Soil Loss Minimization through Land Use Optimization

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Abstract: The optimal allocation of the limited land resources in a watershed scale is one of the most important factors of reducing the volume of soil erosion. Applying optimization techniques can empower the decision-maker or watershed manager to maintain a reasonable balance between environmental flows and demands. The main objective of this research is to study the optimized combination of land allocation to different land uses like forestland, rangeland, orchard, irrigated farming and dry farming for minimized soil erosion in Abolabbas watershed located in Khuzestan province, Iran. For this purpose an optimization problem based on linear programming solution has been formulated in three different land use scenarios including existing land uses, existing land uses and some land management and finally optimum land uses with proper land management. Using simplex method within the LINGO software, the optimal solution was determined. The results demonstrated that the amount of soil erosion could, respectively reduce to the tune of 1.70, 69.77 and 75.85%, in three scenarios, in case of implementing optimal allocation of land resources in different land uses. The results of sensivity analysis also showed that the area of orchard and irrigated lands are the most sensitive parameters in the constraints of soil erosion minimization problem.

Key words: Abolabbas · Land resources · Land use · Linear programming

INTRODUCTION

Soil erosion and mass movements within a watershed area produce sediment which becomes available for transportation. Generation of erosion and sediment-yield maps for areas under soil conservation and vegetation improvement is controlled mainly by considering the extensive effects of soil-wasting processes [1]. Nowadays soil erosion has become a serious environmental threat that resulted from increasing world's population and is one of the major consequences of land use alteration [2]. Land use optimization with utilization of linear programming and geographical information system is a proper management practice to minimize soil erosion in a watershed [3]. A multi-objective linear programming was used to minimize soil erosion resulted from inappropriate land use management and maximize annual agricultural benefits in Siahrood area In Damavand watershed, Iran [4]. The expected annual soil erosion reduced by 5% and the annual net farm income increased by 134%.

Linear and nonlinear programming models were developed in south-east Anatolian watershed in Turkey for determination of optimum cropping pattern, water amount and farm income under adequate and limited water supplies [5]. An optimization problem has been formulated for Brimvand watershed, Iran [6]. The results of the study revealed that the amount of soil erosion and benefit could reduce and increase to the tune of 7.9 and 18.6%, respectively. The amount of soil loss and net benefit in four land uses with contribution of a multi-objective linear programming model was applied in Kharestan watershed, Iran [7]. The results showed that by existing land management, land use optimization decreases soil erosion by 3.7% and increases net income by 163%. The sensivity analysis showed that the area of orchards and rangelands are the most sensitive parameters and have the highest effect on the amounts of net income and soil erosion.

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Considering scarcely documented researches in land use management and protecting watershed resources applying optimization approaches, the present study has been conducted to optimize land resources allocation to orchard, forest, range, irrigated and dry farming land uses by applying a linear programming approach within the Abolabbas watershed in Khuzestan province, Iran.

MATERIALS AND METHODS

Area Description: The study area is located in Abolabbas watershed, east of Baghmalek City in Khuzestan province, Iran. It comprises 286 km^2 and extends between 31°28'23" to 31°40'14" N latitude and 49°59'26" to 50°05'12" E longitude (Figure 1). This area is characterized by cold winters and wet climate condition with an average yearly precipitation of 1019 mm and a minimum and a maximum average annual temperature of 0.8 and 16.3° C, respectively. Maximum, minimum and average elevations are 3305, 660 and 1885 m above sea level, respectively and average land slope is 36.41%. Abolabbas watershed consists of a variety of land uses and slope classes.
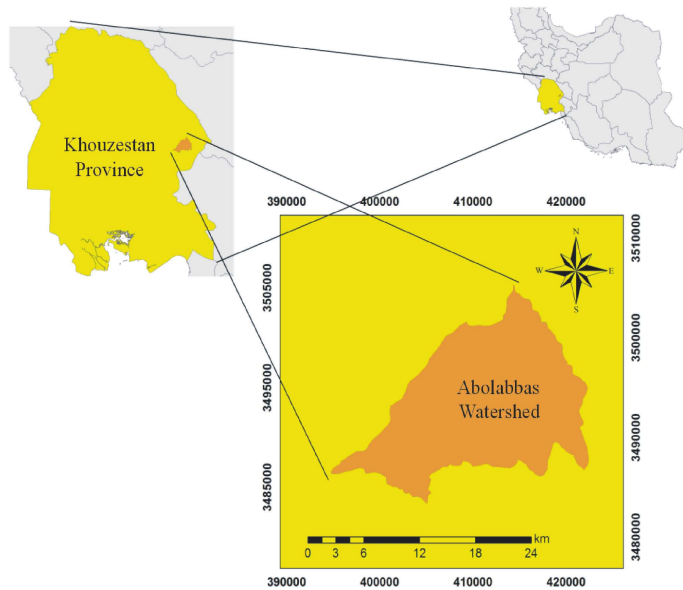

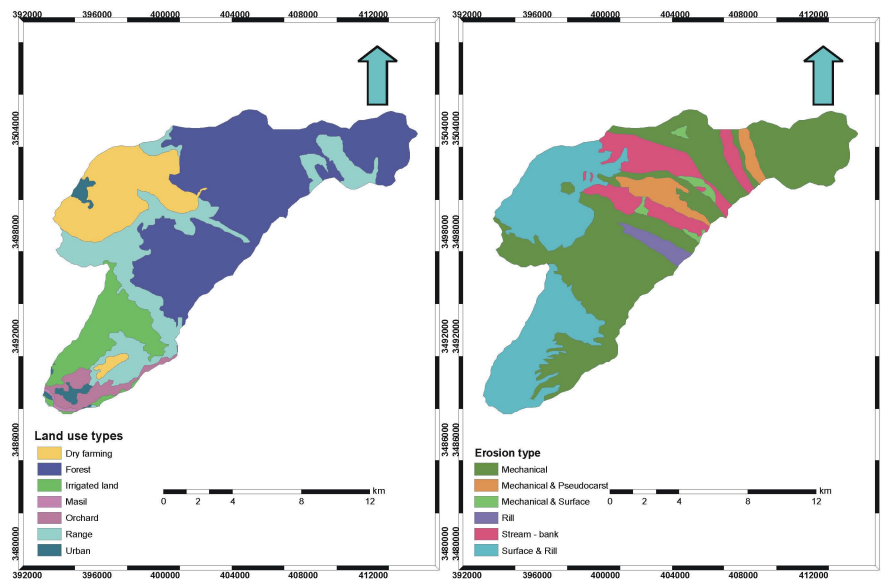Fig. 1: Location map of the experimental area

Fig. 2: Land use type (left) and erosion type (right) maps of the Abolabbas watershed
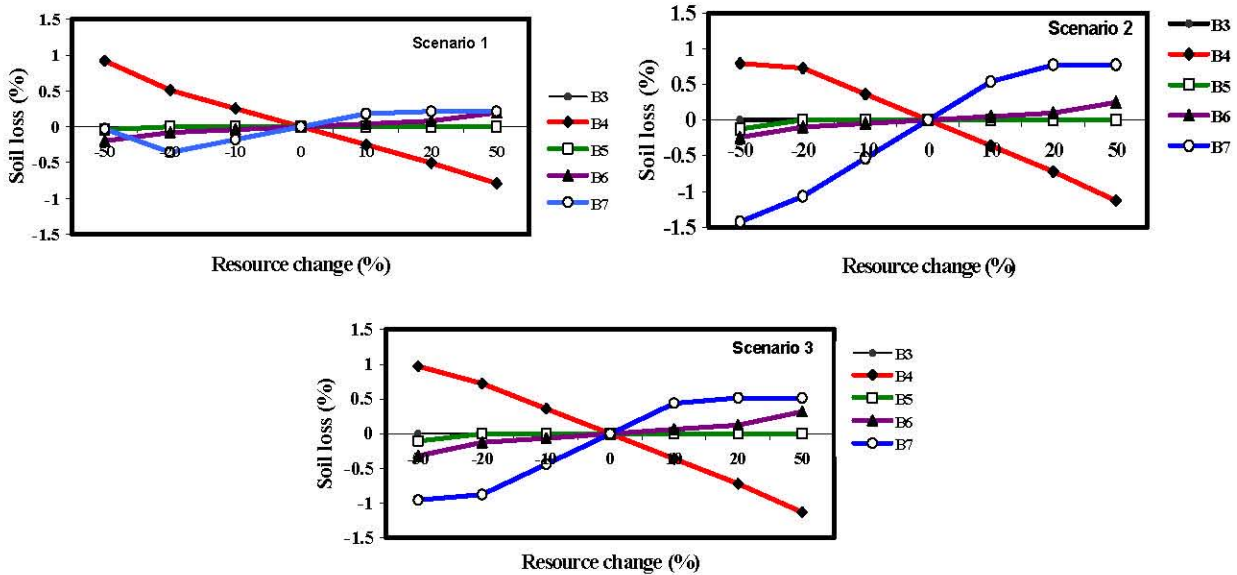
Fig. 3: Sensivity analyses of soil loss minimization functions in three scenarios

The major land uses are range, forest, orchard, irrigated and dry farming with the areas of 12974, 12969, 689, 1454 and 397 ha, respectively.

Data Acquisition: The information and data required computing the amount of soil erosion in each land use and defining constants and coefficients of objective function and constraints, such as soil surface geology, soil, climate, runoff, topography, ground cover, land use, upland erosion and channel erosion and sediment transport were extracted from the available studies of Khuzestan Province Watershed Management Office [8]. The amount of sediment yield and erosion severity was determined using the Modified Pacific South-west Inter-Agency Committee (MPSIAC) model [9] in the GIS environment and applying the sediment delivery ratio equation to get the amount of soil erosion. The 2007 IRS satellite imagery was used to map the existing land uses and controlled by field observation. The erosion type and land use maps have been shown in Figure (3).

Problem Formulation: Based on linearity of objective function and constraints, a linear programming model was applied for three different scenarios of land use and land management. These scenarios are:

Scenario 1: Existing land uses, to show the effect of land use optimization with no any further land management practices.

Scenario 2: Existing land uses with somewhat land management, to show the effect of very simple land management activities.

Scenario 3: Optimum land uses with proper land management, to indicate the effect of both land use optimization and land management on minimizing soil erosion [10,11].

The general form of soil erosion minimization problem can be expressed as:

$$Min(Z) = \sum_{i=1}^{n} C_i X_i \qquad (1)$$

Subject to:

$$\sum_{i=1}^{n} X_i = B \qquad (2)$$

$$X_i \geq 0 \qquad (3)$$

Where: Z is the total annual soil erosion (t), C_i is the amount of annual soil loss per unit area (t ha^{-1}), X_i is the area of each land use (ha), B is the total land area (ha) and n stands for numbers of land uses.

Application of Model: The problem can be written in detail in the following form:

$$Min (Z) = C_1 X_1 + C_2 X_2 + C_3 X_3 + C_4 X_4 + C_5 X_5 \quad (4)$$

The above objective function was then subjected to the following constraints:

$$X_1 = B_1 \tag{5}$$

$$X_2 = B_2 \tag{6}$$

$$X_3 = B_3 \tag{7}$$

$$X_1, X_2, X_3, X_4, X_5 = 0 \tag{8}$$

$$X_3 = B_4 \tag{9}$$

$$X_4 = B_5 \tag{10}$$

$$X_5 = B_6 \tag{11}$$

$$X_3 + X_4 = B_7 \tag{12}$$

$$X_1 + X_2 + X_3 + X_4 + X_5 = B_8 \tag{13}$$

Where: X_1 through X_5 are areas allocated to forest, range, orchard, irrigated and dry farming lands (ha), respectively. C_1 through C_5 are annual soil erosion per unit area of forest, range, orchard, irrigated and dry farming lands (t ha^{-1}). B_1 through B_8 are minimum area of forest, range and orchard and maximum limits of orchard, irrigated and dry lands, orchard plus irrigated lands and total land area, respectively. Because of not being able to make changes in the use of municipal and rock lands, these areas were excluded from land use optimization problem.

RESULTS AND DISCUSSION

The objective function of the soil loss minimization problems for each scenario was formulated as follows:

Scenario 1:

$$Min (Z) = 18.33X_1 + 16.22X_2 + 14.63X_3 + 22.73X_4 + 25.14X_5 \tag{14}$$

By changing the objective function to maximization form, this equation changes to the following simpler form.

$$Max (-Z) = -18.33 X_1 - 16.22 X_2 - 14.63 X_3 - 22.73 X_4 - 25.14 X_5 \tag{15}$$

Scenario 2:

$$Min (Z) = 4.82 X_1 + 5.77 X_2 + 4.56 X_3 + 8.12 X_4 + 8.18 X_5 \tag{16}$$

By changing the minimization function to maximization form, this equation changes to the following simpler form.

$$Max (-Z_2) = -4.82 X_1 - 5.77 X_2 - 4.56 X_3 - 8.12 X_4 - 8.18 X_5 \tag{17}$$

Scenario 3:

$$Min (Z) = 3.85 X_1 + 4.61 X_2 + 3.64 X_3 + 6.49 X_4 + 6.54 X_5 \tag{18}$$

By simplifying the objective function and changing it to maximization form, this equation changes to the following simpler form.

$$Max (-Z) = -3.85 X_1 - 4.61 X_2 - 3.64 X_3 - 6.49 X_4 - 6.54 X_5 \tag{19}$$

The above objective functions were then subjected to the following constraints:

$$X_1 = 12969.74 \tag{20}$$

The forestlands are national resources and government owns them, so the forest area should not be legitimately less than 12969.74 ha (equation 20).

$$X_2 = 12974.87 \tag{21}$$

The second constraints indicated that the rangelands are state ownership, so the rangeland area should not be legitimately less than 12974.87 ha (equation 21).

$$X_3 = 689.84 \tag{22}$$

According to present profit of orchards, the watershed inhabitants have no tendency to change the area of existing orchards of 689.84 ha (equation 22).

$$X_1, X_2, X_3, X_4, X_5 = 0 \tag{23}$$

The fourth constraint is the non-negative variable declaration (equation 23).

$$X_3 = 1535.60 \tag{24}$$

The surface area of existing orchard is 689.84 ha, but it could be increased to 1535.60 ha (Eq. 24). The reason is that the areas of irrigated farms with slope classes more than 5% could be changed to other land use especially orchards.

$$X_4 = 864.29 \tag{25}$$

The sixth constraint is the presently area of irrigated farms is 1454.12 and with respect to the standard conditions could not be more than 864.29 ha (equation 25).

$$X_5 = 286.30 \qquad (26)$$

Slopes greater than 12% are not proper for dry farming cultivation. The sixth constraints indicated that the area under dry farming after applying scientific principles of land suitability could not be more than 286.30 ha (equation 26).

$$X_3 + X_4 = 2399.89 \qquad (27)$$

Since there are sufficient and accessible water supply systems in the Abolabbas watershed, the area under orchard and irrigated croplands could not be more than 2399.89 ha due to existing slope and soil depth (equation 27).

$$X_1 + X_2 + X_3 + X_4 + X_5 = 28486.45 \qquad (28)$$

The last constraint is simple and it is the sum of the areas under the five land uses should be equal to 28486 ha of the available lands (equation 28). Table 1 shows the area and average annual soil loss for each land use. The corresponding simplex method table [12] was extracted based on the formulated problem for the study watershed as shown in tables 2 to 4, respectively.

The soil erosion minimization in the Abolabbas watershed was solved with the help of LINGO computer program. After allocated areas into account, annual soil erosion for each scenario is indicated in tables 5 to 7.

From the tables 4 to 6, it could be found that in the optimized condition, there is no change in rangelands area, while the areas of forestland and orchards should be increased from 12969.84 to 13209.39 and from 689.84 to 1535.60 ha, respectively. Also irrigated farms and dry farms should be reduced from 1454.12 to 480.29 and from 397.88 to 286.30 ha, respectively. In the first scenario, the annual soil loss would have decreased by 8545.94 t (1.70%). In the second scenario, the annual soil loss would have decreased by 349813.61 t (69.77%). In the last scenario, the annual soil loss would have decreased by 380294.11 t (75.85%). The results of the study proved that the linear programming was successfully solved using the LINGO software program [7]. The applicability of linear programming in solving optimization problem was proved in minimizing soil erosion [4,6,7].

The sensivity analysis was also carried out for the soil loss minimization objective function in scenarios 1 to 3. The results have been indicated in Figure 3.

Table 1: Area and soil loss in each land use of Abolabbas watershed

Land use	Area (ha)	Soil loss (t ha^{-1} yr^{-1})	Soil loss (t yr^{-1})
Forestland	12969.74	18.33	237735.33
Rangeland	12974.87	16.22	210452.39
Orchard	689.84	14.63	10092.36
Irrigated farming	1454.12	22.73	33052.15
Dry farming	397.88	25.14	10002.70
Total	28486.45	17.60	501361.52

Table 2: Simplex table of land use optimization of Abolabbas watershed in scenario 1

Functions	X$_1$	X$_2$	X$_3$	X$_4$	X$_5$	Modality	Right hand side
Objective							
1	-18.33	-16.22	-14.63	-22.73	-25.14	Max	0.00
Constraints							
1	1.00	0.00	0.00	0.00	0.00	=	12969.74
2	0.00	1.00	0.00	0.00	0.00	=	12974.87
3	0.00	0.00	1.00	0.00	0.00	=	689.84
4	0.00	0.00	1.00	0.00	0.00	=	1535.60
5	0.00	0.00	0.00	1.00	0.00	=	864.29
6	0.00	0.00	0.00	0.00	1.00	=	286.30
7	0.00	0.00	1.00	1.00	0.00	=	2399.89
8	1.00	1.00	1.00	1.00	1.00	=	28486.45

Table 3: Simplex table of land use optimization of Abolabbas watershed in scenario 2

Functions	X_1	X_2	X_3	X_4	X_5	Modality	Right hand side
Objective							
1	-4.82	-5.77	-4.56	-8.12	-8.18	Max	0.00
Constraints							
1	1.00	0.00	0.00	0.00	0.00	=	12969.74
2	0.00	1.00	0.00	0.00	0.00	=	12974.87
3	0.00	0.00	1.00	0.00	0.00	=	689.84
4	0.00	0.00	1.00	0.00	0.00	=	1535.60
5	0.00	0.00	0.00	1.00	0.00	=	864.29
6	0.00	0.00	0.00	0.00	1.00	=	286.30
7	0.00	0.00	1.00	1.00	0.00	=	2399.89
8	1.00	1.00	1.00	1.00	1.00	=	28486.45

Table 4: Simplex table of land use optimization of Abolabbas watershed in scenario 3

Functions	X_1	X_2	X_3	X_4	X_5	Modality	Right hand side
Objective							
1	3.85	4.61	3.64	6.49	6.54	Max	0.00
Constraints							
1	1.00	0.00	0.00	0.00	0.00	=	12969.74
2	0.00	1.00	0.00	0.00	0.00	=	12974.87
3	0.00	0.00	1.00	0.00	0.00	=	689.84
4	0.00	0.00	1.00	0.00	0.00	=	1535.60
5	0.00	0.00	0.00	1.00	0.00	=	864.29
6	0.00	0.00	0.00	0.00	1.00	=	286.30
7	0.00	0.00	1.00	1.00	0.00	=	2399.89
8	1.00	1.00	1.00	1.00	1.00	=	28486.45

Table 5: Result of land use optimization in Abolabbas watershed, Iran in scenario 1

Land use	Allocated area (ha)	Erosion rate (t ha^{-1} yr^{-1})	Total erosion (t yr^{-1})
Forestland	13209.39	18.33	242128.11
Rangeland	12974.87	16.22	210452.39
Orchard	1535.60	14.63	22465.82
Irrigated farming	480.29	22.73	10916.99
Dry farming	286.30	25.14	7046.74
Total	28486.45	17.30	492815.58

Table 6: Result of land use optimization in Abolabbas watershed, Iran in scenario 2

Land use	Allocated area (ha)	Erosion rate (t ha^{-1} yr^{-1})	Total erosion (t yr^{-1})
Forestland	13209.39	4.82	63669.25
Rangeland	12974.87	5.77	74864.99
Orchard	1535.60	4.56	7002.33
Irrigated farming	480.29	8.12	3899.95
Dry farming	286.30	8.18	2341.93
Total	28486.45	5.32	151547.91

Table 7: Result of land use optimization in Abolabbas watershed, Iran in scenario 3

Land use	Allocated area (ha)	Erosion rate (t ha^{-1} yr^{-1})	Total erosion (t yr^{-1})
Forestland	13209.39	3.85	50856.15
Rangeland	12974.87	4.61	59814.15
Orchard	1535.60	3.64	5589.58
Irrigated farming	480.29	6.49	3117.08
Dry farming	286.30	6.54	1872.40
Total	28486.45	4.25	121067.41

The results of the sensivity analyses indicated that the changes in objective function in three scenarios are linear and they are mostly affected by reduction rather than increasing in resources. It can also be verified that the change of some allocations would create much more impact on the optimal solutions performed by the linear programming [13]. It is seen in Figure (3) that the reduction of orchard plus irrigated lands area increased soil loss severely. On the other hand, the change in soil erosion is mainly affected by variation in orchard and irrigated land uses.

CONCLUSION

These results present the optimized combination of land allocation to different land uses for minimized soil erosion. It could be summarized that the type of land use and its management have a significant effect on the amount of soil erosion. Moreover the results approved that the incorrect human intervention in changing forest and rangelands into other land uses specially irrigated and dry farming lands accelerated soil erosion.

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