [15].

The objective function (cost function) is represented as:

$$Z_{min} = \sum_{j=1}^{n} C_j \sum_{i=1}^{m} L_{ij} \quad (8)$$

where,

Z_{min}, minimum cost (LE).

C_j, cost of pipe of diameter j per meter length (LE).

4.2 Case Study

An area of 1000 feddan cultivated by crops and trees at Ismailia zone, Egypt includes:

- **Crops**

- Maize (150 feddan right, 150 feddan left) using sprinkle irrigation (central pivot).
- Peanut (100 feddan right, 100 feddan left) using sprinkler irrigation (central pivot).

- **Trees**

- Mango (125 feddan right, 125 feddan left) using drip irrigation.
- Citrus (125 feddan right, 125 feddan left) using drip irrigation.

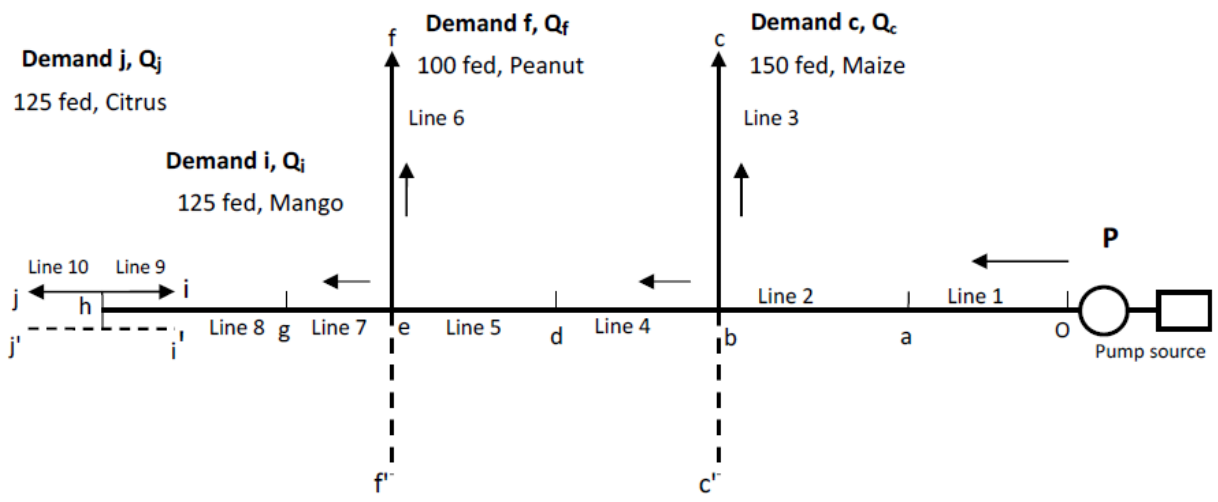
For calculation of water requirement for specified crops and trees, the modified Blaney-Criddle method, [11], for Ismailia zone is used to calculate the potential evapotranspiration, ET_O, which gives maximum value of ET_O = 8 mm/day. Then to get the maximum water requirement, Eq. (2) is used, where the calculation is given in Table 2.

The maximum available time in hours for 500 feddan (half of the cultivated area) is 12 h, therefore the selected time schedule for all demands are: maize 12 h, peanut 10 h, mango 6 h and citrus 6 h. while the starting time for maize, peanut and mango is zero and for citrus is six hours.

On the base of the selected time schedule, the water volume flow rate at each demand is calculated, while the required head for each demand is determined in accordance with the selected developed irrigation system. As a result, the irrigation system diagram with all sets of restrictions is obtained, Fig. 4.

4.2.1 Manual design calculation

The design of the pipeline network is done manually based on the flow rates and demand on each line, where the friction losses per meter length are evaluated for all available diameters. These friction losses are used to validate the first set of restrictions, where friction head loss should not exceed the total allowable frication head loss. The cost of each selected diameter is shown in Table 3. As a result, the corrected manual design of irrigation system is reached, Fig. 5.



Line	1	2	3	4	5	6	7	8	9	10
Length (m)	1000		450	825		365	750		200	200

Fig. 3 Irrigation Model

Table 2 Maximum water requirement

Crops and Trees	ET_O (mm/day)	K_C .C	Efficiency η	W_r (m^3/f.day)	Area (feddan)	V_c (m^3/day)
Maize (Point c)	8	0.840	0.95	29.690	150	4453.5
Peanut (Point f)	8	0.930	0.95	32.800	100	3280.0
Mango (Point i)	8	0.560	0.85	22.136	125	2767.0
Citrus (Point j)	8	0.545	0.85	17.986	125	2248.2

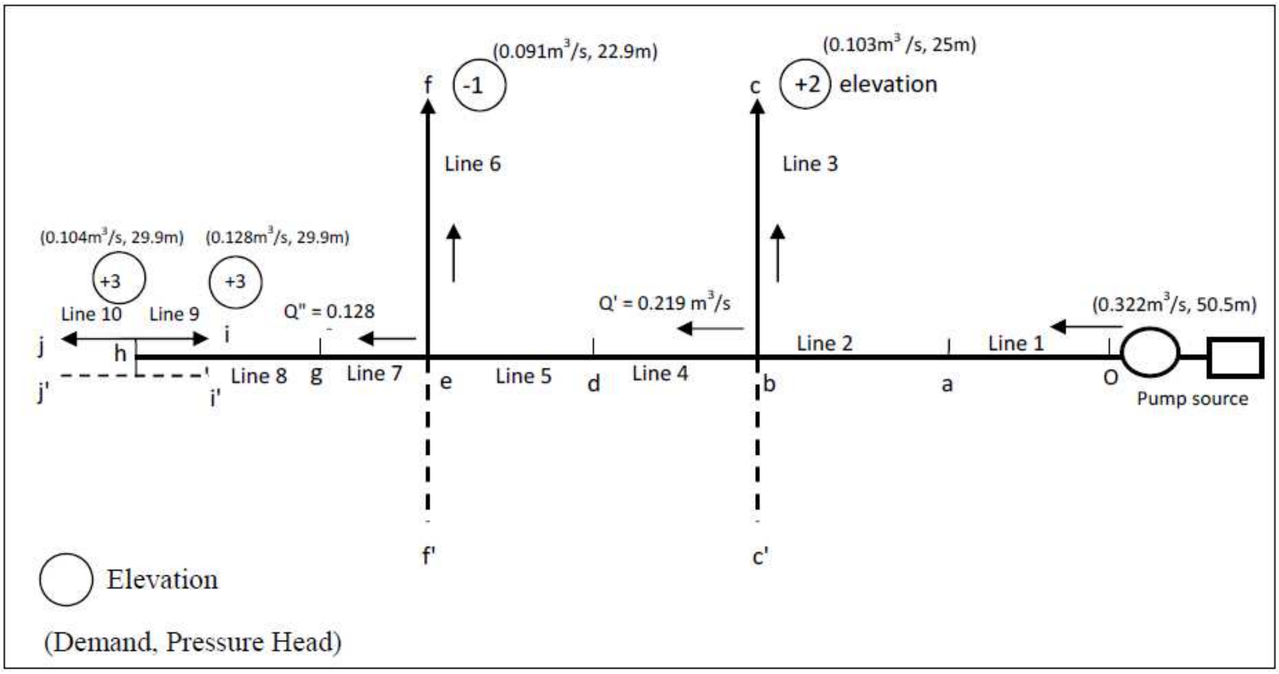


Fig. 4 Irrigation system diagram with all sets of restrictions

Table 3 Cost of selected pipe diameter

Diameter (m)	0.180	0.203	0.250	0.305	0.355	0.400
Price (LE/m)	C_0 = 30	C_1 = 40	C_2 = 60	C_3 = 90	C_4 = 120	C_5 = 240

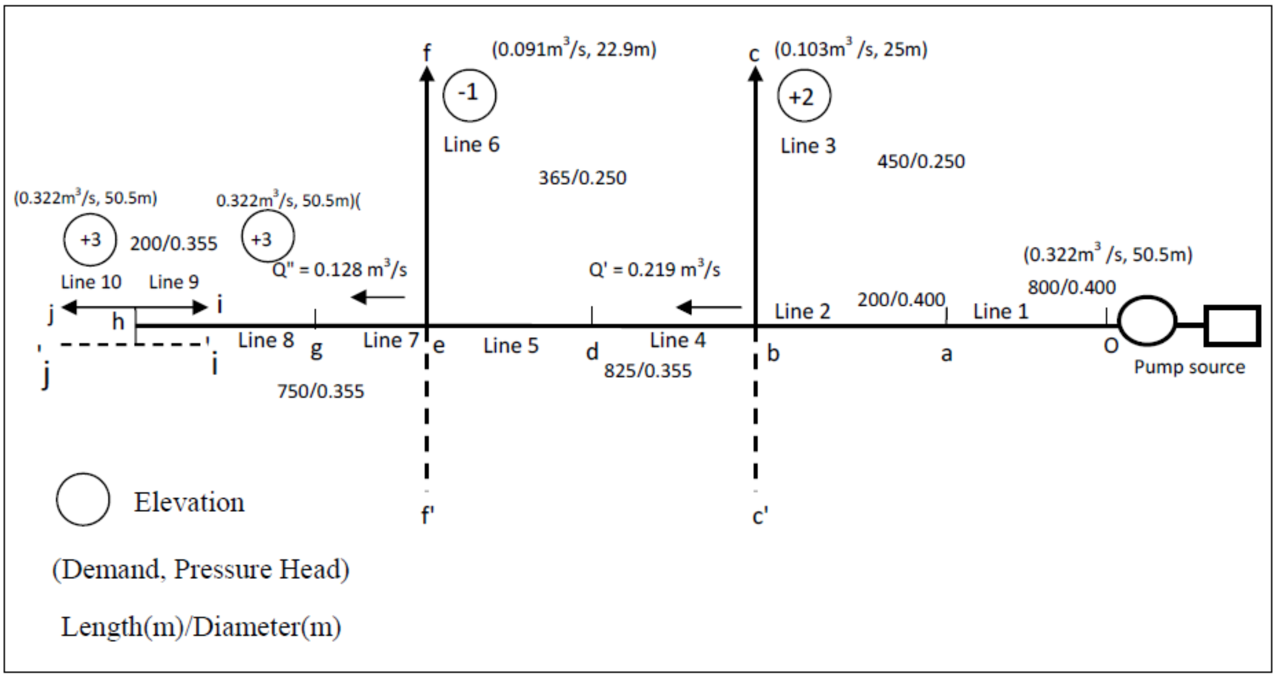


Fig. 5 Corrected manual design irrigation system

4.3 Genetic Algorithm

Genetic algorithm (GA) is an optimization approach which is an alternative to traditional optimization methods. GA technique is most appropriate for complex non-linear models where location of the global optimum is a difficult task. The GA procedure is based on the Darwinian principle of survival of the fittest. GA searches among a population of solutions simultaneously, works with a coding of the variable set and uses probabilistic transition rules, [16].

Standard GA involves three basic functions: selection, crossover and mutation.

Selection: A population of m points (solutions) is selected at random in the solution space. There are many selection methods including: weighted roulette wheel, sorting schemes, proportionate reproduction, and tournament selection, [17,18].

Crossover: It implies two parents with exchange parts of their corresponding chromosomes, two selected points are subsequently used to generate a new point in a certain random manner with occasionally added random disturbance. The one-point can be extended to K-point crossover.

Mutation: It is an insurance policy against lost bits. It works in the level of string bits by randomly altering a bit value. It randomly selects bit on a chromosome then inverts the bit from 0 to 1 or vice versa, [19,20,21]. The generated populations of points are expected to be more concentrated in the vicinity of optima than the original points. Always the cost function values are calculated at all points and compared. A GA optimization run is terminated when it satisfies some kind of convergence criterion.

4.3.1 Optimization of irrigation networks using GA

The GA optimization technique is operated using MATLAB software. The following steps are used to run the GA:

- The first step is to design the required flowchart, Fig. 6.
- The data of irrigation system with all set of restrictions, Fig. 4, are given as input data to GA.
- Select code length L, as nominal value =10.
- Select the population size. Such selection depends on the problem type, number of variables, and code length. The suitable size may be reached by experience. As nominal value, we may select 100. For termination criteria, either reaching certain satisfactory cost function value, or achieving saturation, or after certain no of iterations by selecting the generation number; such selection is based on experience; usually it is selected large enough to ensure convergence. Double or triple of the population size may be considered satisfactory (300).
- Select crossover probability, P_c = 0.6-0.8.
- Select mutation rate, P_m = 0.01-0.03.
- GA selects initial values for pipe lengths and corresponding diameters randomly.
- As GA program applied without physical feeling a penalty of 1,000,000 used to prevent any deviation mentioned in the flowchart also a warning to be written on the screen.
- Write the governing equation (algorithm), under the title %%% calculations %%%.
- Run the GA.

5. RESULTS AND DISCUSSIONS

To have the best irrigation demand and optimum network, it is necessary to choose an adequate and feasible basic irrigation parameters such as pump discharge, pump head, duration time and water delivery period. The GA optimization program is tested for the considered case, Fig. 4, for the GA parameters given in Table 4.

The obtained GA optimization results for GA solutions, for cases A and B together with manual results are shown in Table 5. While the optimum designs of the irrigation system network is shown in Fig. 7.

The generational processes are repeated until a termination condition has been met. The highest ranking solutions fitness has reached a saturation condition.

Comparing the cost results of the first run and the second run with the manual design, Table 5 indicates that the optimum global solutions are reached using GA. To find the best irrigation demand and optimum network pipe diameters, we have to choose the correct parameters which fulfill our requirements, Fig. 4

Therefore GA program is run for optimization of the consider irrigation system with the following parameters, case A:

- Population size (121)
- Generation number (1331)
- Crossover probability (0.8)
- Mutation rate (0.03)

The result of optimum irrigation system design cost function 309,000 L.E.

Case B:

- Population size (100)
- Generation number (200)
- Crossover probability (0.8)
- Mutation rate (0.01)

The result of optimum irrigation system design cost function 308,970 L.E.

The cost function obtained (manual design) 525,900 L.E.

The use of GA optimization method safes 41% of the irrigation system cost compared to the manual design of the studied case.

The diameters obtained by GA fulfill the constraint that the downstream main pipe diameter should equal or less than the previous pipe diameter, as shown in Fig.6.

By using GA program to design the irrigation system, it is clear that at short time 3-4 minute GA appears to be a potential useful approach, which realized the demands and fulfill the optimization required with its cost function.

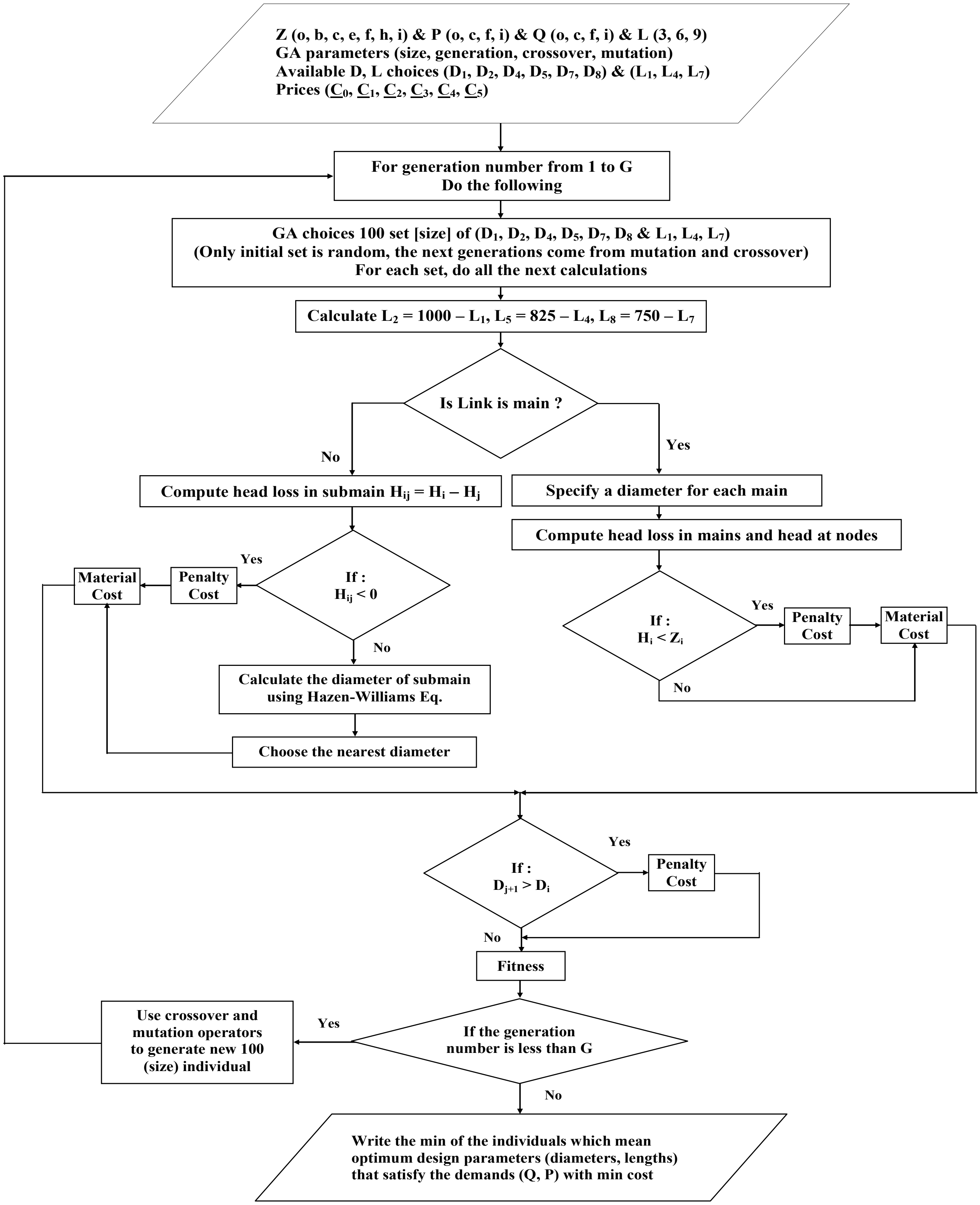


Fig. 6. Flow chart using GA

Table 4 GA parameters

Cases	Population Size	Generation Number GN	Crossover Probability P_c	Mutation Rate P_m
Case A	121	1331	0.8	0.03
Case B	100	200	0.8	0.01

Table 5 Results of optimum irrigation system design

Pipeline	L_1 (0a)	L_2 (ab)	L_3 (bc)	L_4 (bd)	L_5 (de)	L_6 (ef)	L_7 (eg)	L_8 (gh)	L_9 (hi)	L_{10} (hj)
Manual Design										
Length (m)	800	200	450	825		365	750		200	200
Diameter (m)	0.400	0.400	0.250	0.355		0.250	0.355		0.355	0.355
Cost Function (LE)	**525,900**									
Case A										
Length (m)	738	262	450	213	612	365	710	40	200	200
Diameter (m)	0.355	0.355	0.180	0.305	0.305	0.180	0.305	0.250	0.250	0.250
Cost Function (LE)	**309,000**									
Case B										
Length (m)	709	291	450	402	423	365	709	41	200	200
Diameter (m)	0.355	0.355	0.180	0.305	0.305	0.180	0.305	0.250	0.250	0.250
Cost Function (LE)	**308,970**									

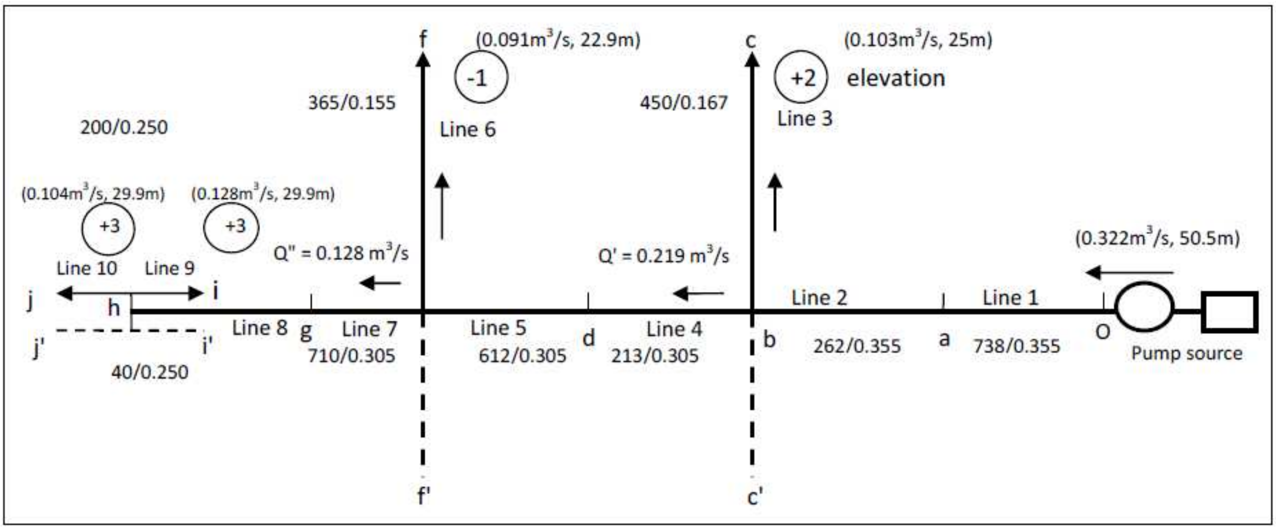


Fig. 7 Optimum design of the irrigation system

6. CONCLUSIONS

The present study shows that it is economically profitable to convert from surface irrigation system to developed irrigation systems for the following reasons:

- Developed irrigation systems ensure correct water application required for plants, thereby promoting uniform plant growth, where high water application efficiency and better uniformity are attained.
- Plants are never stressed by lack of water or over irrigation, as water is supplied with the right quantity at the correct time which leads to maximum yield.
- As water is applied according to water requirement, losses due to evaporation, runoff and draining are minimized. Therefore, the use of developed irrigation systems leads to water saving by 40-50% compared to surface irrigation, which will lead to add new cultivated areas.
- The developed irrigation system components: pumps, main and submain pipe lines, pivot, drip and sprinklers are available in various sizes and specifications to suit any particular requirements. Therefore, developed irrigation systems can be designed to suit any area and crop.
- The genetic algorithm optimization method is useful to reach an optimum design of the irrigation system which satisfies the required flow rates demand at the correct head within the available time duration suitable for different crops and trees.
- The use of GA optimization method safes 41% of the irrigation system cost compared to the manual design of the studied case.

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Nomenclature

C	Canopy factor	(-)
C_f	Friction factor	(-)
C_j	Cost of pipe of diameter j per meter length (LE/m)	
CL	Conveyance losses (mm/day)	
D	Pipe diameter (m)	
ET_C	Crop water consumptive use (mm/day)	
ET_O	Potential evapotranspiration (mm/day)	
FIR	Field Irrigation Requirements (mm/day)	

GA	Genetic Algorithm	(-)
GN	Generation number	(-)
H	Total allowable friction loss	(m)
ha	Hectare	(10000 m^2)
H_d	Minimum head required at demand point	(m)
H_L	Head loss	(m)
H_p	Pump Head	(m)
i	Line Number (i=1,2,……n)	(-)
j	Line Diameter (j=1,2,……m)	(-)
K_C	Crop factor	(-)
L	Pipe length	(m)
m	Number of pipes	(-)
n	Number of available diameters	(-)
P_c	Crossover probability	(0.6-0.8)
P_m	Mutation rate	(0.01-0.03)
Q	Volume flow rate	(m^3/s)
V_C	Water volume	(m^3/day)
W_D	Water duties	(mm/day)
W_r	Water requirements	(m^3/f.day)
Z_{min}	Minimum cost	(LE)
Δh	Friction losses per meter length	(-)
η	Irrigation efficiency	(%)