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Optimal Design Of Canal Section Of Pagladiya Major Irrigation Project By Using Non-Linear Optimization

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Abstract:

Two nonlinear optimization models were formulated—one corresponding to a rectangular canal shape and another to a trapezoidal shape. The main objective of both models is to reduce cost of construction per unit length. These models were handled using Microsoft Excel's Solver; incorporating the necessary variables and constraints to determine the minimum construction cost and the most suitable canal dimensions**.** For the entire canal system Rectangular section is found to be most optimized canal section which leads to a minimum construction cost of Rs. 33,50,98,824.4 (Thirty three crore fifty lakh ninety eight thousand eight hundred twenty four point four); in contrast, a trapezoidal section costs Rs. 46,05,11,223.5 (Forty six crore five lakh eleven thousand two hundred twenty three point five).

Keywords — Pagladiya Major Irrigation Project, Construction cost, Canal design, Crop water requirements, Canal discharge, Rectangular canal section, Trapezoidal canal section, Nonlinear optimization models, Microsoft Excel Solver**.**

I. INTRODUCTION

Optimization modelling is a mathematical approach that identifies the best solution among many alternatives for a given problem. Mathematical optimization can reduce costs and improve overall efficiency.The Pagladiya Major Irrigation Project has been selected as the study area for the present work. It is located in the state of Assam on the northern bank of the Brahmaputra River within Nalbari district. The headwork for the project is proposed to be constructed at Sondha village near Janopar across the Pagladiya River, which is a perennial stream originating from the foothills of Bhutan.

II. STUDY AREA

The project envisages the construction of a headwork across the Pagladiya River at Sondha near Janopar in Nalbari district of Assam, located at latitude 26°26'56.67" N and longitude 91°27'38.08" E. The site at Sondha has been selected for the proposed structure as it lies away from National Highway–27. Development of the irrigation canal network from this location is not expected to cause any damage to NH-27, making it advantageous both in terms of construction cost and reduction in design and execution complexity.

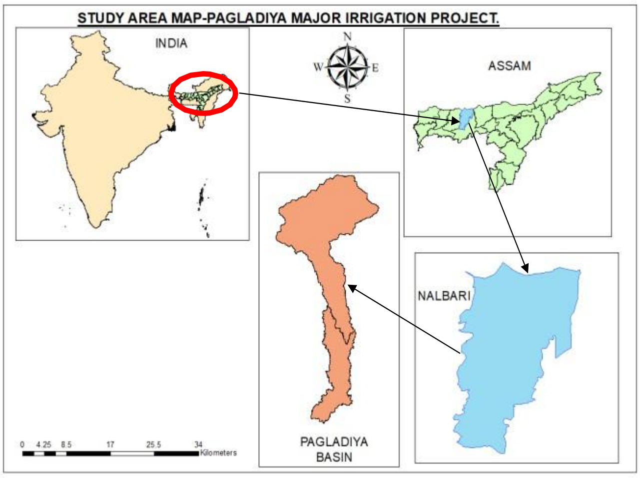

Fig. 1 Location Map of Study Area prepared byArcGIS

The scheme was proposed with the objective of improving irrigation facilities in several parts of Nalbari district, mainly covering the regions of Barkhetri, Paschim Nalbari, Tihu, and Madhupur. The project plans to provide irrigation to Barkhetri through a main canal originating from the headwork structure at Sondha, followed by the extension of irrigation supply to Paschim Nalbari, Tihu, and Madhupur through branch canals drawn from the main canal.

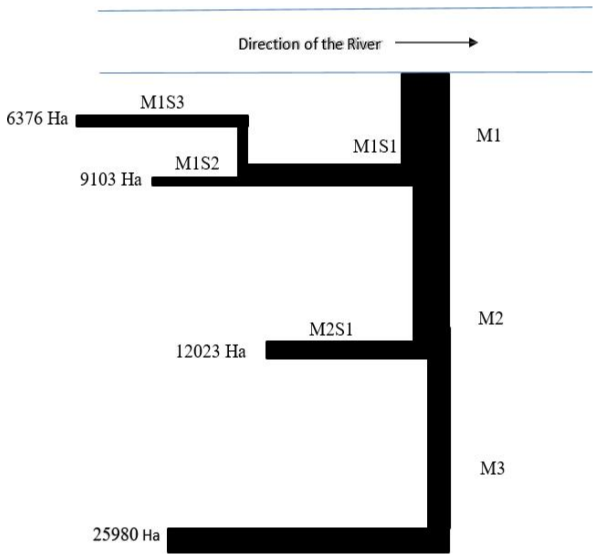

FIG.2 SCHEMATIC LAYOUT OF THE PROPOSED CANAL SYSTEM

III. MATERIALS AND METHODOLOGY

Cultivable area and types of crops cultivated under different places is taken from District Irrigation Plan Nalbari, Assam and Report On Aquifer Mapping And Management Plan Of Nalbari District, Assam (AAP 2021-22) from Central Ground water Board. Cropping Period for Sali, Ahu, oilseed, pulses, Kharif and Rabi vegetables are taken from internet as source.

TABLE 1
TYPES, CROPPING PERIOD OF THE CROPS

SI. NO	Name of crop	Cropping period	Area(in Ha)
1	Sali	June/July to November/December	41273
2	Ahu	February/March to June/July	8466
3	Oil seed	October to March	4999
4	Pulses	October and November	1980
5	Kharif Vegetable	June to July	2245
6	Rabi Vegetable	October to November	5348

Crop Water Requirement data is taken from previous work done on Kulsi River Basin in Kamrup District (Das and Sarma, 2018).

TABLE 2
CROP WATER AND MAXIMUM CROP WATER REQUIREMENT (MM/DEC)

Name of crop	Crop Water Requirement(mm/dec)	Maximum Crop Water requirement (mm/dec)
Sali	543	41.8
Ahu	542.3	53.5
Oil seed	160.5	20.8
Pulses	299.8	34.3
Kharif Vegetable	315.9	45.1
Rabi Vegetable	181.1	24.1

Design Parameters for canal sections is taken from IS : 10430-2000. Schedule of rates (2023-24) is taken from Irrigation department of Govt. of Assam. Required Discharge in the field is calculated by the following equation-

$$\text{Annual Irrigable Area} \times \frac{\text{Max. C.W.R. Per Decadal}}{10\times24\times60\times60} \times \frac{10000}{1000} m^3/s$$

A. Discharge Of The Canal Section

The discharge in a canal is calculated fro manning's equation.

$Q = A \times 1/n \times R^{2/3} \times S^{1/2}$

Where, A= Area of cross section of the canal

n= Manning's rugosity coefficient

R= Hydraulic Radius of the canal

S= Longitudinal Slope Of The Canal

B. Formulation of the rectangular and trapezoidal model

Assume, a rectangular canal section with parameters B, Y, f, and t are the Width of bed, depth of flow, free board and thickness of canal lining respectively. Let, A_f and P_f are the cross sectional area and wetted perimeter of the canal with free board f. These parameters can be written as-

$A_f = B \times (Y + f)$

$P_f = B + 2(Y + f)$

Similarly A, P, R, T, D, V and F_r are the area, wetted perimeter, hydraulic radius, top width, hydraulic depth, velocity of flow in the canal and Froude's no of the canal without freeboard respectively. These parameters can be written as, $A=B \times Y$

$P=B + 2Y$

$T=B$

$D=A / T$

$R=A / P$

$F_r=V / \sqrt{gD}$; where, g = Acceleration due to gravity = 9.81 m^2/s.

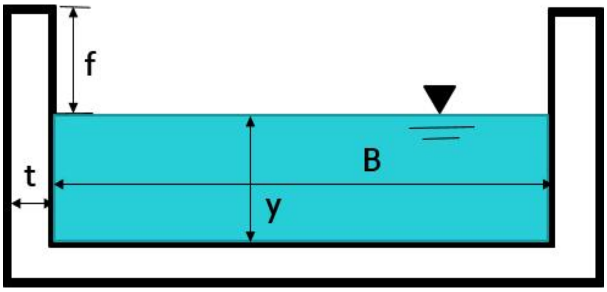

Fig. 3 Cross section of rectangular canal section

Again assume, a trapezoidal canal section with parameters bed width of the canal (B), flow depth (Y), Manning's roughness coefficient (n), thickness of the canal lining (t), free board (f), and side slope in the ratio 1:Z (V:H) = 1:1 on both sides.

Let, A_f and P_f are the cross sectional area and wetted perimeter of the canal with free board f. These parameters can be written as-

$A_f= (B+Z(Y+f)) \times (Y+f)$

$P_f= B+ 2(Y+f)\sqrt{(1 + Z^2)}$

Similarly A, P, R, T, D, L, V and F_r are the area, wetted perimeter, hydraulic radius, top width, hydraulic depth, length of slanting side, velocity of flow and Froude's no of the canal without freeboard. These parameters can be written as,

$A= (B+ZY) \times Y$

$P= B + 2Y\sqrt{1 + Z^2}$

$T= B + 2ZY$ $D= A/T$

$L= Y \sqrt{1+Z^2}$

$R= A/ P$

$F_r=V/\sqrt{Gd}$

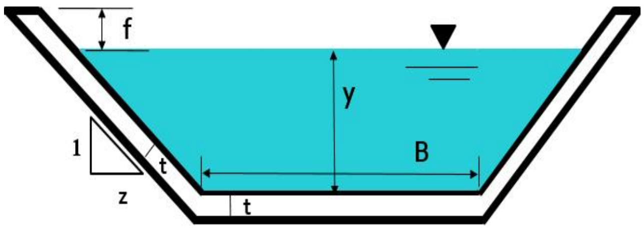

Fig. 4 Cross-Section Of Trapezoidal Canal Section

C. Objective Function

The objective function of the Nonlinear Programming (NLP) model comprises the excavation and lining costs, aimed at minimizing the overall construction expenses for the Pagladiya Major Irrigation project canal.

(i) For Rectangular canal section-

Min R=Cost of excavation + Cost of lining

= C_1 x Cross-sectional area of the canal+ C_2 x Cross sectional area of lining

= $C_1 \times B \times (Y+f) + C_2 \times (B+2 \times (Y+f)) \times t$

Where, Min R = Minimum cost of construction of canal per running meter.

C_1 = Cost of excavation per cubic meter.

C_2 = Cost of lining per cubic meter.

B = Width of the canal.

Y = Depth of the canal.

f = Free board provided in the canal.

t = Thickness of lining.

(ii) For Trapezoidal canal section-

Min R = Cost of excavation + Cost of lining

= C_1 x Cross-sectional area of the canal+ C_2 x Cross sectional area of lining.

= $C_1 \times \{(B +Z(Y + f)\}(Y + f)) + C_2 \times (B \times t) + \{C_2 \times 2 \times ((Y + f) \times \sqrt{(1 + Z^2)} \times t)\} + \{C_2 \times (B \, xt)\}$

Where, Min R = Minimum cost of construction of canal per running meter.

B = Width of the canal.

Y = Depth of the canal.

f = Free board provided in the canal.

t = Thickness of lining.

1: Z (V: H) =side slope.
Z=1(side slope is considered as 1:1 for Trapezoidal section)
The values of C_1 and C_2 are taken as per Schedule of rates for the year 2023-24 of the Irrigation department of Govt. of Assam.
Where,
C_1 = 303.62 Rs. =Earthwork in excavation in ordinary soil.
C_2 = 8386.85 Rs. =CC Work in lined canal in prop 1:2:4 with river shingles of size 6 mm to 20 mm free from dust, dirt and other foreign materials.

D. *Constraints*

(i) Discharge in the canal:
The discharge calculated from Manning's formula for the canal is greater than or equal to the discharge required or the design discharge for the canal.

(ii) Condition of most economic canal section:
The condition for most economic rectangular canal section is B=2Y.
For a Trapezoidal Section, hydraulic radius, R=Y/2, Half the top width equals to one of its sloping side.

(iii) Width of the canal :
The width of the canal cannot be negative, i.e. B > 0. Considering the construction point of view, let the minimum width of the canal be 0.1m.

(iv) Depth of the canal:
The depth of the canal cannot be negative i.e. Y > 0. Let the minimum depth of the canal be 0.1m.

(v) Limiting velocity:
The limiting velocity for the canal is considered as per IS: 10430-1982 which is provided is table 6.4. The limiting velocity for cement concrete lining is 2.7 m/s.

(vi) Critical velocity:
According to IS: 10430-2000, the critical velocity obtained by any formula should be less than the velocity of the canal obtained by Manning's formula. The critical velocity obtained by Kennedy's formula i.e.
$V_O = 0.546 \times D^{0.64}$

The value of V_O should be less than the velocity in the canal obtained by Manning's formula.

(vii) Flow condition:
The Froude's number calculated for the canal section should be less than 1(one) to maintain the subcritical flow condition in order to avoid hydraulic jump in the canal. $Fr = V/\sqrt{gD}$,
Where ,
V = velocity of flow in m/sec ,
g=acceleration due to gravity ,
D=hydraulic depth

(viii) Top width:
The top width for main canal and branch canal in case of Rectangular canal section are 6.75 m and 6 m respectively.The top width for main canal and branch canal in case of Trapezoidal canal section are 15.75 m and 15.6 m respectively.

E. *Variables*

The optimization model involves two variables-
(i) Bed width of the canal.
(ii) Depth of the canal.

IV. RESULTS AND DISCUSSIONS

Using crop water requirement data obtained from earlier studies and applying discharge equation, the required field discharge (m^3/s) is computed.

TABLE 3
TYPE OF CROPS GROWN, NET ANNUAL IRRIGABLE AREA AND FIELD DISCHARGE REQUIRED

Location	Type of crops grown & net irrigable area (in Ha)	Annual irrrigable area (in Ha)	Field discharge required (m^3/s)
Barkhetri	Sali=17526	25980	11.1
	Ahu=2698		
	Oil seed=2476		
	Pulses=1517		
	Vegetable(Kharif)=1171		
	Vegetable(Rabi)=592		

Madhupur	Sali=4370	6376	2.7
	Ahu=585		
	Oil seed=776		
	Pulses=157		
	Vegetable(Kharif)=126		
	Vegetable(Rabi)=362		
Paschim Nalbari	Sali=9424	12023	5.1
	Ahu=588		
	Oil seed=1093		
	Pulses=179		
	Vegetable(Kharif)=217		
	Vegetable(Rabi)=522		
Tihu	Sali=7072	9103	3.9
	Ahu=474		
	Oil seed=654		
	Pulses=127		
	Vegetable(Kharif)=271		
	Vegetable(Rabi)=505		

As considerable water losses are expected due to seepage, evaporation, and inefficiencies in channel design, and since lining and improved management practices are intended to reduce these losses, a conveyance efficiency of 80% is assumed to estimate the discharge required at the canal head (m^3/s).

TABLE 4

REQUIRED FIELD DISCHARGE AND CANAL DISCHARGE

Designation	Field Discharge required (m^3/s)	Discharge required by the canal (m^3/s)
M1	22.7	28.4
M1S1	6.6	8.3
M1S2	2.7	3.4
M1S3	3.9	4.9
M2	16.1	20.1
M2S1	5.1	6.4
M3	11	13.8

A. Calculation Of Width & Depth From Manning's Equation

From Discharge required by the canal and by using manning's equation, Optimum Width And Optimum Depth is calculated.

TABLE 5

WIDTH AND DEPTH OF RECTANGULAR AND TRAPEZOIDAL SECTION CALCULATED USING MANNING'S EQUATION

SL. No	Designation	Discharge (m^3/s)	Rectangular Section		Trapezoidal Section	
			Width (B) in m	Depth (Y) in m	Width (B) in m	Depth (Y) in m
1	M1	28.4	6.0	3.0	5.2	3.2
2	M1S1	8.3	3.8	1.9	3.3	2.0
3	M1S2	3.4	2.8	1.4	2.3	1.4
4	M1S3	4.9	3.1	1.5	2.7	1.6
5	M2	20.1	5.3	2.6	4.6	2.8
6	M2S1	6.4	3.4	1.7	3.0	1.8
7	M3	13.8	4.6	2.3	4.0	2.4

B. Canal Optimization By GRG Solver

We input the objective function, variables, and constraints into the solver to solve the nonlinear programming model. The model generates the canal section by evaluating the variables that meet all constraints and the optimal value of the objective function

TABLE 6

OPTIMUM DEPTH, OPTIMUM WIDTH AND OPTIMUM COST PER RUNNING METRE LENGTH CALCULATED BY GRG SOLVER

Designation	Discharge (m^3/s)	Rectangular Section						Trapezoidal Section					
		Width (m)	Depth (m)	Cost of Construction Per Running Meter (Rs.)	Optimum Width (m)	Optimum depth (m)	Optimum Cost of Construction Per Running Meter (Rs.)	Optimum Width (m)	Optimum depth (m)	Cost of Construction Per Running Meter (Rs.)	Optimum Width (m)	Optimum depth (m	Optimum Cost of Construction Per Running Meter (Rs.)
M1	28	6	3	13624.80	5.98	2.99	13550.68	5.2	3.2	25731.26	1.9	3.1	18084.72
M1S1	8.3	3.8	1.9	7312.65	3.77	1.88	7236.61	3.3	2	13715.01	1.20	1.98	9842.87
M1S2	3.4	2.8	1.4	5122.11	2.70	1.35	4911.48	2.3	1.4	9156.26	0.86	1.42	6889.69
M1S3	4.9	3.1	1.5	5650.01	3.09	1.55	5730.05	2.7	1.6	10710.55	0.98	1.62	7933.79
M2	20	5.3	2.6	11429.31	5.25	2.62	11416.07	4.6	2.8	21758.25	1.67	2.76	15410.02
M2S1	6.4	3.4	1.7	6399	3.42	1.71	6438.99	3	1.8	12176.35	1.09	1.79	8833.97
M3	14	4.6	2.3	9644.15	4.56	2.28	9536.01	4	2.4	18076.72	1.45	2.39	13040.66

V. CONCLUSION

For the rectangular canal section, the optimum construction cost for canals M1, M1S1, M1S2, M1S3, M2, M2S1, and M3 is estimated to be ₹13,550.68, ₹7,236.61, ₹4,911.48, ₹5,730.05, ₹11,416.07, ₹6,438.99, and ₹9,536.01 per running metre, respectively. In the case of the trapezoidal canal section, the corresponding optimum construction costs for M1, M1S1, M1S2, M1S3, M2, M2S1, and M3 are projected as ₹18,084.72, ₹9,842.87, ₹6,889.69, ₹7,933.79, ₹15,410.02, ₹8,833.97, and ₹13,040.66 per running metre, respectively. By comparing both the sections as shown in Fig-6.1, for the entire canal system Rectangular section is found to be most optimized canal section which leads to a minimum construction cost of Rs. 33,50,98,824.4 (Thirty three crore fifty lakh ninety eight thousand eight hundred twenty four point four); In contrast, a trapezoidal section costs Rs. 46,05,11,223.5 (Forty six crore five lakh eleven thousand two hundred twenty three point five). The Trapezoidal Section costs 37.42 % more than rectangular section.

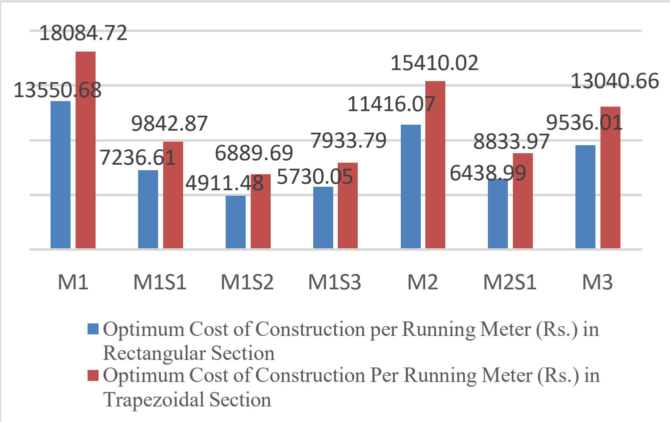

Fig. 5 Comparison of Optimum Cost of Construction per Running Meter (Rs.).

The present work focuses on rectangular and trapezoidal canal section models because these shapes are simple to construct on site. Future studies may examine other forms, such as oval or compound sections, while still aiming to keep construction costs low for similar discharge in different open canal designs. Optimal dimensions for these additional canal shapes could also be determined, allowing a comparison of the lowest construction cost and section sizes across multiple canal types. In this study, it is considered that there is a abrupt shift in canal dimensions when moving from Major to Minor Canals. However, it may be more realistic during field practice to assume a gradual shift in section dimensions when moving from Major to Minor Canals.

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