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Optimal design of piped irrigation network: A case study of Bakhari Distributary of Pench Irrigation Project, India

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ABSTRACT
Conventional method for supplying water for irrigation in India by canal networks has certain limitations such as huge seepage losses, evaporation losses, land acquisition problems, thefts etc. To overcome these limitations, nowadays piped distribution networks are becoming popular. Network of pipes for conveying water, form a major part of investment in irrigation project (up to 70% of the total project cost). This cost can be reduced by Efficient and optimal design of piped irrigation network. In the present study, design of the pipe distribution network has been carried out using EPANET 2.0 for Bakhari Distributary of Pench Irrigation Project, India and the respective cost of the network has been calculated. Analysis and design have been carried out by critical path method for same network. The results obtained from critical path method have been optimized using linear programing method with LINGO 17.0 solver. The results of above said methods have been compared. The linear programing optimization technique has provided a distinctive reduction in the overall cost of irrigation water distribution network over the EPANET 2.0 based design. Total cost saving up to 18.64% has been achieved by using linear programing optimization technique for the design of present case study area. The methodology can be further extended to large pipe irrigation networks to reduce the present canal losses, there by optimizing the water use.
Keywords – Piped network, Linear programming, LINGO 17.0, EPANET 2.0, Optimization.

I. INTRODUCTION

Agriculture plays a vital role in India's economy. Maximum percentage of the rural households depend on agriculture as their principal means of livelihood. The present rapid demand of water for irrigation purpose increases day by day. It is necessary for irrigation engineer to design efficient irrigation system. Present irrigation canal system has various drawbacks such as 45%-50% of seepage losses [1] and evaporation losses, thefts are the serious issues along with maintenance of the canal. To overcome these issues exiting canal system is to be replaced by pressurize system (pipe network). The pressurize system consist of the key components as, reservoir, pipes, pumps, valves, etc. Irrigation system consists of branch network. Irrigation network system for existing irrigation projects is a branching type. Loop system is more reliable as alternate routes are available for conveying water to the demand nodes. But it is costlier than branch type system. Reliability is preferred to economy. Therefore branch systems are mostly used in irrigation network system. The aim of the present work is to get the optimal design for given irrigation water distribution pipe network. The main objective of the study is to minimize the overall cost of the piped irrigation network without violating any design constraints. There are two types of constraint i.e. flexible and rigid constraint. Flexible constraint includes the constraint which are flexible in nature i.e. minimum velocity (0.6m/s), maximum velocity (2.5m/s), minimum head (0.6m) requirement etc. [2] and rigid constraint includes the constraint which cannot be violated i.e. minimum head loss[3], minimum pressure at junction node etc. Rigid constraint used in formulating a model in linear programing method [3] with LINGO 17.0 solver, which provide a global optimal solution on the basis of given constraint. In the present study the topology of the irrigation network, water requirement i.e. demand are predefined and the optimization is oriented to find the minimum cost of piped irrigation network. A case study of Bakhari distributary of Pench Irrigation Project is taken and design is carried out by EPANET 2.0 using flexible constraints. This irrigation network is also designed by critical path method [4] and optimized by linear programing method [3] using LINGO 17.0 solver using flexible as well as rigid constraints. Results obtained by both approaches have been compared. Linear programing optimization technique is one of the simple and convenient method for optimization.

II. STUDY AREA

The area selected for the present study is Bakhari distributary of Pench irrigation project. Index map of study area is shown in Figure 1. The field data used in this study is collected from water resources department (irrigation department), Nagpur. Pench irrigation project is multipurpose project with objective of irrigation, domestic and industrial water supply. The main dam is constructed on river Pench, a tributary of river Kanhan in Godavari basin. The dam is located near Navegaon Khairy village in Nagpur district of Maharashtra and has left and right bank canal (LBC & RBC) system to irrigate 104476 ha annually. The dam has the gross storage capacity of 230Mm^3 and the live storage capacity is 180Mm^3. The LBC has the total length of 32.850 km with design discharge of 90 cumec at a head to irrigate 73900 ha, while the RBC has a length of 484 km with design discharge of 28.4 cumec to irrigate 30576 ha annually. Besides irrigation, the RBC supplies water to Nagpur Municipal Corporation and thermal power stations at Koradi and Khaperkheda. The distributary selected for study is located in Kanhan branch canal of LBC of Pench irrigation project. Kanhan branch canal is the first branch canal off taking at running distance of 13.625 km at right side of LBC. Length of Kanhan branch canal is 14.5 km. It has two sub branches namely Warada sub branch and Kanhan sub branch, and five distributaries namely Bakhari distributary**,** Warada distributary, Tekadi distributary, Gahuhiwara distributary and Kanhan tail distributary. Bakhari distributary offtakes from Warada sub branch canal of Bakhari Distributary at running distance of 5565 m on left side. Total length of this distributary is 18.865 km. The command area lies in Nagpur district. It is a ridged unlined canal having irrigation area on both side. The canal network of Bakhari distributary consist of 16 minors and 33 nodes from which 17 are direct outlets (DO).

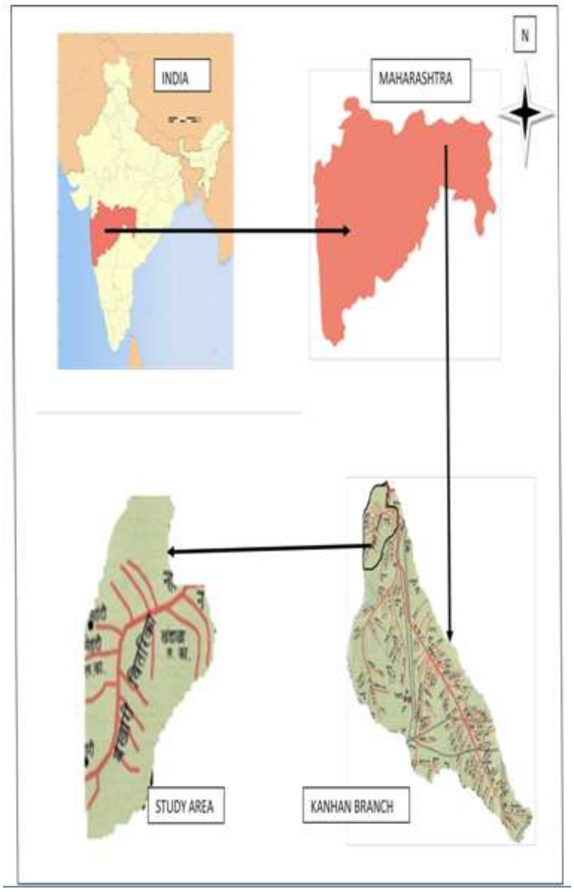

Fig. 1: Index map of study area

III. METHODOLOGY

3.1 Analysis and design of network using EPANET

The layout of pipe network is extracted from the base map of the study area and is prepared in EPANET 2.0. The entire distribution network consists of 33 pipes, 33 junctions, 1 source reservoir from which water is transferred by pressure which is shown in Figure.2.

3.1.1 Steps followed in EPANET 2.0

a. Assigning the units of flow as lps, fix the head loss formula to Hazen – Williams (H – W).

b. Nodal demands and elevations of nodes are given to the network as an input.

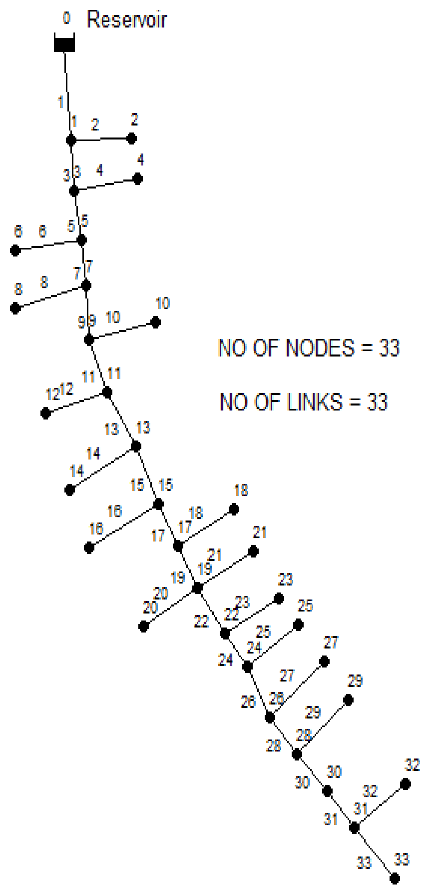

Fig.2 network from EPANET 2.0

c. The hydraulic properties like length, diameter, roughness etc. are to be assigned to the network based on the method of importing into EPANET platform
d. After assigning input data to network, thoroughly check the pipes and nodes are connected properly at intersections and reservoir nodes.
e. Run the hydraulic analysis
f. Repeat the step so that minimum velocity, maximum velocity and head requirement constraint are not violated.
g. Cost of irrigation to be calculated.

3.2 Analysis and design using critical path method [4] and optimized using linear programing method [3] with LINGO 17.0 solver.

Using same input parameters as used in EPANET, the optimization of the network had been carried out to optimize the diameters and minimize the total cost of pipes.

a. Using critical path method [4] initial diameters as per given demands and minimum head available are calculated.

b. Then objective function is defined to obtain optimal solution [3].

Objective function:

$$\text{Min. T.C.} = \Sigma\, C_{\text{pipes}} \tag{1}$$

$$\text{Min T.C.} = \sum_{j=1}^{Nl} \sum_{j=1}^{Ncp} Cij \, . \, Lij \tag{2}$$

Where,

T.C. - Total cost of pipe

$$\text{T.C.} = \sum_{n=1}^{N_l} k \, . \, L_{x.} D_x^m \tag{3}$$

C - Cost of single pipe
Cij - Cost of pipe per meter in Rs [7]
Lij - Length of pipe in meter
Nl - Number of links in network
Ncp = Number of commercial pipes
K, m – Cost constants
L_x – Length of the pipe in meter
D_x – Diameter of pipe in mm.

c. Constraints are, defined using minimum head available condition.

$$H_j^{avl.} \geq H_j^{min.}$$
$$H_f \leq H_o - H_j^{min.}$$
$$H_o - H_j^{min.} \geq \sum_{x \in p} \frac{k_1 . L_x . Q_x^q}{C_{Hwx}^q . D_x^r} \tag{4}$$
$$H_o - H_j^{min.} \geq \sum_{i=1}^{Nl} \sum_{j=1}^{Ncp} S_{ij} . L_{ij} \tag{5}$$
$$L_{ij} \geq 0 \tag{6}$$

Where,

$H_j^{avl.}$ – Available head at node j
$H_j^{min.}$ – Minimum head at node j
H_f – Head loss over the length L
S_{ij} – Slope in between nodes i and j
C_{Hwx} - Hazen's William's Constant
Q – Flow through the pipe in m^3/min.
L - Length in metre
k_1 – Constant = 2.215×10^{12}
D – Diametre of pipe in mm.
q-1.85
r – 4.87

d. Model formulation in the from of objective function and constraints is given to LINGO as an input.

e. Program is run to get global optimal solution.

f. Total cost of irrigation is calculated.

IV. Results

The network for Bhakari distributary is analysed:

4.1 Results obtained from EPANET 2.0 are indicated in Table1, 2 and 3.

Table 1 shows the details of network such as node id, nodal demand in liter per second, head in meter at node etc. These data is use for the further analysis.

Table. 1 Details of nodes in network.

Node ID	Demand in L/S	Head in m	Pressure head in m
Junction1	0	308.47	2.21
Junction3	0	308.28	2.4
Junction5	0	307.98	2.3
Junction7	0	307.89	2.27
Junction9	0	307.74	2.14
Junction11	0	307.36	1.86
Junction13	0	307.11	1.71
Junction15	0	306.83	1.53
Junction17	0	306.63	1.43
Junction19	0	306.05	0.95
Junction22	0	305.74	0.74
Junction24	0	305.56	0.66
Junction26	0	305.33	0.53
Junction28	0	305.18	0.48
Junction31	0	304.94	0.44
Junction33	113	304.62	2.32
Junction2	141	307.26	1.26
Junction4	62	307.24	2.24
Junction6	62	306.8	1.75
Junction8	50	307.47	2.27
Junction10	99	305.77	1.67
Junction12	61	306.8	1.4
Junction14	61	306.55	1.25
Junction16	142	306.01	1.01
Junction18	132	305.74	0.74
Junction20	61	305.51	0.91
Junction21	61	305.31	0.91
Junction23	61	305.12	1.82
Junction25	31.5	304.62	0.62
Junction27	78.7	304.42	2.32
Junction29	138.7	304.3	1.5
Junction30	56	304.44	1.84
Junction32	0	305.03	0.43
Reservoir0	0	308.48	0

Table number 2 shows the details of pipe network such as link id, length of link in meter, diameter of pipe in mm, flow through pipe in liter per second and flow velocity in meter per second. These are the output after analysis and design of network for above input.

Table. 2 Details of pipe in network.

Link ID	Length in m	Diameter in mm	Flow in L/S	Velocity in m/s
Pipe 3	685	1500	1269.9	0.72
Pipe 5	390	1200	1207.9	1.07
Pipe 7	135	1200	1145.9	1.01
Pipe 9	155	1100	1095.9	1.15
Pipe 11	470	1100	996.9	1.05
Pipe 13	345	1100	935.9	0.98
Pipe 15	270	1000	874.9	1.11
Pipe 17	170	900	732.9	1.15
Pipe 19	680	900	600.9	0.94
Pipe 22	560	900	478.9	0.75
Pipe 24	430	900	417.9	0.66
Pipe 26	340	800	386.4	0.77
Pipe 28	185	700	307.7	0.8
Pipe 33	285	450	113	0.71
Pipe 2	1200	500	141	0.72
Pipe 4	825	350	62	0.64
Pipe 6	940	350	62	0.64
Pipe 8	500	350	50	0.52
Pipe 10	2250	450	99	0.62
Pipe 12	455	350	61	0.63
Pipe 14	460	350	61	0.63
Pipe 16	810	500	142	0.72
Pipe 18	990	500	132	0.67
Pipe 20	450	350	61	0.63
Pipe 21	610	350	61	0.63
Pipe 23	510	350	61	0.63
Pipe 25	510	250	31.5	0.64
Pipe 27	900	400	78.7	0.63
Pipe 29	900	500	138.7	0.71
Pipe 32	480	350	56	0.58
Pipe 30	265	600	169	0.6
Pipe 31	150	600	169	0.6
Pipe 1	50	1600	1410.9	0.7

Table number 3 shows the details of cost of pipe network for diameter provided. Cost as per given in schedule rate [8] and hence total cost of network is to be calculated.

Table.3 Details of cost of network.

Link ID	Length in M	Diameter in mm	Rate in Rs/m	Total cost in Rs
Pipe 3	685	1500	20951	14351435
Pipe 5	390	1200	13964	5445960
Pipe 7	135	1200	13964	1885140
Pipe 9	155	1100	12053	1868215
Pipe 11	470	1100	12053	5664910
Pipe 13	345	1100	12053	4158285
Pipe 15	270	1000	10505	2836350
Pipe 17	170	900	8969	1524730
Pipe 19	680	900	8969	6098920
Pipe 22	560	900	8969	5022640
Pipe 24	430	900	8969	3856670
Pipe 26	340	800	7197	2446980
Pipe 28	185	700	5802	1073370
Pipe 33	285	450	3635	1035975
Pipe 2	1200	500	4071	4885200
Pipe 4	825	350	3110	2565750
Pipe 6	940	350	3110	2923400
Pipe 8	500	350	3110	1555000
Pipe 10	2250	450	3635	8178750
Pipe 12	455	350	3110	1415050
Pipe 14	460	350	3110	1430600
Pipe 16	810	500	4071	3297510
Pipe 18	990	500	4071	4030290
Pipe 20	450	350	3110	1399500
Pipe 21	610	350	3110	1897100
Pipe 23	510	350	3110	1586100
Pipe 25	510	250	1931	984810
Pipe 27	900	400	3407	3066300
Pipe 29	900	500	4071	3663900
Pipe 32	480	350	3110	1492800
Pipe 30	265	600	5035	1334275
Pipe 31	150	600	5035	755250
Pipe 1	50	1600	23347	1167350

Total cost of irrigation pipe network based on EPANET 2.0 design is 10.489 crore.

4.2 Results are obtained from critical path method and optimized by linear programing method with LINGO 17.0 solver are presented in Table 4. Table 4 shows, the link is divided in one or two link as per results obtained (e.g. L11, L12 indicate that link number 1 and length of link divided in to two sub link i.e. 1,2 according to diameter required.) and details of diameter and corresponding length of pipe.

Table.4 Details of cost of network

Pipe	Link	Length m	Diameter mm
01	L11	50.00	1200
02	L21	318.160	500
	L22	881.140	400
03	L31	394.550	1100
	L32	290.450	1000
04	L41	816.720	300
	L42	8.280	200
05	L51	390.00	1100
06	L61	481.70	350
	L62	458.30	300
07	L71	111.87	1100
	L72	23.13	1000
08	L81	425.00	300
	L82	75.00	200
09	L92	155.00	1000
10	L101	1366.50	400
	L102	883.50	350
11	L111	470.00	1000
12	L121	302.91	300
	L122	152.09	200
13	L131	345.00	1000
14	L141	322.50	300
	L142	137.50	200
15	L152	270.00	900
16	L161	503.40	400
	L162	306.60	350
17	L172	170.00	900
18	L181	763.30	400
	L182	226.70	350
19	L192	680.00	800
20	L201	561.20	300
	L202	48.80	200

21	L211	382.00	300
	L212	68.00	200
22	L222	560	700
23	L231	475.90	300
	L232	34.10	200
24	L242	430.00	700
25	L251	119.55	300
	L252	390.45	200
26	L261	340.00	700
27	L271	617.25	400
	L272	282.75	350
28	L281	185.00	700
29	L291	690.67	500
	L292	209.33	400
30	L301	265	500
31	L311	150.00	500
32	L322	480.00	300
33	L332	285.00	350

Total cost of irrigation pipe network obtained based on the said approach is 8.533 crore.

V. CONCLUSION

From the present study following are the conclusions.

The total cost of the irrigation pipe network at Bakhari distributary from EPANET of 2.0 and linear programing method of design optimization is calculated and found to be 10.489 crore and 8.533 crore respectively.

In optimization using linear programing method with LINGO solver 17.0, 18.64% of the total cost can be reduced.

Thus linear programing method is simple as well as convenient for irrigation pipe water distribution network optimization but prior to that initial diameters have to be calculated by using critical path method.

Analysis and design by EPANET 2.0 is simple and easy but its time consuming as trial and error process.

This work is helpful in deciding the method of designing and optimization in case of irrigation pipe water distribution network.

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