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RESEARCH ARTICLE

SUSTAINABLE MICRO-LEVEL AGRICULTURAL WATER MANAGEMENT POLICIES.

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Abstract

In the present study an attempt has been made to develop sustainable water management policy for Nuh Region of Haryana State, India.MATLAB based optimization model have been developed and applied to study area with the aim of maximization of net benefits, considering optimal utilization of available land, water and human resources with emphasis on food security, nutritional requirements and employability of the available human labour of the area. In order to facilitate the implementation of the proposed policy, Decision Support Tables (DSTs) have been created. These DSTs were grouped into three categories: DST- I: Optimal Cropping Pattern Policies, DST- II: Optimal Operational Policies and DST- III: Optimal Crop Water Use Policies.

Introduction:-

Nuh region comes under Mewat district of Haryana state India is a socio-economically backward area. The main occupations of the people are agriculture and agro based dairy business. The region does not have any river and it depends mainly on canal water and groundwater for its water demands. Though the region is 45 km south of one of the most developed cities of India i.e. Gurugram, still Nuh suffers as a region of backwardness. Meos, the main population of the region, are natural agriculturists but were deprived of proper irrigation. Agriculture is the backbone of Nuh development and this district has been striving to compete with other regions in this regard. A policythatcan optimally utilize existing land, human and water resources of Nuh regionand has the ability to provide economic stability, employability, food & nutritional requirements is the need of the hour.

System analysis techniques are powerful tools, capable of dealing with complex water resource systems and have been applied in various water resources planning studies. Normally two approaches of analysis of operation research are employed and they are optimization techniques and simulation modeling. Further it may be sub-grouped conveniently as a) optimization studies b) multi-level, multi-objective, and multi-criteria studies c) integrated studies (Rao, 2014;Taha, 2010; Rao, 2000;Kothari 1999).

Numerous researchers (Smith, 1973; Maji and Heady, 1980; Sritharan, *et al*., 1988; Khare, 1994; Rao, 1996, 1999; Singh, 2001; Sethi, 2002; Otieno, 2010; Hamada, 2011; Adibe 2012; Rao, 2013, 2015) have applied linear programming model for optimal utilization of water resources and are of the view that there is no single method available for solving all optimization problems, each has its pros and cons. Researchers have been using optimization where limited sources are competing with each other in evolving optimal policies. MATLABimplements the simplex algorithm to solve and thoroughly analyzes optimization problems quickly &effectivelythan traditional programming languages.In the present study MATLAB based optimization model have been developed and applied to the study area to evolve sustainable micro-level agricultural water management policies.

Methodology:-

The proposed methodology comprises of three stages
Stage 1 – Data acquisition and analysis
Stage 2 – Identification, development and application of the model to evolve policy
Stage 3 – Micro-level (village level) Analysis of evolved policy to generate DSTs

Stage 1:-

Data pertaining to land, water and human resources have been collected and analyzed to obtain following key parameters which are used in stage 2.

KEY INPUT PARAMETERS	
1. Water available for irrigation (**IW**)	7. Fertilizer (nutrient) Use (FU)
2. Cultivable Area Kharif season (CAK)	8. Total Emission (N_2O) Existing Condition (TEEN)
3. Cultivable Area of Rabi season (CAR)	9. Total Emission (CO_2) of Existing Condition (TEEC)
4. Net Return from each crop (NR)	10. Lower Bound of crop area based on food (lb)
5. Human Labour Requirement (HLR)	11. Upper Bound of crop are as storage (ub)
6. Human Labour Availability (HLA)	12. Crop Water Requirements (NIR)

STAGE 2:-

Optimization Model:-

Objective of the proposed model is economic development that is maximizing the benefits subjected to constraints based on population sector, agriculture sector, water sector and environmental & industrial sectors.

Objective Function:-

The objective function has been formulated for maximizing net benefits generated from the cropping activity in the study area with area of crops as decision variables
The objective function of the optimization model (LP) model can be written as

$$MAX(Z) = \sum_{j=1}^{nod}\sum_{i=1}^{noc} NR_{j,i} \times A_{j,i} \qquad \text{...(1)}$$

Where

noc= Number of crops
nod= Number of divisions (villages) of the study area (=119)
$NR_{j,i}$= Net Return from i^th crop of j^th division (village)
$A_{j,i}$= Area of i^th crop of j^th division(village)

That is

$$\begin{aligned} Z = \\ & NR_{1,1}\cdot A_{1,1} + NR_{1,2}\cdot A_{1,2} + NR_{1,3}\cdot A_{1,3} + \cdots\cdots\cdots\cdots\cdots\cdots\cdots NR_{1,12}\cdot A_{1,12} + \\ & NR_{2,1}\cdot A_{2,1} + NR_{2,2}\cdot A_{2,2} + NR_{2,3}\cdot A_{2,3} + \cdots\cdots\cdots\cdots\cdots\cdots NR_{2,12}\cdot A_{2,12} + \\ & \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots + \\ & \cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots\cdots + \\ & NR_{119,1}\cdot A_{119,1} + NR_{119,2}\cdot A_{119,2} + NR_{119,3}\cdot A_{119,3} + \cdots\cdots\cdots NR_{119,12}\cdot A_{119,12} \qquad \cdots(2) \end{aligned}$$

Constraints:-

The objective function is subjected to following constraints:

1. Annual water use constraints
2. Monthly water use constraints
3. Groundwater draft constraints
4. Land use Constraints in Kharif season
5. Land use Constraints in Rabi season

6. Environmental Emission Constraints (N_2O)
7. Environmental Emission Constraints (CO_2)
8. Human Labour Constraints
9. Food security constraints
10. Land use constraints for some crops
11. Domestic water use constraints
12. Livestock water use constraints
13. Industrial water use constraints

MATLAB:-

MATLABs optimization toolbox provides a function **linprog (**linprog.m), which implements the simplex algorithm to solve a linear programming problem. 'linprog.m' module has been used foranalyzing the developed optimization LP model for various scenarios of the case study.

linprog:-

It solves linear programming problems specified by

$$\min_x f^T \cdot x \quad such\ that \begin{cases} A \cdot x \le b \\ Aeq \cdot x = beq \\ lb \le x \le ub \end{cases} \qquad \cdots (3)$$

Where

A	The matrix of coefficients oflinear inequality constraints: $A \cdot x \le b$
b	Vector of coefficients of corresponding right-side vector: $A \cdot x \le b$
Aeq	The matrix of coefficients of linear equality constraints: $Aeq \cdot x = beq$
Beq	Vector of coefficients of corresponding right-side vector: $Aeq \cdot x = beq$
f	The vector of coefficients for the linear term in the linear equation $f^T \cdot x$
x	Vector of design variables
lb, ub	Lower and upper bound vectors (or matrices).

Table 1− Output arguments of linprog:-

S.NO	Argument	Description
1	exitflag	An integer identifying the reason for the optimization algorithm terminated. ("1" function converged to a solution)
2	fval	The value of the objective function f at the solution x.
3	Output	Contains information about the results of the optimization.
4	*x*	The solution found by the optimization function. If exitflag > 0, then x is a solution; otherwise, x is the value of the optimization routine when it terminated prematurely.

Application of the model:-

During this stage model was applied for existing scenario of resources. Existing scenario consists of four cases (case 1, case 2, case 3 and case 4). Each case further subjected to four conditions (A, B, C and D). That is a total of 16 cases (4 x 4 =16) as shown in table 2 were analyzed.

Table 2− Number of cases considered for model analysis based on existing scenario:-

EXISTING SCENARIO															
CASE1				CASE2				CASE3				CASE4			
A	B	C	D	A	B	C	D	A	B	C	D	A	B	C	D

CASE1: subjected to constraints 1, 3, 4, 5, 7, 8,9,10, 11, 12, 13

CASE2: subjected to constraints 1, 3, 4, 5, 6, 7, 8,9,10, 11, 12,13

CASE3: subjected to constraints 2, 3, 4, 5, 7, 8,9,10, 11, 12, 13

CASE4: subjected to constraints 2, 3, 4, 5, 6, 7,8,9,10, 11, 12, 13

A: lb ≥area based on food requirements & ub≤ area based on storage requirements

B: lb ≥ 0 & ub- no boundsC: lb ≥ 0 & ub- no bounds (except tomato ≤ 100)

D: lb ≥area based on food requirements & ub- no bounds(except tomato ≤ 100)

lb: lower boundub: upper bound

Case- 1 model analyses the optimal utilization of resources considering water use Constraint- 1 (that is total water required by all crops shall be less than or equal to total available water in that year) and emission Constraint- 7 (that is total emissions (as CO_2 from groundwater pumping) from optimal cropping pattern shall be less than or equal to total emissions from existing cropping pattern satisfying remaining constraints for proposing a policy. In Case- 2 model analyses the optimal utilization of resources considering an additional emission Constraint- 6 in comparison with Case- 1 satisfying all the remaining constraints for proposing a policy. Whereas in comparison with Case- 1, Case- 3 is subjected to water use Constraint- 2 (that is total water required by all crops in a particular month shall be less than or equal to total water available in that particular month) instead of Constraint- 1 and satisfying all the remaining constraints for proposing a policy. Similarly in comparison with Case- 2, Case- 4 is subjected to water use Constraint- 2 instead of Constraint- 1and subjected to all the remaining constraints for proposing a policy. The notations used in the development of model and its corresponding syntaxes are shown in table 3.

Table 3- Notations used in Model and corresponding syntaxes

SNO	**Notations**	**Syntax**
1	Z	$f^T \cdot x$
2	$NR_{j,i}$	f^T
3	$A_{j,i}$	x
4	$NIR_{j,i} \times A_{j,i} \leq TWA$ $GWD \leq GWA$ $A_{j,i} \leq CA_K$, $A_{j,i} \leq CA_R$ $TEON \leq TEEN$, $TEOC \leq TEEC$ $hlr_{j,i} \times A_{j,i} \leq TLA$	$A \cdot x \leq b$
5	Additional equality constraints used in post optimal analysis	$Aeq \cdot x = beq$
6	$A_i \geq mnaf_i$	$x \geq lb$ $lb \leq x \leq ub$
7	$A_i \leq mxas_i$	$x \leq ub$ $lb \leq x \leq ub$

Sample input to optimization model being explained through table 4. The developed optimization model in the present study has been run for all the 16 cases and the results were tabulated in Table 5.

Table 4 – Input to Optimization model for Case 1A, Case 1B, Case 1C & 1D

$$f = \begin{bmatrix} -27.35 & -7.52 & -6.18 & -4.29 & -2.979 & -20 & -21.87 & -15.51 & -86.08 & -28.63 & -4.6 & -22 \end{bmatrix}$$

$$A = \begin{bmatrix} 1.195 & 0.291 & 0.054 & 0.108 & 0.223 & 0.525 & 0.399 & 0.427 & 0.692 & 0.604 & 0.36 & 0.53 \\ 1 & 1 & 1 & 1 & 1 & 1 & 0 & 0 & 0 & 0 & 0 & 0 \\ 0 & 0 & 0 & 0 & 0 & 0 & 1 & 1 & 1 & 1 & 1 & 1 \\ 191 & 120 & 127 & 127 & 82 & 82 & 147 & 107 & 228 & 125 & 127 & 72 \end{bmatrix}$$

$$b = \begin{bmatrix} 25653.88 & 35927 & 35927 & 20969400 \end{bmatrix}$$

$CASE\ 1A$

$$lb = \begin{bmatrix} 1996 & 12583 & 2353 & 2584 & 100 & 1856 & 279 & 1980 & 94 & 14163 & 2349 & 1570 \end{bmatrix}$$

$$ub = \begin{bmatrix} \inf & 13000 & 4157 & 7534 & 200 & 3000 & 418 & \inf & 100 & \inf & 2350 & 2900 \end{bmatrix}$$

$CASE\ 1B$

$$lb = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$ub = \begin{bmatrix} \inf & \inf & \inf & \inf & \inf & \inf & \inf & \inf & \inf & \inf & \inf & \inf \end{bmatrix}$$

$CASE\ 1C$

$$lb = \begin{bmatrix} 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 & 0 \end{bmatrix}$$

$$ub = \begin{bmatrix} \inf & \inf & \inf & \inf & \inf & \inf & \inf & \inf & 100 & \inf & \inf & \inf \end{bmatrix}$$

$CASE\ 1D$

$$lb = \begin{bmatrix} 1996 & 12583 & 2353 & 2584 & 100 & 1856 & 279 & 1980 & 94 & 14163 & 2349 & 1570 \end{bmatrix}$$

$$ub = \begin{bmatrix} \inf & \inf & \inf & \inf & \inf & \inf & \inf & \inf & 100 & \inf & \inf & \inf \end{bmatrix}$$

$$Aeq = [\ ] \,\&\, beq = [\ ]$$

Table 5-Model Output for various Scenarios (all 80 Cases)

SNo	PARTICULARS	Code	AREA	WATER	NB	HL	ENS
1	*SCENARIO1_CASE1A*	*S1C1A*	*55293.9*	*25653.88*	*1050.17*	*6810507*	*67342*
~~2~~	~~SCENARIO1_CASE1B~~	~~S1C1B~~	52873.1	25653.88	3197.32	6714881	124727
~~3~~	~~SCENARIO1_CASE1C~~	~~S1C1C~~	71854.0	25653.88	1322.15	8911243	86159
4	*SCENARIO1_CASE1D*	*S1C1D*	*71854.0*	*25653.88*	*1139.69*	*9865886*	*78417*
5	*SCENARIO1_CASE2A*	*S1C2A*	*52783.9*	*25653.88*	*998.62*	*6455106*	*59932*
~~6~~	~~SCENARIO1_CASE2B~~	~~S1C2B~~	45424.7	25653.88	1173.53	5754570	59932
~~7~~	~~SCENARIO1_CASE2C~~	~~S1C2C~~	71854.0	25653.88	1294.04	10314980	59932
8	*SCENARIO1_CASE2D*	*S1C2D*	*57774.9*	*25653.88*	*1055.34*	*7563419*	*59932*
9	**SCENARIO1_CASE3A**	**S1C3A**	**33804.9**	**16472.89**	**744.88**	**4381563**	**42733**
~~10~~	~~SCENARIO1_CASE3B~~	~~S1C3B~~	44047.8	17069.56	965.46	5925191	53814
~~11~~	~~SCENARIO1_CASE3C~~	~~S1C3C~~	31568.8	19179.06	831.54	4489260	36738
12	**SCENARIO1_CASE3D**	**S1C3D**	**33804.9**	**16472.89**	**744.88**	**4381563**	**42733**
13	**SCENARIO1_CASE4A**	**S1C4A**	**33804.9**	**16472.89**	**744.88**	**4381563**	**42733**
~~14~~	~~SCENARIO1_CASE4B~~	~~S1C4B~~	44047.8	17069.56	965.46	5925191	53814
~~15~~	~~SCENARIO1_CASE4C~~	~~S1C4C~~	31568.8	19179.06	831.54	4489260	36738
16	**SCENARIO1_CASE4D**	**S1C4D**	**33804.9**	**16472.89**	**744.88**	**4381563**	**42733**

AREA, WATER, NB, HL and ENS columns of Table 5 show the values of the total optimal cropping areas (ha), total water use requirements, total net benefits (in million ☐), total human labour requirement (in man-days) and total emissions respectively. Corresponding cases are shown in column with its heading as Code.

Analysis of these results were carried out in different stages to eliminate impracticable cases and select suitable cases giving due significance to optimal utilization of water, land and human resources and sustainable food and nutritional security and agricultural economy keeping in view the environmental concerns.

It was observed that when ❶ lower bound of cropping areas were positive i.e. lb ≥ 0 and upper bound of cropping areas has no limits i.e. no-bounds (ub→∞) [all Cases having letter **B**(e.g. SCENARIO1_CASE1**B**, SCENARIO1_CASE2**B** etc.) in Table 5] and when ❷ lower bound was positive i.e. lb ≥ 0 and upper bound has no limits except tomato crop having an upper limit of 100 ha [all cases having letter **C**(e.g. SCENARIO1_CASE1**C**, SCENARIO1_CASE2**C** etc.) in table 5], model has responded differently in both situations. As there was no upper limit on any cropin situation ❶, model allocated maximum area to tomato crop (as it gives maximum benefits) in Rabi season and sorghum crop in kharif season (as it uses less water) for all cases. Whereas in situation ❷ model selected two crops sorghum & pulses in Kharif season and tomato & wheat in Rabi season, as there was a limit of 100 ha on tomato crop, for all cases and allocated total cultivable areas in both the seasons to these crops. Thus optimal cropping policies were found to be skewed towards one or two crops in both Kharif and Rabi seasons. All these 8 cases (4+4=8) were unable to fulfill basic minimum food requirements and thus the proposals with conditions B and C where lower bound was ≥ 0 were eliminated in the first stage for all scenarios (shown in ~~STRIKE THROUGH~~).

In the next stage ofanalysis remaining 8cases were considered. The basic difference between Cases- 1 & 2 and Cases- 3 & 4 was with regard to water requirements. Total water required by all crops should be less than or equal to total water available for irrigation in Cases- 1 & 2, whereas in Cases- 3 & 4 total monthly water required by all crops shall be less than or equal to total water available in respective months.

During the analysis of Cases- 3 & 4 for all cases, it was observed that allocation of areas to crops was less than that of corresponding cases of 1 & 2. This was due to disparity between monthly water requirement and availability of water in some months for Cases- 3 & 4. Thus in the absence of any provisions to reserve excess canal water (during the months of April, May, June, July, August, September, and December) water was wasted. This may lead to excessive use of groundwater during some months when not desired and insufficient availability of water when desired.

In Cases- 1 & 2 model optimally utilizes the total quantity of water available for irrigation and allocates more optimal cropping areas to crops. This has resulted in full utilization of water resources and hence increased cropping areas naturally followed by better food and nutritional security and hence increased labour employment and net benefits. Thus proposals concerned with Cases- 3 & 4 (total 4 cases) were eliminated in the next stage (shown in **FONT**in Table 5). In the subsequent analysis, remaining 4 cases (shown in *FONT* in *T*able 5) as listed below in Table 6.

Table6-Model Output for Existing scenario and four policies

Particulars	AREA (ha)	WATER (ha.m)	NB (million ☐)	HL (man-days)	ECO$_2$e (kg/yr)
EXIST CROP PATTERN	*50795.0*	*26302.59*	*998.503*	*6615562*	*181602136*
(1) *SCENARIO1_CASE1A*	*55293.9*	*25653.88*	*1050.17*	*6810507*	*127818184*
(2) *SCENARIO1_CASE1D*	*71854.0*	*25653.88*	*1139.69*	*9865886*	*131118534*
(3) *SCENARIO1_CASE2A*	*52783.9*	*25653.88*	*998.62*	*6455106*	*125610004*
(4) *SCENARIO1_CASE2D*	*57774.9*	*25653.88*	*1055.34*	*7563419*	*125610004*

Outof all the four proposed policies policy 2 is using less water resources and cropping more area and providing more benefits and employment. To implement it at ground level further analysis was carried out and Decision Support Tables were evolved.

STAGE 3:-

In order to facilitate the implementation a chosen policy, DSTs have been created. These Decision Support Tables help water resources planner and government authorities in proper implementation of the policy at ground level. These DSTs are grouped into three categories: DST- I: Optimal Cropping Pattern Policies, DST- II: Optimal Operational Policies and DST- III: Optimal Crop Water Use Policies.

DST- I: Optimal Cropping Pattern Policies:-

This DST provides optimal cropping pattern policies at micro level. That is village level optimal cropping pattern policies (for each village) comprising of information about area of each crop that is to be cultivated in each village. Thus this DST- I is a 119 × 12 matrix that comprises of 119 villages and corresponding cropping areas of all crops (12 crops under consideration).

DST- II: Optimal Operational Policies:-

This DST provides village level optimal operational policies comprising of information about monthly irrigation water required by each village, to implement optimal cropping pattern policies. Similar to DST- I this is also a 119 × 12 matrix that corresponds to 119 villages and water required in each month by each village (i.e. 12 months January to December).

DST- III: Optimal Crop Water Use policies:-

This Decision Support Table provides village level optimal monthly crop water use policies for each crop (for all 12 crops) in each month. Therefore, it consists of 12 sub DSTs (say 12 matrices) each of 119 × 12 size. Thus DST 1 provides water use policy for January of all 119 villages and corresponding optimal crop water use requirements of all 12 crops in that month. Similarly DST2, DST3, DST4, DST5, DST6, DST7, DST8, DST9, DST10, DST11 and DST12 provides water use policies for every month (February to December) of all 119 villages and corresponding optimal crop water use requirements of all 12 crops in the respective months.

Conclusions:-

Evolved policy proposes to irrigate 41.45% more area than that of existing cropping pattern and cropping area requirements of individual crops to meet out food and nutritional security requirements of the study area. Existing condition estimated to generate agriculture human labour employment of 5784 female and 17352 male per day whereas evolved policy is likely to provide 8626 female and 25878 male labour (per day) employment for the study area. That is, generation of 11368 or about 49 percent (female: 2842 & male: 8526) more agriculture human labour employment per day than existing.Environmental aspects were studied by computing emissions as CO2e (equivalent emission in kg/year). It was observed that in comparison with existing condition, evolved policy emits 27.80% less emissions. Net benefits (in million ☐) from existing and evolved policies are assessed as 998.503 and 1139.686 respectively. That is, proposed policy is likely to contribute 14% more returns than that of existing condition. It is also concluded that existing cropping policy contributing ☐ 3478 and proposed policy contributing ☐ 3970 per capita per annum for the prospective population in 2011. That is 14.14 percent more contribution to per capita per annum income.To implement the evolved policy at village level Decision support tables were proposed which shall be useful to the water resources planners and government authorities.

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