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PJBS

ISSN 1028-8880

Pakistan
Journal of Biological Sciences

ANSInet
Asian Network for Scientific Information
308 Lasani Town, Sargodha Road, Faisalabad - Pakistan

Pakistan Journal of Biological Sciences 8 (7): 1064-1073, 2005
ISSN 1028-8880

Open Canal Irrigation Network Optimization: A Case Study for Burdur-Turkey

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Abstract: In open canal irrigation networks, conveyance of water from the resource to plots through the best route under current topographical and ownership distribution restrictions is an important problem. This problem is especially significant for countries such as Turkey in which open canal systems constitute most of the irrigation networks. In this study, the shortest path, minimum spanning tree, network flow and transshipment models were applied to a state-owned irrigation network in Burdur-Turkey for open canal irrigation network optimization by taking the modifications required by the topography also into consideration and the results obtained from the models were compared with the current applications.

Key words: Irrigation networks, optimization, shortest path, minimum spanning tree, network flow, transshipment

INTRODUCTION

High-yield agricultural system includes the activities able to provide an optimum balance among all components of resource utilization. The most important of these activities are effective water distribution and utilization. An effective optimization is needed to achieve success in these activities. When the issue was considered in irrigational perspective, the resources to be optimized or the resources of which the most suitable combinations are to be provided will be; irrigation area, irrigation facilities, water resource, plant water needs and the other related sub-activities[1]. The problem in classical irrigation networks is the conveyance of water from the resource to plots through the best route under current topographical and ownership distribution restrictions.

In Turkey, most of the already established irrigation networks or the ones still under construction consist of open canal systems[2]. An important disadvantage of open systems over closed ones is the fact that they caused almost 20% of the project area not to be benefited from the water in the cases where water intake points are far from the plot[1]. The necessity to pass the irrigation water diverged from the network over the neighboring land especially constitutes a problem. Due to these kinds of reasons, net irrigation ration in Turkey is about 60%[3]. In addition, reuse of drainage water due to insufficient water resources causes soil salinization.

Route determination in open canal networks is more dependent on experiences of project engineer than scientific methods. It is impossible for the route designed by using the experiences of engineer and selected among a few alternatives always to be the best route[4].

The model able to yield the optimum canal route should both have the capacity to provide the water need of each plot and the alternative routes between the first and the last point should be suitable for current land allocation and topographic pattern. In other words, the model able to yield the optimum route should resolve the two-way problem. One of them is to convey the necessary amounts of water to all plots in project area; and the other is the necessity to reach to all plots with the best route among the alternative routes[5].

Open canal systems are generally used in irrigation networks in Turkey. The ratio of low-pressure or medium-high pressure piped irrigation networks is about 4.3%[2]. That is why in this study, beside the evaluation of approaches used in optimization of pressurized irrigation networks, mainly the models used in optimization of open canal systems were emphasized.

When the world literature was taken into consideration, it was seen that the studies on open canal network optimization were very limited compared to the studies on closed irrigation network optimization. Therefore, in this study, approaches used in optimization of pressurized systems were also analyzed and models used in open canal optimization were evaluated.

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Considering the techniques applied, optimum route selection studies exhibit a vide range diversity. One of the simplified approaches proposed by Alperovits and Shamir[6] reduces the complexity of the original non-linear nature of the problem by solving a sequence of linear sub-problems. This approach has been adopted and subsequently improved by many researchers.

The approaches used can be classified as follows: reduced gradient techniques used in determination of optimum pipe sizes, hydrant and storage capacities[7]; modified box complex optimization technique used in determination of optimum storage height, pump head and pipe sizes[8,9]; mixed binary linear programming technique used in determination of water delivery problems, the shortest network link, the best discharge in each branch and optimum pipe sizes[10]; generalized minimal spanning tree algorithm[11], generalized network flow optimization model[12] and incapacitated generalized transshipment algorithm[13] all yielding the shortest path; quickest transshipment with a polynomial number of maximum flow computations yielding the most economical water delivery cost[14] and genetic algorithm method yielding the highest benefit[15-18].

One of the rare studies aiming to apply the optimization techniques on open canal systems was carried out in Thailand. It was emphasized that water use efficiency in most parts of networks were low and uneconomical and also stated that irrigation projects were implemented mainly based on engineer experiences without taking the scientific methods into consideration. They also stated that a well-designed network would eliminate these deficiencies and evaluated minimum spanning tree, shortest path and out-of-kilter algorithms on a sample plot. Based on the total network length, they found the minimum spanning tree model more appropriate over the other models[19].

In this study, the models used in optimization of open canals were gathered under two groups:

A) Models minimizing only the path (canal length)
  a) Shortest Path Model
  b) Minimum Spanning Tree Model

B) Models optimizing systems cost while finding the minimum path (models assuming the discharge-cost relation constant)
  a) Network Flow Model
  b) Transshipment Model

In this study, shortest path and minimum spanning tree models from the first group and network flow and transshipment models from the second group were resolved for an area and compared with each other. As it was stated in methods chapter, due to the characteristics of open canals, necessary modifications about elevation differences were carried out.

MATERIALS AND METHODS

This study was carried out on 3 100 da of Burdur-Murseller irrigation district constructed by General Directorate of Rural Affairs (Fig. 1). There are 47 irrigation plots with different size and dimensions in this area. Water enters into field via a canal from the highest elevation of the specified area. The difference in elevation between the highest and the lowest point of the area is about 50 m.

Current canal network is shown in Fig. 2. This area was opened for irrigation following the design and implementation of the irrigation network by the help of engineer experiences without using any optimization techniques. As seen in the Fig. 2, since the parcellation pattern was not taken into consideration during the irrigation network design, water cannot be delivered to all parcels.

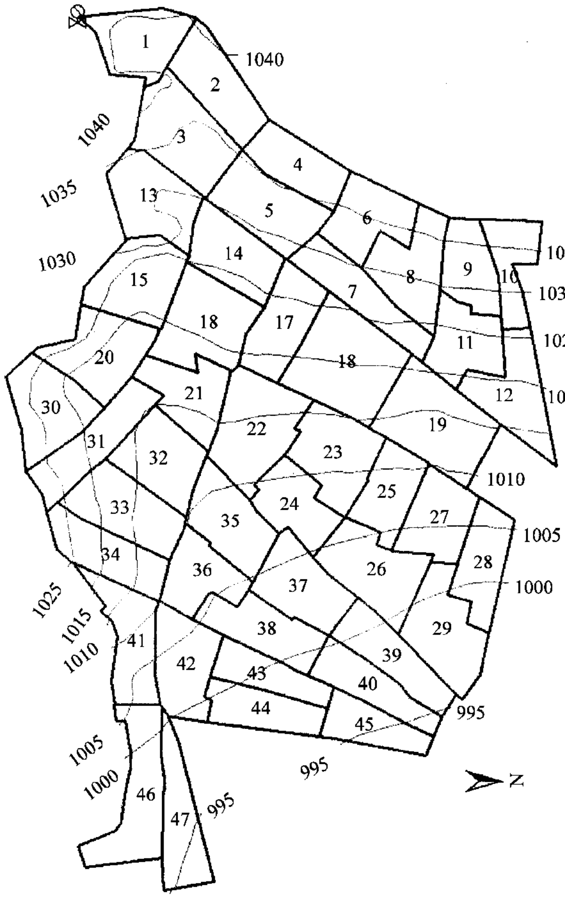


Fig. 1: Burdur-Murseller irrigation district

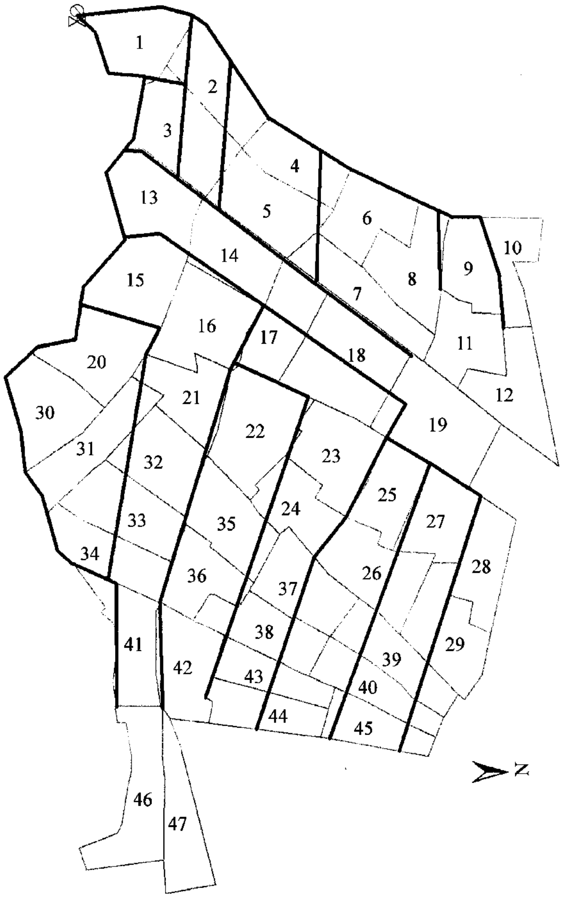


Fig. 2: Current canal network in Burdur-Murseller irrigation district

The models: The models considered were explained below under two groups.

The models minimizing only the path: Shortest Path and Minimum Spanning Tree are included in this group. Both methods need some modifications to be applied in irrigation networks. These modifications are necessary especially for open canal water conveyance systems.

Shortest Path Model-Modified (SP-M): The shortest path problem is the problem of finding the shortest path among the alternative paths from a certain starting node to an end node. This technique is based only on selection of the smallest total path among the possible paths between two target points. In other words, only a part of nodes between starting and ending points are included in solution and the others are omitted. The shortest path model able to be applied in several issues is solved by graphical algorithms[20].

In the shortest path model, the main objective is to reach from a single source point to a single target point. The shortest path between source and end nodes is determined among the alternative paths without taking the canal capacities into consideration.

When the shortest path approach is applied exactly to open canal systems, canal network will not pass thorough some plots. However, in open canal systems the water taken from a source has to be delivered all plots and the need of all plots have to be submitted. When the water resource and water intake point of each plot are taken as node points, water resource will be the starting node, water will be delivered to each node via the branches in canal system and as it was in the shortest path approach some node points are excluded from the solution. Therefore, some modifications are needed for the shortest path model to be applied in an irrigation network. The approach followed in SP-M model in this study was defined below:

1. Water resource in project area was taken as the "starting node" and the water intake points of each plot were taken as "water intake node".
2. All the alternative branches were determined based on the elevations of water intake points and they were marked on map.
3. The shortest path between water resource and plot were determined by applying the shortest path method on each plot for "water intake node" and "starting node". In other words, optimum solution was taken for each plot provided that water resource was taken as the starting node in every case. Then, when we reach out n-1 number of solutions for n number of plots.
4. The shortest paths determined for each plot were drawn on same map and "the shortest open canal network" was obtained.
5. Capacities of the branches constituting the previously obtained open canal network were calculated based on unit water needs of plot receiving water from these branches and the sizes of plots.
6. Branch costs were calculated by multiplying branch length and capacities with the unit costs and the total network cost were determined.

WinQSB software developed by Yih-Long Chang was used to solve the shortest path method for each node[21].

Minimum Spanning Tree Model-Modified (MST-M): This method provides a relation of the all nodes with each other provided that total connection length was the smallest. Although all the points are included in solution, only the distance between points are taken as the limitation. Greedy algorithm is used to solve minimum spanning tree models[20]. This algorithm reaches a solution in stages. In the first stage, any node can be selected as starting node and the nearest node among the nodes to be connected to this node is selected and the first branch is formed in this way. In the next stage, the nearest nodes to current branches or the nodes on the branches are selected and the process goes on in similar way until all the nodes are connected.

The important issue in minimum spanning tree model is the connection of the nearest node to the current branching in each stage. However, in open canal systems, whether the elevation difference of the nearest node to current branching is suitable or not is an important issue. If the nearest point is located at an elevation higher than the elevation of the connection point on current branches, this connection can not be performed and then the next nearest point is evaluated.

The approach followed in MST-M in this study was defined below:

1. Water resource and the water intakes in each plot were taken as the node points.
2. Branch lengths between the points were determined based on plot boundaries.
3. Elevation of each node was determined.
4. Instead of starting from any node, water resource node point (node with the highest elevation) was taken as starting point.
5. The distance and the elevation difference between the starting node (water resource) and the other nodes to be connected were determined. The nodes with improper elevation differences (the ones left at higher elevations) were eliminated, the nearest node with proper elevation difference was selected and then the first branch was formed.
6. The process was repeated until all the nodes was connected to the network.
7. Capacities of the branches constituting the previously obtained open canal network were calculated based on unit water needs of plot receiving water from these branches and the sizes of plots.
8. Branch costs were calculated by multiplying branch length and capacities with the unit costs and the total network cost were determined.

WinQSB software was used to solve the shortest path method for each node[21].

Models optimizing systems cost while finding the minimum path: The linear models considered in this group minimize the total canal cost and they find the shortest path between the points in one hand and take the capacity along the distribution line into consideration on the other hand. In this way, both the path and the capacity are determined together.

Discharge-cost relation was assumed to be constant in both network flow programming and transshipment methods used in this study. In other words, the cost of unit canal length for unit discharge along all the branches between the starting point and end point was assumed to be the same.

Network Flow Programming (NF): This model minimizes the total canal cost taking the irrigation water needs of the nodes in the network and the distance between the nodes into consideration. In other words, canal network with minimum cost is determined by this method based on water needs of the nodes and the capacity of the network branch. Structurally, network flow model is a "pure network flow programming" model. It was assumed that there was not any water loss along the network. In addition, discharge-cost relation is constant. Network flow model of the system consisting of m node and n branch is mathematically expressed as[20];

Objective Function:

$$Z_{\min} = \sum_{k=1}^{n} c_k x_k \text{ or,}$$

$$Z_{\min} = \sum_{k=1}^{n} (d.L_k).x_k$$

Limitations:

$$\sum_{k \in K_{0(1)}} x_k - \sum_{k \in K_{T(1)}} x_k = b_i \qquad (I=1, 2, 3,....., m)$$

$$0 \le x_k < u_k \qquad (k=1, 2, 3,....., n)$$

where:

x_k = Flow in branch k between the nodes i and j (m^3/s),

c_k = Unit cost of flow in branch k ($\$/m^3/s$),

d = Canal cost for unit discharge and unit length ($\$/m\ m^3/s$),

L_k = Canal length for branch k (m)

b_i = Net flow obtained in the node i (out flow-input flow; m^3/s)

If $b_i > 0$ then i is a source point,
$b_i < 0$ then i is a demand point,
$b_i = 0$ then i is an transhipment point.

u_k = Maximum capacity of branch k (m^3/s)
$K_{0(I)}$ = Set formed by the branches going out from the node i
$K_{T(I)}$ = Set formed by the branches reaching to the node i

The first sum in initial limitation equation represents the total flow going out from the node i and the second sum represents the total flow reaching to the node I. If b_i on the left side of the equation is positive then node i will be in source position, if it is negative then the node i will be in water demanding position and if it is equal to zero then the node is to be in a transshipment position without any branching or addition.

This approach was exactly utilized in optimization of open canal system. MS Excel add-in (math programming and network solver) was used for solution[22]. While data set preperation, node elevations were taken into consideration to provide a flow and the alternative branches were determined based on elevation differences. L_k distances between nodes and discharge demands of the nodes (water resource capacity as positive, water needs of water demand points as negative) were inputted into model. At the end, canal route with the minimum cost and the capacities of each branch were determined.

Transshipment Model (TS): This model technique is a derivative of transportation technique. In transshipment technique, a network with distributor points is also mentioned beside a network formed only by source and target points. The responsibility of distributor points is to receive the water needed by its own plot then pass the remaining water into another node. In this way, the distributor points will a resource point for another node coming after itself and will be a target node for another point coming before itself[23,24].

The transshipment model can be written as follows:

Objective Function:

$$Z_{min} = \sum_{i=1}^{m+n} \sum_{j=1}^{m+n} C_{ij}(x_{ij} + t_0) \qquad (i,j=1, 2, 3,....., m+n) \text{ or,}$$

$$Z_{min} = \sum_{i=1}^{m+n} \sum_{j=1}^{m+n} (d.L_{ij}).(x_{ij} + t_0) \qquad (i,j=1, 2, 3,....., m+n)$$

Limitations:

$$\sum_{j=1}^{m+n} x_{ij} = \begin{cases} a_i + t_0 & (i = 1, 2, 3, ...,m) \\ t_0 & (i = m + 1, m + 2, ..., m + n) \end{cases}$$

$$\sum_{i=1}^{m+n} x_{ij} = \begin{cases} t_0 & (j = 1, 2, 3, ...,m) \\ b_j + t_0 & (j = m + 1, m + 2, ..., m + n) \end{cases}$$

$$x_{ij} \geq 0$$

where:
c_{ij} = The cost of unit discharge from source point i to discharge point j ($\$/m^3/s$). It is determined by: $c_{ij} = d.\ L_{ij}$
d = For unit discharge and unit length, cost of canal conveying water from source point i to discharge point j ($\$/m\ m^3/s$),
L_{ij} = Canal length between source point i to discharge point j (m),
x_{ij} = Amount of flow conveyed from point i to point j (m^3/s),
t_0 = Amount of transshipment (m^3/s). Value of t_0 is determined by $t_0 \geq \sum_{i=1}^{m} a_i$
m = Number of source point in network,
n = Number of demand point in network,
a_i = Amount of discharge to be send out from the point i (m^3/s),
b_j = Amount of discharge demanded at point j (m^3/s).

In this way, (mxn) dimensioned matrix in transportation model is increased to (m+n) x (m+n) dimensions.

This approach was exactly utilized in optimization of open canal system. WinQSB software was used for solution[21]. While data set preparation, node elevations were taken into consideration to provide a flow and the alternative branches were determined based on elevation differences. At the end, canal route with the minimum cost and the capacities of each branch were determined.

Canal cost determination: While determining canal cost for unit discharge and unit length (d), canals in current irrigation network in project area; their lengths and discharges were taken into consideration (Fig. 2). Unit prices of the year 2004 was used to determine the cost of canals in canal network and canal costs were determined for unit length and unit discharge. Average canal capacity was determined with weighted average by taking the canal length into consideration.

RESULTS

Canal cost: Unit cost values obtained by using 2004 unit prices for different canal capacities was given in Table 1.

As it can be seen from Fig. 3, discharge-cost relation for different canal capacities was obtained as a curvature. Unit cost decreases with increasing capacities. Since the canal costs for different capacities were not taken into consideration in the evaluated models, a constant cost corresponding to an average canal capacity was taken into consideration.

Average canal capacity obtained by weighted average is 0.125 m^3/s and the corresponding canal cost is 176 $\$/m\ m^3/s$. This value was used in optimization models.

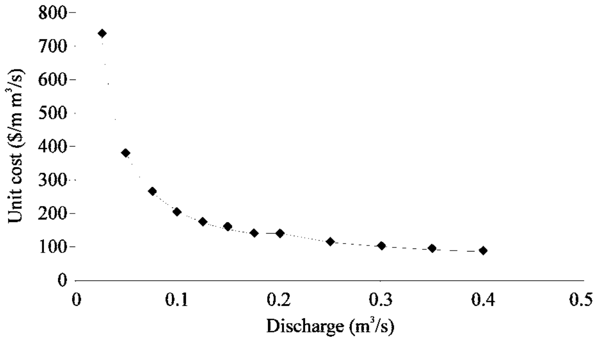


Fig. 3: Discharge-cost relation for the current canal network in project area

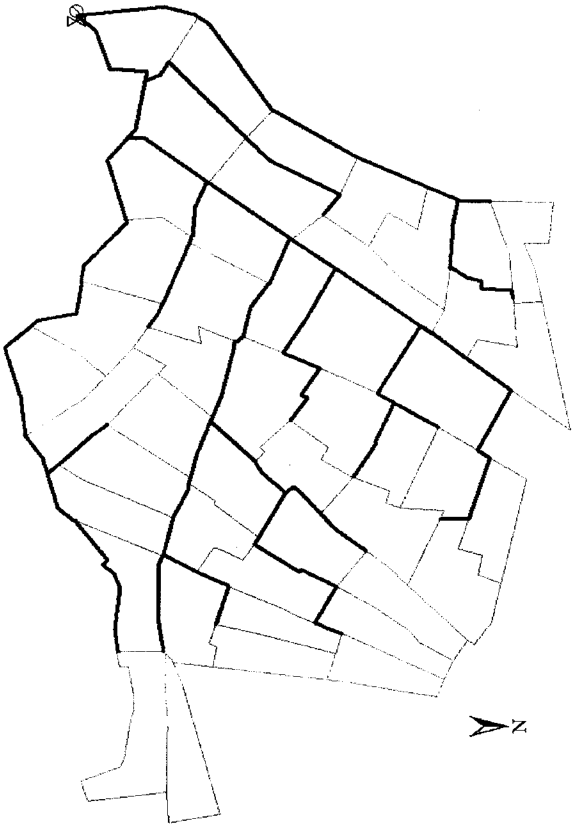


Fig. 4: Optimum canal network (for SP-M, NF and TS models)

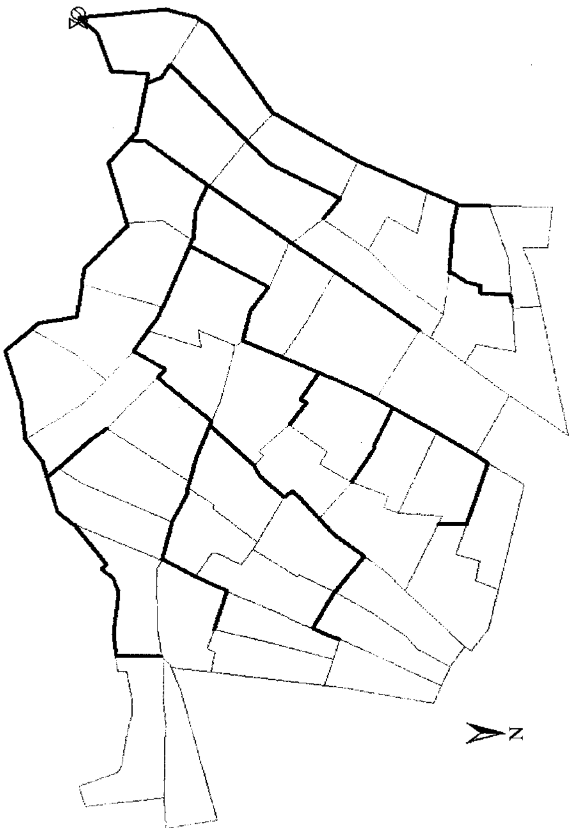


Fig. 5: Optimum canal network (for MST-M model)

Model solution results

Shortest Path-Modified (SP-M): Total canal length in this network was determined as 13 888 m (Fig. 4). Following the optimum canal network determination, capacity of each branch was determined based on irrigation module and the plot area served by this branch. Branch cost was determined by multiplying branch capacity with the cost corresponding to this capacity. The total cost for the shortest path model is $ 81 209.

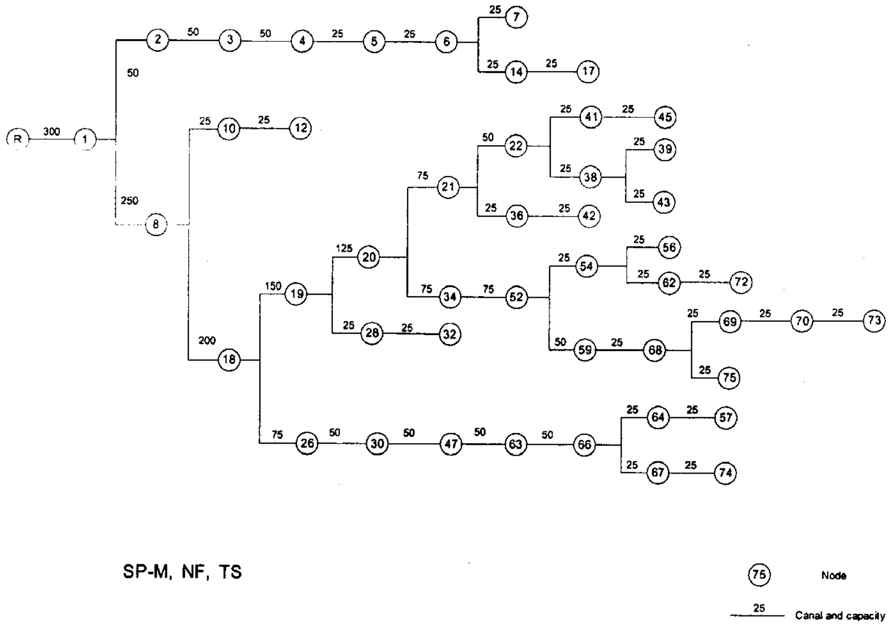
Minimum Spanning Tree-Modified (MST-M): Total canal length in this network was determined as 12 921 m (Fig. 5). The total cost of the network was determined as explained in the shortest path model and it was $ 82 494.

Network Flow Model (NF): Optimum canal cost obtained in this model was $ 81 209. Optimum canal route obtained in this model was the same as the one obtained from the shortest path model (Fig. 4). Total canal length was 13 888 m.

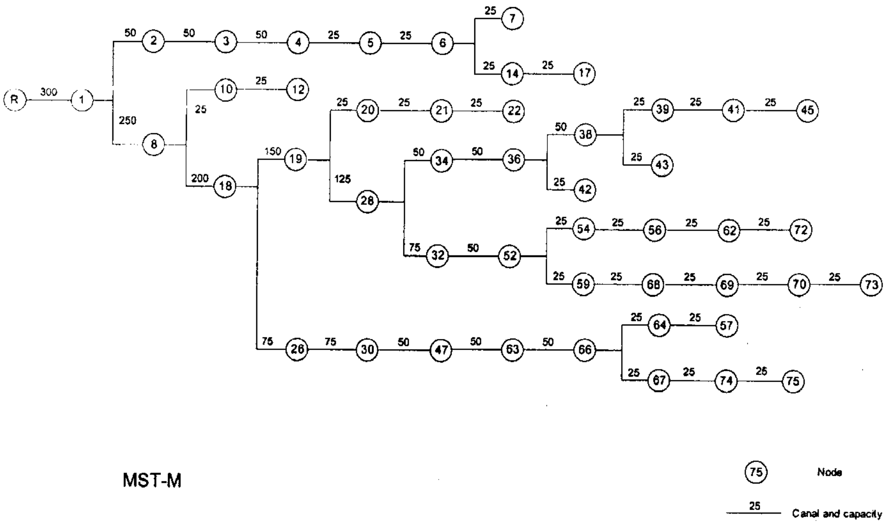
Transshipment model (TS): Optimum canal cost obtained in this model was $ 81 209. Optimum canal route obtained

Table 1: Cost of canals designed and constructed by General Directorate of Rural Affairs[2]

Canal Capacity (m^3/s)	0.025	0.050	0.075	0.100	0.125	0.150	0.175	0.200	0.250	0.300
Unit length cost (\$/m)	18.3	19.0	19.8	20.3	22.0	24.2	24.8	27.9	28.5	31.1
Unit length, unit discharge cost, d, (\$/m m^3/s)	734.0	381.0	263.0	203.0	176.0	161.0	142.0	140.0	114.0	104.0



SP-M, NF, TS



MST-M

Fig. 6: Water distribution plan and selected canal capacities

in this model was the same as the one obtained from the shortest path model (Fig. 4). Total canal length was 13 888 m.

Optimized water distribution plan and the selected canal capacities based on the models used were schematized in Fig. 6.

DISCUSSION

As seen in the Table 2, minimum canal lengths from the models minimizing the total path were determined as 13 888 m in SP-M and 12 921 m in MST-M. Total canal length obtained

Table 2: Comparison of the results

Items		Shortest path model	Minimum spanning tree model	Network flow model	Transshipment model	Current network
Unit canal cost for average capacity ($/m m^3/s)		-	-	176	176	-
Model results	Minimum canal length (m)	13 888	12 921	-	-	-
	Minimum canal cost ($)	-	-	81 209	81 209	-
Calculated values	Total canal length (m)	-	-	13 888	13 888	15 958
	Total canal cost (A) (for average capacity, $)	81 209	82 494	81 209	81 209	141 680
	Total canal cost (B) (based on discharge-capacity relation, $)	266 839	248 885	266 839	266 839	309 170

from MST-M is less than the one obtained from SP-M (Table 2).

NF and TS minimizing the total canal cost both yielded the same results, in other words the same canal cost ($ 81 209) and the same canal network (13 888 m). These models also yield the amount of flow (canal capacity) to be realized from which node to which node. Based on these results, the canal network obtained is similar to the one obtained from SP-M and total canal length is 13 888 m. When the total canal length was taken into consideration, MST-M yielded the shortest canal length. Based on the results obtained from the other three methods, canal network and total canal length were similar to each other.

In order to compare total canal costs, canal costs of the network obtained in the first two models have to be calculated by the similar approaches. For each branch of canal network obtained in the first two approaches, branch discharge, branch length and by multiplying average capacity with unit canal cost the branch cost were determined then by summing the branch costs total canal costs were obtained (canal cost A). Total canal cost in the SP-M was same as the ones in NF and TS ($ 81 209) because the canal network for these three models was the same. On the other hand, total canal cost in MST-M was $ 82 494 which is higher than the cost of other approaches. When the total canal cost was considered, SP-M, NF and TS yielded the smallest canal cost. Although MST has yielded the best results about total canal length, a higher value on total cost left us face to face with a dilemma. However, this cost as explained earlier, was calculated based on a constant canal unit canal cost determined for average capacity. This approach used in the last two models actually does not represents the real situation since the unit cost of a canal is not constant but variable for different canal capacities. It can be seen from Fig. 3 that unit cost was considerably high in low discharge canals and unit cost decreased with increasing capacities. Therefore, discharge-cost relation is not constant. That is why, it is impossible to state that NF and TS assuming an average unit canal cost has calculated realistic canal costs and minimized the cost.

For each model evaluated in this study, discharge of each branch constituting the canal network obtained by solutions, total canal costs (canal cost B) corresponding to these discharges and determined by using the canal cost given in Fig. 3 were presented in Table 2. While determining these values, canal capacities used in application corresponding to discharge of each branch were taken into consideration.

For example, if the discharge of a branch is 0.065 m^3/s, then the unit cost of this canal will be taken as 263 $/m m^3/s since the capacity of the canal to pass this discharge is 0.075 m^3/s in application.

Total canal costs determined by real discharge-cost relations were determined as $ 266 839 for the SP-M, NF and TS all of which have the same canal network and $ 248 885 for MST-M which has a shorter network than the others.

Following conclusions can be drawn based on these results:

- MST-M yielding the best results about the total canal length has also yielded the best result on total canal cost determined by discharge-capacity relation.
- NF and TS minimizing the total canal cost were found to be insufficient in determination of the shortest and the cheapest canal network since a constant unit canal cost was used for an average capacity.
- Total canal costs determined by NF and TS minimizing the total canal cost was found to be significantly far from representing the real canal costs. The reason for this is to use an average unit cost in the models instead of real discharge-cost relation. For example, total canal cost given by network flow model was $81 209 (this value was determined for 176 $/m m^3/s unit cost corresponding to an average discharge of 0.125 m^3/s used in the model).

The total cost of the same canal network by real discharge-cost relation is $ 226 839 and this value is higher than the value yielded by the model. Large differences between Cost-A and Cost-B can be related to longer canals with lower capacities but high costs.

Canal lengths and canal costs for current canal network was presented in Table 2. When the current canal network length (15 958 m) was compared to the one obtained by MST-M model, it can be seen that canal length of current network is 123.5% longer. Similarly, canal costs are also higher. However, parcellation conditions were not taken into consideration while designing the current canal network. This conclusion emphasize the importance of application of an optimization model in open canal system irrigation network design considering both total costs and water delivery to every plot.

As seen from the results, the approaches considered in this study and used in open canal network optimization are found to be insufficient since they were either not taking network cost into consideration or taking a constant unit canal cost for an average capacity. That is why, for further studies, it was thought that the optimization models minimizing the total canal cost taking discharge-unit cost relation based on not an average capacity but current capacity would be beneficial.

Professional experiences of engineers dealing with the design of open canal systems are certainly important. However, combining these experiences with optimization techniques inevitable to design more economical and more beneficial canal networks.

In this study, only the canal costs were taken as irrigation system cost and the costs of architectural structures (bridge, conduit and etc.) were not taken into consideration since they were assumed to be constant over the project area and do not effect the model results. For further studies, costs of these kinds of structures other than canals can be taken into consideration in optimization studies.

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