J. Agr. Sci. Tech. (2011) Vol. 13: 717-726

Optimizing Management of Soil Erosion in Orazan Sub-basin, Iran

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ABSTRACT

Land use optimization is one of the appropriate methods for soil conservation programs that allow watershed managers and decision makers to choose the best land use practices. With the objective of optimizing land use to minimize soil erosion, the present research was conducted in one of the Taleghan sub-basins in Iran, namely, Orazan sub-basin, with an area of 2,706 ha. To achieve the objective, the area, the erosion rate, and the net income value of each land use was assessed according to the pertinent standards. Then, limitations and objective functions were determined and the optimization problem was solved by using Steuer method (1995) and ADBASE software. The results revealed that optimizing land use while taking into consideration the legal restrictions (Article 56 of The Forest and Rangeland Nationalization Law) leads to a decrease of 10.29 percent in erosion rate (from 18253.39 t y^{-1} to 16373.51 t y^{-1}) and 17.71 percent lower net income(from 2,382.12 to 1,960.28 million Rials). In contrast, optimization without consideration to legal restrictions would result in 22.24 percent increase in the net income and 6.93 percent decrease in erosion rate.

Keywords: ADBASE software, Erosion, Land use, Optimization, Orazan sub-basin, Steuer method.

INTRODUCTION

Today, the entity of the management sciences appears in modeling methods. Linear programming is one of the most important applied tools for optimal utilization of the rare resources in the management sciences. The agricultural and natural resources decision makers usually face multi-objective planning, unlike those in industries.

Erosion is one of the most important indicators that actually shows the results of the actions and reactions of the effective factors in a watershed; therefore, erosion minimization can be a very important objective in watershed management planning. Because of this, land use optimization is a useful tool in soil conservation that allows watershed managers and decision makers to choose the best land use practices.

In Orangabad region, India, a group of land use designers used Geographic Information System (GIS) and satellite images for soil characteristics analysis in land use optimization . Their study indicates that the shallow soils of the district are suitable for growing most of the annual crops while the perennials are to be planted in the deeper soils (Maji *et al.*, 2003).

To minimize soil erosion in the Barimond watershed located in Kermanshah Province, Iran, Jalili (2004) employed land use optimization by using linear programming.

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[DOR: 20.1001.1.16807073.2011.13.5.9.0]

He showed that linear programming was an appropriate tool and land use optimization decreased soil erosion by 7.78%, increased the annual income by 118.62%, and accentuated decrease in dryland farming and expansion of orchards.

Nikkami (1999) applied optimization model for assessment of the environmental and economical effects of erosion reduction in one of the Damavand Watershed sub-catchments in Iran. The model results showed 5% decrease in sediment yield and 134% increase in the annual income of the region.

Mohseni Saravi *et al.* (2003) accomplished optimal utilization pattern of watershed resources using goal programming for the Garmabdasht sub-catchment of Gharaso Watershed in Golestan Province, Iran. The results showed that an economically-based proposal was better than the other suggestions because it was multi-objective.

Suresh developed a kind of land use optimization model in the Ramganga watershed. He used linear programming with erosion minimization as the main objective based on new practices at G.B. Pant University, India (Das and Fellow, 2003).

Riedel (2003) investigated land use optimization using linear programming and GIS in a mountainous watershed, north of Thailand. The results showed that linear programming and GIS integration was successful.

Kralisch and Beckstein (2003) investigated land use multi-objective optimization by using artificial neural networks (ANN) in Germany. They introduced a method based on ANN with the ability to provide an optimal management decision for the complex and increasing problems of watersheds. Liu and Stewart (2004) assessed decision support system for multi-objective decision-making in natural resources management in South Africa.

The above literature review showed that various studies have been carried out on optimization in agriculture and specially cultivation patterns (Singh and Singh, 1999).

The main objective of the present study is to optimize land use activities of the Orazan watershed in such a way that soil erosion is minimized while maximizing the land use economic income. Integrating a soil erosion model with GIS would serve to handle the complexity of modeling huge volumes of input parameters and overlaying data themes containing spatially distributed factors. Combination of the results would provide a guideline for decision makers or watershed managers to optimize the use of water and soil resources for long term sustainability.

MATERIALS AND METHODS

Study Area

Orazan, one of the sub-basins of Taleghan Watershed in north-central part of Iran, between 36˚06´25˝to 36˚10´45˝N latitude and 50˚52´ 05˝ to 50˚54´ 25˝ E longitude, was selected as the study area. This part of the Taleghan Watershed is mainly mountainous with a maximum, minimum, and mean elevation equal to, respectively, 3,280, 1,870, and 2,506 meters. It covers 2,706 ha with annual average precipitation of 690 mm and temperature of 3.06˚C.area The climate of the studyis cold semi-humid, according to the modified De Martonne method, while it is classified as higher elevations based on the Emberger classification (Irrigation and Reclamation Department, 1993) (Figure 1).

Soil Erosion Estimation in Each Land Use

Soil erosion estimation in various land uses was calculated by MPSIAC (Pacific Southwest Inter Agency Committee) and EPM (Erosion Potential Method) models and researches carried out in the Orazan sub-basin (Taheri, 2005; Maleki, 2001, and Irrigation and Reclamation Department, 1993). The steps were as follows:

Figure 1. Study area (Orazan sub-basin) on Iran map.

Estimation of sediment yield in the rangeland using MPSIAC model.

Estimation of sediment delivery ratio (SDR) in the rangeland.

Estimation of soil erosion in the rangeland.

Estimation of soil erosion in various land uses using EPM model.

Estimation of specific soil erosion in different land uses (t ha^{-1} y^{-1}) (Tables 1, 2).

Assessment of the effects of different land uses on the soil erosion rate.

Maps Preparation

Land use map was provided by a range management study in the Orazan sub-basin and field works using Arc/Info and Arc/View. The elevation, slope, and aspect maps were extracted from topographic map at the scale of 1:50000. The slope map was prepared in four classes(less than 5%, 5-10%, 10-20% and more than 20%) based on the required standards for different land uses. Soil depth

Table 1. Linear multi-objective simplex tableau of Orazan sub-basin problem.

Equation (1)	X_1 (2)	X_2 (3)	X_3 (4)	Type (5)	RHS (6)
Objective 1	4.28	0.40	2.12	Max	0.00
Objective 2	-8.35	-5.84	-6.69	Max	0.00
Constraint 1	1	0	0	$\geq$	920.61
Constraint 2	0	0	1	$\geq$	161.1
Constraint 3	1	1	1	$\geq$	2706.46
Constraint 4	1	0	0	$\leq$	226.21
Constraint 5	0	1	0	$\leq$	2234.99

Columns 2 through 4 in this table present decision variables, which in rows 2 and 3 have currency and sediment yield units, respectively. Number 1 and 0 in the remaining rows show the presence or absence of the decision variable in constraints, respectively. Row 2 and 3 of column 5 indicate the maximization or minimization form of the objective functions while the remaining rows indicate the equality or inequality form of the constraints. The last column gives the Right Hand Side (RHS) value of each constraint, which represents land availability in ha.

Table 2. Total erosion and total net income under current land use and optimization output(juridical and no juridical limitation) for Orazan sub-basin.

	Land Use	Orchard	Rangeland	Dryland	Total
	Specific Erosion ($t\ ha^{-1}\ y^{-1}$)	8.35	5.84	6.69	--
	Net Income (10^6 Rial $ha^{-1}y^{-1}$)	4.28	0.40	2.12	--
Current Land Use	Allocated Area (ha)	226.21	2234.99	245.26	2706.46
	Total Erosion ($t\ y^{-1}$)	1888.85	13052.34	1640.79	18253.39
	Net Income (10^6Rial y^{-1})	968.18	893.99	519.95	2382.12
Optimization Output (juridical limitation [a])	Allocated Area (ha)	226.21	2480.25	0	2706.46
	Total Erosion ($t\ y^{-1}$)	1888.85	14484.66	0	16373.51
	Net Income (10^6Rial y^{-1})	968.18	992.1	0	1960.28
Optimization Output (no juridical limitation)	Allocated Area (ha)	471.47	2234.99	0	2706.46
	Total Erosion ($t\ y^{-1}$)	3936.77	13052.34	0	16989.11
	Net Income (10^6Rial y^{-1})	2017.89	893.99	0	2911.88

[a] The Iran Forest and Rangeland Nationalization, Act of 56 (fixing and controlling of governmental national land)

map was prepared using land component map, soil map, and representative profiles in each land unit. Slope, soil depth, and land use maps were then overlapped to extract the distribution of the land uses in different slopes and soil depths.

Computing Water Requirements in the Study Region

Human and domestic animals water requirements were estimated using socio-economic studies in the region as well as field surveys. Also, dryland crops and orchard water requirements were calculated based on the types and areas of different crops and trees, potential evapotranspiration in the region (Ghavami, 1990), and crop coefficients (Farshi *et al.*, 1997).

Estimation of Benefit/Cost of Different Land Uses

Net income of dryland farming and orchards was evaluated through the use of questionnaire. First, data of yield, price, and the area of each crop or fruit tree was collected and used to determine the gross income rate of dryland farming and orchards. Then, the total cost was assessed based on the costs of crop cultivation, management care, harvest, and transport to the market. Finally, the net income was estimated from the difference between gross income and the total cost.

The net income of the rangeland was computed using the previous range management study in the region. The rangeland conditions were studied using four factors method in the Orazan sub-basin. These conditions were classified by comparing the rangelands at the time of the study with its potential situation regarding vegetation canopy cover, vegetation combination, soil conservation, and residue condition. Three different rangeland conditions were distinguished. Economical analyses were done taking into account the rangeland production in each condition and the areas under each rangeland type. Unlike the cultivated areas, due to governmental ownership, no cost was considered for these rangelands.

Estimation of Erosion Cost in Different Land Uses

There is no research on the evaluation of economical losses due to sediment yield in the study area. Therefore, it is difficult to evaluate it directly. However, these losses can be estimated by evaluation of the fertile soil loss. To estimate economic losses due to sediment yield one has to apply the lost soil to the eroded area based on the depth of the root zone in each land use (Nikkami, 1999).

The depth of the lost soil in each land use was calculated by considering the amount of sediment yield in that land use, the appropriate rooting depth of the vegetation(root zone), and the soil bulk density as follows:

$$\text{Lost Areas}\,(m^2\ ha^{-1}) = \frac{E}{R \times S} \qquad (1)$$

Where: E is Erosion Rate in (ton ha^{-1})
R is Root zone in (m) and
S is Soil bulk density in (ton m^{-3})

Estimated lost areas were multiplied by the economic net income of each land use to estimate the economic cost due to sediment yield in each land use.

Estimation of Area in Each Land Use

Due to the absence of any change in the use of municipal lands, these areas were excluded from land use optimization. Therefore, municipal lands are subtracted from the total area and the remaining area is considered as the total area for optimization. According to the results of the overlay operation of land use and slope maps within GIS, the distribution of land use activities in different slope classes is extracted. For proper management of agricultural lands (Berngel, 2000; Rastegar, 1992), it is not recommendable to have dryland farming on slopes greater than 20% and irrigated farms on slopes greater than 10%. Actual recommended slopes are less than these numbers in order to avoid soil erosion and reduction of crop yield. Therefore, irrigated farms on more than 10% slopes and dryland farming on more than 20% slopes were deducted in the optimizing formulations.

The suitable depths of soil were classified based on proper management of agricultural lands. Thus, soil depths map was delineated in four categories including, very deep (deeper than 100 cm), deep (60-100 cm), medium depth (30-60 cm) and shallow depth (less than 30 cm). The soils of Orazan sub-basin fell into two groups (very deep and medium depth). In this step, there are standard references for selecting suitable land use for the combined soil depth and slope conditions. The existence or absence of water is the problem that should be addressed for land use characteristics, considering other conditions and limitations characteristics of the regions. Finally, water availability was used for decision making.

Formulation of the LP Optimization Model

Based on linearity of the objective function in this study area problem, multi-objective linear programming is chosen. Also, the simplex method is not the conversion of a multi-objective optimization into a single-objective one (Cohon, 1978; Kalavathy, 2001). Therefore, the simplex method was chosen to solve the multi-objective linear programming problem in the Orazan sub-basin.

Post-optimality analysis involves conducting sensitivity analysis to determine which parameters of the model are the most critical ones in determining the solution. Sensitivity analysis often begins with the investigation of the effect of changes in the amount of the resources. The reason is that there is generally more flexibility in setting and adjusting these values than there is for the other parameters of the model. The economic interpretation of the dual variables as shadow price (Nikkami, 2002) is extremely useful for deciding which changes should be considered.

RESULTS

Water Requirements in the Region

The estimated annual water requirements of the human population, livestock and farmlands in the Orazan sub-basin were 18,584, 56,327, and 847,286 m^3, respectively, resulting in a total water requirement of 921197 m^3 y^{-1}. Due to the existence of water resources in the study area with the total annual discharge of 2,138,268 m^3, there is no water deficit in the study area.

Estimation of Benefit/Cost of Land Uses in the Region

In 2006, the exchange rate for $1US was 8,300 Rials (Iranian currency). Based on the procedure, gross income in each hectare of orchards and dryland farming was estimated at 8.46 and 2.70 million Rials, respectively, and the corresponding cost was 4.18 and 0.58 million Rials. Therefore, the net income in each hectare of orchards and dryland farming was 4.28 and 2.12 million Rials, respectively. The weighted average dry-forage production in the Orazan sub-basin was calculated at 324.24 kg ha^{-1} for rangelands. Assuming that 40% of the produced forage is equivalent to the total digestible nutrients (TDN), the total produced TDN was 129.7 kg ha^{-1}. Thus, considering that 230 kg y^{-1} TDN is required for each animal unit (sheep), annually, 0.56 animal units could be supported per hectare of the rangeland. Also, the average weight of each animal unit in the area is 35 kg (Mesdaghi, 1995; Moghadam, 1998). Therefore, the total weight of the living animal units is 19.73 kg/ha. Considering the price of living sheep in 2006, which was 20500 Rial kg^{-1}, the total amount of economic production of the rangelands was 0.40 million Rial ha^{-1}. On the other hand, due to the governmental ownership of the rangelands in the study area, no cost was considered for meat production. Also, the other animal products such as milk, wool, and manure (fertilizer) were not taken into account as income.

Solution of the Problem

According to the computations in the previous sections, the general form of the optimization problem can be written as follows:

$$Max(Z_1) = 4.28X_1 + 0.40X_2 + 2.12X_3 \quad (2)$$

$$Max(-Z_2) = -8.35X_1 - 5.84X_2 - 6.69X_3 \quad (3)$$

There are six constraints of the land use optimization model. These constraints and their justifications are discussed below.

Constraint 1: $X_1 \leq 920.61$ (4)

The first constraint indicates that the present area under orchard, which is 226.21 ha, could increase up to 920.61 ha. The reason for these constraints is the areas with slope class over 5% and sufficient soil depth. These lands could be changed, if necessary, to other land uses, especially orchards, by terracing and planting permanent vegetations.

Constraint 2: $X_3 \leq 161.1$ (5)

Slopes more than 20% with low soil depth are not suitable for dryland farming.

Constraint 3: $X_1 + X_2 + X_3 = 2706.46$ (6)

The third constraint is the area limitations of the Orazan sub-basin after subtracting the municipal lands. The sum of the areas under the four land uses can be neither increased nor decreased from the 2,706.46 ha of the available lands in the area.

Constraint 4: $X_1 \geq 226.21$ (7)

Based on the reasons given for Constraint 1, the fourth constraint shows the present area under orchards. In these lands, due to suitable income, there is no land use change.

Constraint 5: $X_2 \geq 2234.99$ (8)

The fifth constraint indicated that area under the rangelands should be at least 2,234.99 ha. The reason for this constraint is that the government owns the rangelands and can not change its existing land use. Many rangelands have been illegally converted into improper dryland farming, which could be restored.

Constraint 6: $X_1 \times X_2 \times X_3 \geq 0$ (9)

The last constraint is the non-negative declaration, i.e., the areas allocated to each land use must be positive.

The LP model formulation of the existing problem in Orazan sub-basin can be written as:

Objective function 1: $Max(Z_1) = 4.28X_1 + 0.40X_2 + 2.12X_3$ (10)

Objective function 2: $Max(-Z_2) = -8.35X_1 - 5.84X_2 - 6.69X_3$ (11)

Subject to the following constraints:

$X_1 \leq 920.61$ (12)

$X_3 \leq 161.1$ (13)

$X_1 + X_2 + X_3 = 2706.46$ (14)

$X_1 \geq 226.21$ (15)

$X_2 \geq 2234.99$ (16)

$X_1 \times X_2 \times X_3 \geq 0$ (17)

Where: Z_1= Annual net income of the whole watershed (in 10^6 Rial y^{-1}), Z_2= Annual sediment yield of the whole watershed (t y^{-1}), X_1= Area allocated to orchard (ha), X_2= Area allocated to rangeland (ha), and X_3= Area allocated to dryland farming (ha).

Simplified objective functions and their constraints discussed above are entered in Table 1 as a revised linear multi-objective simplex tableau.

After solution of the revised simplex tableau in Table 1 by computer program of Steuer (1995), the proposed areas for orchards (X1), rangelands (X2), and dryland farming (X3) are shown in Table 2. Also, Table 2 shows the areas for current land use in Orazan sub-basin. Furthermore, land use was optimized for the case lacking juridical limitations in the study area. Table 2 shows the results of this optimization output.

Sensitivity analysis showed that decrease or increase in the economic benefits was most sensitive to the decrease or increase in the maximum orchard areas. Also, objective function sensitivity analysis and erosion minimization showed that negative or positive changes in the minimum rangelands area caused the greatest increase and decrease in the erosion rate. Overall, changes in the maximum orchard areas had the largest effect on income, while changes in the minimum rangeland areas had the greatest effect on erosion in the Orazan sub-basin.

DISCUSSION

Erosion in Each Land Use

Data in Table 2 show that erosion rate was considerably reduced after performing optimization in comparison with the previous condition. After taking the allocated areas into account, average annual erosion rate for the entire study decreased to 16373.51 t y^{-1}. Compared with the values before optimization (18253.39 t y^{-1}), the annual erosion rate would decrease to 16373.51 t y^{-1}(or by 10.29%). Also, Table 2 shows that, after optimization, the net income rate would increase by 22.24% and erosion rate would decrease by 6.93% that is very important for sustainable management of the watershed. Nikkami(1999) and Jalili (2004) also found similar result in one of the Damavand sub-basins and Barimond watershed in Kermanshah Province i.e. land use optimization decreased annual erosion rate by 5% and 7.8%, respectively. The results also show that the least erosion has occurred in rangelands while the largest erosion was in orchards, with the erosion in dryland farming in the middle of these two land uses. This is similar to the results of Agarazi and Godosi (2001) that showed the least erosion for the rangelands.

Sadeghi (2003) reported that erosion in farmlands was 2.4 times more than that of rangelands. Khaledian and Habibi (2001) argue that the maximum erosion occurs in dryland farming and the least erosion happens in meadows and grasslands. The results of this research agree with the previous research; but, they disagree with Ebrahimi *et al*. (2001) since they have assigned the minimum erosion rate to orchards, the maximum to dryland farming, and the average of these extremes to the rangelands.

Allocated Area to Each Land Use

Table 2 show that land use changes have occurred mostly in dryland farming and rangelands. Considering the costs and erosion rates in these land uses, it seems that one of the main reasons for soil erosion reduction is a decrease in dryland farming area. The results of the present study showed a decrease of 100 percent in dryland farming areas and an increase of 4.69 percent in rangeland areas in compare with the current land use. Also, Nikkami (1999) and Jalili (2004) arrived at recommendations similar to the present study i.e. drastic decrease in dryland farming areas, in one of the Damavand sub-basins and Barimond watershed as they suggested, respectively, 100% and 50% decreases in dryland farming areas. However, with respect to changes in orchards areas, the result of the present research is different from those of Nikkami (1999) and Jalili (2004), as they suggested, respectively 3.5% and 13.5% increase in orchards areas, because they found the maximum erosion rate in this type of land use. The findings of the present study do not confirm Nikkami (1999) and Jalili(2004).

Income in Each Land Use

The results of this research show that land use optimization not only would lead to reduction in erosion but would also increase income in the watershed. Table 2 clearly imply the decrease of the total net income from 2382.12 MRial y^{-1} to 1960.28 MRialy^{-1} after optimization, equivalent to 17.71%. This result is different from those of Nikkami (1999) and Jalili (2004) that showed, respectively, 134% and 118.62% increase in the net income in one of the Damavand sub-basins and Barimond watershed. The reason for this problem is that it would be impossible to increase orchard areas that have the maximum erosion in the study area. If there were no juridical limitations for land use change in the rangelands, land use optimization would have caused not only 6.93% reduction in erosion but also 22.24% increase in the net income i.e increase the net income from 2,382.12 MRials to 2,911.88 MRials.

ACKNOWLEDGEMENTS

The authors are profoundly grateful to Mrs. Taheri for providing the data, Mr Jalili for assisting in data analysis, and Mr Asaln Panjeh for English editing of the paper. This research, with registration number of 7201012/1/2, was supported by the Natural Resources Faculty, Tehran University.

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بهینه‌سازی کاربری اراضی به منظور کمینه‌سازی فرسایش خاک در زیرحوزه آبخیز اورازان، ایران

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چکیده

برنامه‌ریزی خطی ابزاری کارآمد در بهینه‌سازی بوده و بهینه‌سازی کاربری اراضی یکی از راه‌کارهای مناسب برای حفاظت خاک می‌باشد. تحقیق حاضر با هدف بهینه‌سازی کاربری اراضی به منظور کمینه نمودن فرسایش در یکی از زیرحوزه‌های حوزه آبخیز طالقان به نام حوزه آبخیز اورازن با مساحت ۲۷۰۶ هکتارانجام شده است. بدین منظور با محاسبه مساحت، میزان فرسایش و درآمد خالص هر یک از کاربری‌های اراضی زیر حوزه آبخیز مورد مطالعه، با توجه به استانداردهای مورد نیاز هر یک از کاربری‌های اراضی سطح هر یک از کاربری‌ها استخراج، و با تعیین محدودیت‌ها و توابع هدف با استفاده از روش پیشنهاد شده توسطSteuer (۱۹۹۵)و مدل ADBASE مسئله بهینه‌سازی حل شد. نتایج تحقیق حاضرنشان می‌دهد که در صورت در نظر گرفتن محدودیت قانونی(ماده ۵۶ قانون ملی شدن مراتع) میزان فرسایش از ۱۸۲۵۳/۳۹ تن در سال به ۱۶۳۷۳/۵۱ تن در سال(۱۰/۳٪) کاهش و میزان سودآوری از ۲۳۸۲/۸۸به ۱۹۶۰/۲۸ میلیون ریال(۱۷/۷۱٪) پس از بهینه سازی کاربری اراضی کاهش خواهد یافت و در صورت عدم تبعیت از ماده۵۶ قانون ملی شدن مراتع، بعد از اجرای مدل میزان سود ۲۲/۲۴٪ افزایش، و میزان فرسایش نیز به مقدار ۶/۹۳٪ کاهش می‌یابد.