OPTIMIZING THE MANAGEMENT OF SOIL EROSION USING GIS

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ABSTRACT

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The dynamic nature of erosion and associated processes and their dependence on climatic, pedological, land cover, land use, and management factors result in spatial and temporal variability. Computing and mapping this variability will produce information which is essential for designing dams, reservoirs, channels, soil conservation management plans, and the evaluation of on-site and off-site damages by soil erosion, land use projects, and transport of pollutants.

This thesis presents the Modified Universal Soil Loss Equation (MUSLE) as a promising tool for the spatial modeling of soil erosion by water integrated with the SPatial ANalysis System (SPANS)-GIS. The information that resulted from this integration was used for land-use optimization to minimize sediment yield and maximize watershed farm income by a multi-objective linear programming model.

These models were applied to Syahrood, one of the sub-basins of Damavand watershed in Iran, where soil erosion by water is one of the major land-related problems. Runoff erosivity, soil erodibility, slope length, slope steepness, cover management, and erosion control practice factors were computed and included in the digitized and computed Thiessen polygon, land component, slope and land-use maps of the watershed. The sediment yield of each land use was computed by overlaying these maps with the appropriate models in the SPANS-GIS. The optimization process allocated dryland-farming areas to rangelands if no changes are made to the current supporting practice system. The expected annual sediment yield from the entire sub-basin was reduced by 2420 t/y (or by 5%) and the annual net farm income was increased by 3.99 billion Iranian Rial/y (or by 134%).

Results demonstrated that interfacing MUSLE with a GIS is an effective method for the prediction of soil erosion in large watersheds with limited data sets. Overlay operations enable the land manager to obtain higher quality results in a shorter period of time compared to manual calculations. A GIS simplifies the extracting of necessary factors from the databases. However the SPANS-GIS 6.0 was weak in preparing a slope map from the digital elevation database for such mountainous areas.

The results indicate that application of land-use optimization methods to reduce sediment yields has great potential in the study area and in other watersheds. The methodology developed in this study can provide a useful tool for watershed managers to reduce sediment yield (soil conservation) while increasing the income of the local inhabitants.

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To My Family

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LIST OF SYMBOLS

Symbol	Description	Unit
A	Average annual soil loss	$\frac{t}{ha.y}$
R	Average annual rainfall erosivity factor	$\frac{MJ.mm}{ha.h.y}$
K	Soil erodibility factor	$\frac{t.ha.h}{ha.MJ.mm}$
L	Slope length factor	dimensionless
S	Slope steepness factor	dimensionless
C	Cropping system factor	dimensionless
P	Supporting practices factor	dimensionless
S_y	Sediment yield	t
Q	Peak flow	m^3/s
V	Volume of water applied to the area	m^3
P_t	Daily rainfall	mm
S_r	Retention parameter	mm
CN	Runoff curve number	dimensionless
DA	Drainage area	ha
t_p	Time to peak of the unit hydrograph	h
c_t	Coefficient based on type of land	dimensionless
L_w	Length of the watershed	m

L_c	Distance from the outlet to the center of the watershed	m
c_j^k	Objective function coefficient	
x_j	Decision variable	
a_{ij}	Technological coefficient	
b_i	Right-hand side coefficient	
m	Number of constraints or slack variables	
n	Number of decision variables	
p	Number of objective functions	
f_j^k	Reduced cost	
A	Hydrologic soil group with minimum infiltration of 7.62-11.43 mm/h	
B	Hydrologic soil group with minimum infiltration of 3.81-7.62 mm/h	
C	Hydrologic soil group with minimum infiltration of 1.27-3.81 mm/h	
D	Hydrologic soil group with minimum infiltration of 0.5-1.27 mm/h	
Z_1	Annual net farm income of whole watershed	10^6 Rial/y
Z_2	Annual sediment yield of whole watershed	t/y
X_i	Surface area of each land use	ha
C_i	Annual sediment yield per unit area in each land use	t/ha.y
A_i^1	Amount of net farm income per unit area of each land use	10^6 Rial/ha
A_i^2	Production cost per unit area of each land use	10^6 Rial/ha
A_i^3	Cost due to soil loss per unit area of each land use	10^6 Rial/ha
B_i	Surface area of each land use	ha

X_1	Area allocated to orchard	ha
X_2	Area allocated to rangeland	ha
X_3	Area allocated to irrigated land	ha
X_4	Area allocated to dryland	ha
A_1^1	Amount of net farm income per unit area of orchard	10^6 Rial/ha
A_1^2	Production cost per unit area of orchard	10^6 Rial/ha
A_1^3	Erosion cost per unit area of orchard	10^6 Rial/ha
A_2^1	Amount of net farm income per unit area of rangeland	10^6 Rial/ha
A_2^2	Production cost per unit area of rangeland	10^6 Rial/ha
A_2^3	Erosion cost per unit area of rangeland	10^6 Rial/ha
A_3^1	Amount of net farm income per unit area of irrigated land	10^6 Rial/ha
A_3^2	Production cost per unit area of irrigated land	10^6 Rial/ha
A_3^3	Erosion cost per unit area of irrigated land	10^6 Rial/ha
A_4^1	Amount of net farm income per unit area of dryland	10^6 Rial/ha
A_4^2	Production cost per unit area of dryland	10^6 Rial/ha
A_4^3	Erosion cost per unit area of dryland	10^6 Rial/ha
C_1	Annual sediment yield per unit area of orchard	t/ha.y
C_2	Annual sediment yield per unit area of rangeland	t/ha.y
C_3	Annual sediment yield per unit area of irrigated land	t/ha.y
C_4	Annual sediment yield per unit area of dryland	t/ha.y

B_1	Maximum limit of orchard surface area	ha
B_2	Surface area of irrigated land	ha
B_3	Surface area of dryland	ha
B_4	Surface area of orchard plus irrigated land	ha
B_5	Total area	ha
B_6	Minimum limit of orchard surface area	ha
B_7	Surface area of rangeland	ha
y_i^*	Shadow price for resource *i*	t or 10^6 Rial

CHAPTER 1

INTRODUCTION

1.1 Background and statement of the problem

Soil is produced as a result of the decomposition of rocks by chemical, physical, biological, and climatological processes. Tens of thousands of years may be required in the formation of differentiated layers of soil. The process is slow enough that soil can be considered a nonrenewable resource. Climate, overland cover, geology, topography and land uses promote a combination of events that control the amount of soil removal and transport, either by water or by wind.

The woodcutting, overgrazing, and destructive cultivation that caused devastation in the Middle East thousands of years ago (Lowdermilk, 1948) has continued in the intervening years until there is little land left that has not suffered man-made degradation. Pearse (1970) contends that rangeland deterioration (and erosion) has accelerated since 1950, primarily due to a doubling or tripling of livestock numbers, extensive plowing of rangelands, firewood cutting, expansion of well drilling into formerly inaccessible areas, and better transportation facilities. Destruction of vegetative cover on sandy soils in Iran has led to increased wind erosion and required strenuous efforts to stabilize the dunes that have formed (Niknam and Ahranjani, 1976). The area of abandoned arable land in Iran has doubled in recent years and the number of livestock on grazing lands is estimated to be two to three times the carrying capacity.

Accelerated erosion is the result of two factors: improper management of productive soils and exploitation of marginal lands (Dregne, 1982); both mean using lands without considering their suitability.

The primary energy causing erosion by water is gravity, through falling precipitation and flow down the terrain slope. Raindrop splash and overland flow detach soil particles which are then transported down-slope by the kinetic energy transferred from the water flow to the sediment (Canali, 1992).

The sorting action by erosion agents causes removal of a high proportion of the clay[1] and humus[2] from the soil and leaves the coarse sand[3] and rock fragments[4] behind. Most of the soil fertility is associated with clay and humus. These components also are important in microbial activity, soil structure, permeability, and water storage. Thus, an eroded soil is degraded chemically, physically and biologically.

The eroded soil becomes sediment that covers bottomlands and man-made structures. Gullies, sand dunes, and other obvious signs of erosion are examples of using the lands without proper management. Proper management implies long-term usefulness as well as satisfying current needs. The cost of erosion in terms of yield reduction is difficult to determine. Based on data relating topsoil loss to yield reductions, just 2.5 cm of topsoil loss is enough to reduce U.S. wheat yields an average of 60 million bushels (bushel = 35.21 liter) every year (Dregne, 1982).

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[1] A soil separate consisting of particles <0.002 mm in equivalent diameter (S.S.S.A., 1998).

[2] Total of the organic compounds in soil exclusive of undecayed plant and animal tissues, their "partial decomposition" products, and the soil biomass. The term is often used synonymously with soil organic matter. (S.S.S.A., 1998).

[3] A soil particle between 1.0 to 0.5 mm in diameter (S.S.S.A., 1998).

[4] Unattached pieces of rock 2.0 mm in diameter or larger that are strongly cemented or more resistant to rupture. (S.S.S.A., 1998).

Deterioration in the quality of cropping and grazing land as a result of erosion reduces productivity and increases expenditure on fertilizers to maintain fertility. In extreme cases yields become so poor that land has to be taken out of cultivation (Morgan, 1986). Many researchers have observed declining crop yields with decreasing topsoil depth (Segarra, 1992). Erosion adds to the cost of producing food and other soil products and thereby increases the cost of living. Taking ruined land out of production places a greater load on the remaining land and drives up production costs. Implementing expensive erosion control practices also adds to production costs.

Perhaps the most costly result of soil erosion is related to damage done by the soil particles that are dislodged and moved downwind or downstream. Sedimentation[1] raises streambeds, reducing the depth and capacity of the channels. This causes navigation problems and can lead to severe flooding. Sedimentation of lakes and reservoirs reduces their capacity, value, and life expectancy (Frederick et al., 1991). Erosion has become an environmental problem that must be remedied for the sake of clean air and water. Soil particles adsorb pollutants such as pesticides, fertilizers, and different industrial and municipal chemicals that are best kept out of water by keeping the soil on the land (Glymph, 1972; Foster, 1988; Singh, 1992; Wanielista and Yousef, 1993). Keeping sediment out of water lowers the supply of plant nutrients in the water and thereby reduces unwanted growth of algae and other vegetation, which is an important problem in most rivers, reservoirs and lakes. Changing the aquatic environment of streams and lakes reduces their value for home and industrial use, recreation, and fish and wildlife (Frederick et al., 1991). Controlling soil erosion keeps streams, ponds, and lakes from

[1] Deposition of soil particles after the processes of detachment and transportation (Renard et al., 1989).

filling as rapidly with sediment. Reservoir capacities are thus maintained for recreation, flood control, power generation, and irrigation.

Regarding the time needed for soil formation under different climatic, topographic, and biological conditions, Birkeland (1974) concluded that 10^5 to 10^6 years are required to develop weathered surfaces on granite rocks, and longer periods are required for non-granite rocks. The development of a mollic horizon[1] requires from 200 to 3000 years (Birkeland, 1974).

The prevention of soil erosion, which means reducing the rate of soil erosion to approximately that which would occur under natural conditions, relies on selecting appropriate strategies for soil conservation (Morgan, 1979). Although it is impossible to stop soil erosion completely under natural conditions, there is a great need to control erosion for proper land and water use planning. This requires awareness of sediment yield[2] and foreseeing changes such as in land use. Therefore, sediment yield determination as a base for proper land and water use planning is of great importance. Since most watersheds, particularly small watersheds, are often un-gauged, sediment yield determination cannot be made due to lack of data. Predicting sediment yield for such watersheds is imperative.

Estimates of watershed sediment yield are required for solution of a number of problems. Design of dams and reservoirs, transport of pollutants, design of soil conservation practices, design of stable channels, determination of the effects of basin

[1] A surface horizon of mineral soil that is dark colored and relatively thick, contains at least 5.8 g/kg organic carbon, is not massive and hard or very hard when dry, and has a base saturation of >50% when measured at pH 7 (SSSA, 1998).
[2] The amount of eroded soil that is delivered to a point in the watershed that is remote from the origin of the detached soil particles (Renard et al., 1989).

management, off-site damage evaluation, and cost evaluation of a water-resources project are some of the example problems (Singh, 1992).

A major problem in the area of spatial data modeling has been the complexity of handling, manipulating, and managing large volumes of input parameters and data. In recent years, modeling in a Geographic Information System (GIS) environment, which refers to creation of digital databases interacting with a mathematical model, has been developed. GIS is now providing the opportunity and tools to spatially organize and effectively manage huge quantities of data for modeling.

Land-use optimization, on the other hand, is one of the appropriate strategies for soil conservation. It can empower the decision-maker or watershed manager to choose from different land-use scenarios to reach the best decision between the different combinations of variables.

Development of a methodology and associated tools for modeling the management of soil erosion could be one of the research components. Integration of a soil erosion model with a GIS should provide an effective method for the prediction of soil erosion in a vast area. To reduce the environmental and economical impact of soil erosion resulting from improper management of land-use activities, a study was initiated by Iranian Ministry of Construction on Syahrood, one of the sub-basins of Damavand watershed in Iran.

1.2 Objectives

The main objective of present study was to develop a new methodology and associated tools to predict the sediment yield with greater reliability in watersheds with deficiency of recorded rain gauge data. A subsequent objective was to optimize land-use activities of a watershed in such a way that soil erosion is minimized while maximizing the agricultural economic income.

Integrating a soil erosion model with a 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.

1.3 Thesis organization

The work presented in this thesis consists of six chapters:

Chapter 1 introduces general information about soil erosion, its on-site and off-site problems, and the need for its prediction. Objectives of this study are also part of this chapter.

Chapter 2 gives some background information about predicting soil erosion, GIS, and optimization. USLE, RUSLE, MUSLE, and WEPP are introduced as available soil erosion prediction models. ARC/INFO, ArcView, IDRISI, GRASS, and SPANS are introduced as the most popular GIS packages for spatial data modeling. Multi-objective linear programming is also introduced as a powerful model in optimization.

Chapter 3 introduces Syahrood one of the sub-basins of Damavand watershed in Iran as the study area. This chapter also, presents the procedure of developing spatial database for modeling soil erosion in a GIS environment.

Chapter 4 explains the first part of technical approach, containing the integration of MUSLE with SPANS-GIS for modeling soil erosion under different land uses of Syahrood sub-basin.

Chapters 5 presents the second part of technical approach, minimizing soil erosion while maximizing agricultural economic income by utilizing the simplex method of multi-objective linear programming.

Discussion and conclusions of the results and necessary future work related to the area of this research are covered in Chapter 6.

CHAPTER 2

LITERATURE REVIEW

This chapter is divided into three sections. Section 2.1 presents background on soil erosion and sediment yield prediction. A brief discussion of the most famous soil erosion models such as the Universal Soil Loss Equation (USLE), Revised Universal Soil Loss Equation (RUSLE), Modified Universal Soil Loss Equation (MUSLE), and Water Erosion Prediction Project (WEPP), is the subject of this section. In Section 2.2, Geographic Information Systems (GIS), their organization, fundamental components of geographically referenced data, and modeling in GIS environments are presented. Finally, operational research, optimization techniques, and multi-objective programming are discussed in Section 2.3.

2.1 Soil erosion

2.1.1 Introduction

Water erosion is a serious problem in subhumid, semiarid, and arid regions. Inadequate moisture and periodic droughts reduce the periods when growing plants provide good soil cover and limit the quantities of plant residue produced. Erosive rainstorms are not uncommon and they are usually concentrated within the season when cropland is least protected (Wischmeier and Smith, 1978).

Ellison (1946) has defined soil erosion as a process of detachment and transportation of soil materials by erosive agents, such as water and wind. Water, as rainfall and runoff, is the active agent for the basic process of water erosion (Cook, 1936). The third soil erosion process is deposition (Ekern, 1950), and it happens when sufficient energy is no longer available to transport the soil particles any further (Morgan, 1986).

The energy available for erosion takes two forms: potential and kinetic (Morgan, 1979). Potential energy results from the difference in height of one body with respect to another. This energy in the form of rainfall causes splash erosion. The potential energy for erosion is converted into kinetic energy, the energy of motion of the running water. This kind of energy in running water causes interrill, rill, gully, and riverbank erosion. Figures 2.1 and 2.2 represent typical forms of interrill, rill and gully erosion.

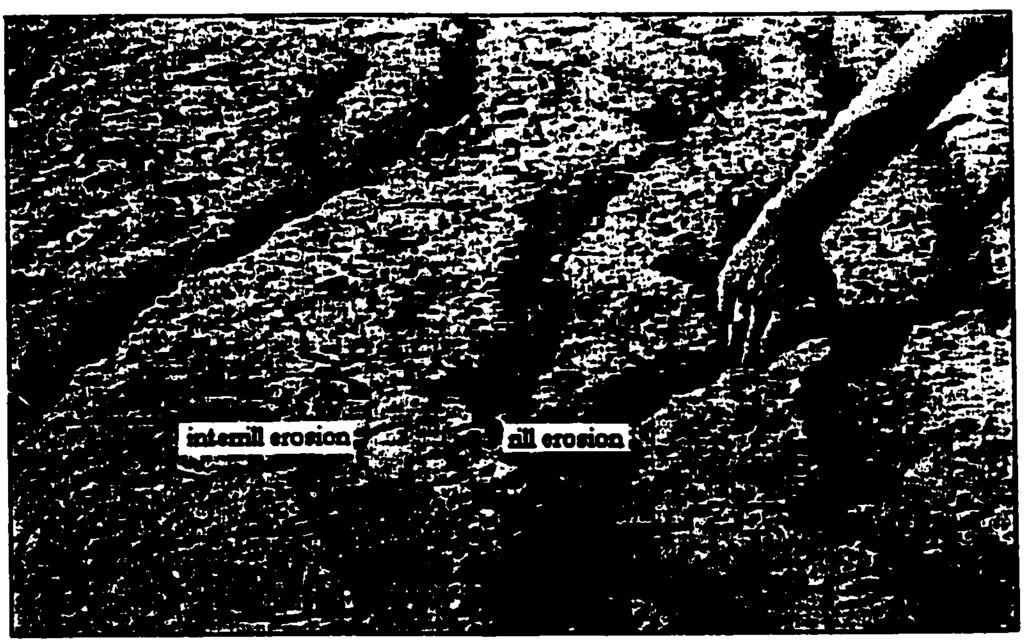

Figure 2.1 Typical form of interrill and rill erosion

One of the needs in the area of soil erosion control, as in all areas of science, has been to develop quantitative relationships among many factors, such as slope, rainfall, runoff, soil physical properties (texture, structure, permeability, etc.), and crop cover, that influence erosion (Pratt, 1979). Erosion prediction is the most widely used and most effective tool for use, management, assessment of land, soil conservation planning and design in watersheds (Laflen et al., 1991).

Figure 2.2 Typical form of gully erosion

2.1.2 Soil erosion prediction

2.1.2.1 Before Universal Soil Loss Equation (USLE)

The first comprehensive effort to quantify some of the factors affecting soil erosion began with the establishment of the erosion plots in 1914 by M.F. Miller, at the University of Missouri. The runoff that accumulated in the concrete tanks at the end of the plots was scooped, weighed, and sampled. H.H. Bennett, a soil surveyor in the Bureau of Soils in Washington D.C., observed the results from the control plots of Miller. He recognized the need for similar studies in other areas of the U.S. where soils, rainfall, and cropping practices differed widely from those at the Missouri control plots (Browning, 1979).

Development of equations for calculating field soil loss began in about 1940 in the Corn Belt states. In 1940 Zingg published an equation relating soil-loss rate to length and percentage of slope. In the following year, Smith added crop and conservation-practice factors and the concept of a specified soil-loss limit, to develop a graphical method for selecting conservation practices needed on specific soil conditions of the Midwest U.S. (Wischmeier and Smith, 1965).

Progress in developing an equation to predict soil loss was made after World War II (Sukresno, 1991). Browning and coworkers in 1947 added soil erodibility and management factors and prepared a set of tables to simplify field use of the equation in Iowa (Wischmeier and Smith, 1965).

Further equations and methods were developed over the next ten years. Smith and Whitt in 1947 presented a method for estimating soil losses for claypan soils[1]. Soil loss ratios at different slopes were given for contour farming[2], strip-cropping[3], and terracing[4]. They developed tables and curves to calculate soil loss from a field including tables for tolerable soil loss. The following year, Smith and Whitt presented an equation for

[1] A dense, compact, slowly permeable layer in the subsoil having a much higher clay content than the overlying material, from which it is separated by a sharply defined boundary. Claypans are usually hard when dry, and plastic and sticky when wet (S.S.S.A., 1998).

[2] This practice is that of performing field operations, such as plowing, planting, cultivating, and harvesting approximately on the contour. It reduces surface runoff by impounding water in small depressions and decreases the development of rills, in which the high water velocity results in destructive erosion (Schwab et al., 1981).

[3] The practice of growing two or more crops in alternating strips along contours, often perpendicular to the prevailing direction of wind or surface water flow (S.S.S.A., 1998).

[4] To decrease the length of the hillside slope, thereby reducing sheet and rill erosion, and retaining runoff in areas of inadequate precipitation, terraces are constructed in these regions (Schwab et al., 1981).

predicting soil loss based on slope gradient, slope length[1], soil erodibility[2], and supporting practices (Sukresno, 1991).

Musgrave in 1947 showed that the primary factors influencing the rate of erosion are intensity and amount of rainfall, flow characteristics of surface runoff, soil erodibility, and protective effects of vegetation cover. This, in turn, was called the Musgrave equation. Lloyd and Eley in 1952 further developed the Musgrave equation to estimate soil loss from large watersheds and to estimate sheet erosion[3] rates in an attempt to determine sediment delivery rates from watersheds. Graphics were used for this solution (Sukresno, 1991).

An equation for estimating soil loss under different management and conservation practices on various soils in Illinois was presented by Van Doren and Bartelli in 1956. Nine factors were used in their equation. Where soil loss (A) was a function of slope gradient (S), slope length (L), conservation practices (P), soil erodibility (K), intensity and frequency of 30-minute rainfall (I), previous erosion (E), management (M), and rotation (R). The equation is based on the evaluation of different factors influencing the amount of soil movement. The soil loss factor, as measured on standard research plots, was adjusted to site conditions based on data from previous researchers and factors for prior erosion and management levels (Sukresno, 1991).

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[1] The horizontal distance from the origin of overland flow to the point where either (i) the slope gradient decreases enough that deposition begins or (ii) runoff becomes concentrated in a defined channel (Renard et al., 1989).

[2] A measure of the soil's susceptibility to detachment and transport by the agents of erosion (Lal, 1988).

[3] The removal of a relatively uniform thin layer of soil from the land surface by rainfall and largely unchanneled surface runoff (S.S.S.A., 1998).

2.1.2.2 Universal Soil Loss Equation (USLE)

The National Runoff and Erosion Data Center of the United States was established by the United States Department of Agriculture-Agricultural Research Service (USDA-ARS) at Purdue University in 1954 to develop the USLE. The Data Center was given the responsibility for locating, assembling, and consolidating all available data on runoff and erosion studies throughout the United States.

More than 8000 plot-years of basic runoff and erosion data from more than 49 locations were assembled. These data were edited, coded, and recorded on punch cards at the Data Center for summarizing and overall statistical analysis. Wischmeier and Smith (1965) developed the Universal Soil Loss Equation (USLE) which was first published in Agriculture Handbook 282. The USLE has been continuously refined through research and gathering of additional data. Wischmeier and Smith (1978) developed the new USLE for predicting rainfall erosion losses. This model and its guide were published in Agriculture Handbook 537.

Predicting soil loss *(A)* by this method, requires the assessment of six factors (Wischmeier, 1976 and Wischmeier and Smith, 1978):

$$A = RKLSCP \tag{2.2}$$

where

A = Average annual soil loss[1] $(\frac{\text{metric ton}}{\text{hectare.year}})$ or $(\frac{\text{t}}{\text{ha.y}})$

R = Average annual rainfall erosivity[2] factor, which is the sum of individual storm erosivity values, EI (E is the total energy for a storm and I is the storm's

[1] Conversion from U.S. to SI Units by Foster et al. (1981).

[2] An expression of the ability of erosive agents to cause soil detachment and its transport (Lal, 1988).

maximum 30-minute intensity), for qualifying storms over a time period

$$(\frac{\text{megajoule.millimeter}}{\text{hectare.hour.year}}) \text{ or } (\frac{\text{MJ.mm}}{\text{ha.h.y}}).$$

K = Soil erodibility factor $(\frac{\text{metric ton.hectare.hour}}{\text{hectare.megajoule.millimeter}})$ or $(\frac{\text{t.ha.h}}{\text{ha.MJ.mm}})$

L and S = Slope length and steepness, respectively (dimensionless).

C and P = Cropping system and supporting practices. respectively (dimensionless).

The USLE estimates long-term average annual or seasonal soil erosion for specific combinations of physical and management conditions (Wischmeier, 1976 and Wischmeier and Smith, 1978). Estimates of soil loss using the USLE were compared with measured values on 208 natural runoff plots, representing more than 1700 plot-years of data, to assess the error associated with the USLE predictions.

The USLE is used in models such as Areal Nonpoint Source Watershed Environment Response Simulation, ANSWERS (Beasley and Huggins, 1982) and Problem-Oriented Computer Language for Hydrologic Modeling, HYMO (Williams and Hann, 1973). Many researchers have used it. Hayes, (1976), Farmer and Fletcher, (1976), Brooks, (1976), Evans and Kalkanis, (1976), Robinson, (1979), Batista, (1989), Sukresno, (1991), Osborn et al., (1976), McCool et al., (1976), Roose, (1976), Aina et al., (1976), Foster, (1979), Moldenhauer, (1979), Kirby and Mehuys (1986, 1987), and Montas and Madramootoo (1991) are just a few.

2.1.2.3 Modified Universal Soil Loss Equation (MUSLE)

In many watersheds, only daily precipitation data are available which is insufficient for determining the rainfall intensity and estimating the rainfall erosivity factor (R). Williams (1975) replaced the R factor with a term that includes both the peak discharge and total amount of water applied to the field during a storm. His Modified Universal Soil Loss Equation (MUSLE) is given by:

$$S_y = 11.8(QV)^{0.56} KLSCP \qquad (2.3a)$$

where

S_y = Sediment yield (t)

Q = The peak flow (m^3/s)

V = The volume of water (m^3) applied to the area

$$Q = 0.042DA/t_p \text{ with } t_p = c_t(L_w L_c)^{0.0792} \qquad (2.3b)$$

$$V = \frac{(P_i - 0.2S_r)^2}{P_i + 0.8S_r} \text{ with } S_r = 25.4(\frac{1000}{CN} - 10) \qquad (2.3c)$$

where

P_i = Daily rainfall (mm)

S_r = Retention parameter (mm)

CN = Runoff curve number which depends on land use and management, hydrologic conditions, hydrologic soil group

DA = Drainage area (ha)

t_p = Time from the onset of excess rainfall to peak of the unit hydrograph (h)

c_t = Coefficient based on type of land (1.8-2.2)

L_w = Length of the watershed (m)

L_c = Distance from the outlet to the center of the watershed (m)

K, L, S, C, and P are as defined in the USLE

Williams (1975) found that MUSLE can be applied to large watersheds if sediment sources are uniformly distributed over the watershed and if major watershed tributaries are hydraulically similar. Fogel et al. (1976) used this model to present a method of forecasting watershed sediment yield. Bashier (1985) successfully used the MUSLE to model the sediment yield on Siran watershed in Pakistan. Krishna et al. (1988) used this model in the SWRRB model (Simulator for Water Resources in Rural Basins) for agriculture and grassland on a watershed near Riesel, Texas.

Renard et al. (1989) updated the USLE (Wischmeier and Smith, 1978) as the Revised Universal Soil Loss Equation (RUSLE), by revising the R, K, C, and P factors.

The United States Department of Agriculture (USDA)-Water Erosion Prediction Project (WEPP) is another effort by the National Soil Erosion Research Laboratory to develop an erosion prediction model (Agassi, 1996). The first phase of developing the WEPP project lasted from 1985 until 1989 (Laflen et al., 1991). This model is able to deal with deposition of eroded soil and practices that drastically change the hydrology of the field.

2.1.3 Conclusion

Sediment yield determination as a base for proper land and water use planning is of great importance. It is required for solution of a number of problems. Design of dams, reservoirs, channels, and soil conservation practices, determination of the effects of basin management, off-site damage evaluation, transport of pollutants, and cost evaluation of a water-resources project are some of the example problems.

Since most watersheds, particularly small ones, are often un-gauged, sediment yield determination cannot be made due to lack of data. Among the models, MUSLE as a soil erosion prediction model is the only one that can handle lack of recording rain gauges.

2.2 Geographic Information Systems (GIS)

2.2.1 Introduction

A major problem in the area of modeling, and soil erosion modeling as well, has been the inability to efficiently handle, manipulate, and manage large volumes of input data. The collection of data about the spatial distribution of significant properties of the earth's surface, people, animals, and plants has long been an important part of the activities of organized societies. Until relatively recently, however, most of these data were kept in the form of paper documents and maps. They could be read off easily, but only with difficulty could they be used to analyze the patterns of distribution of attributes over the earth's surface and the processes that had given rise to them.

Developments in both computer technology and mathematical tools for spatial analysis that have taken place in the second half of the 20th century have made many things possible, among them the ability to store, retrieve, and display data about all aspects of the earth's surface (Huxhold, 1991).

Developments in Geographic Information Systems (GIS) as a unique computational tool provide the opportunity to spatially organize and effectively manage input data for analyzing and modeling and eventually visualizing model outputs. GIS is becoming a basic tool for a wide variety of earth science and land-use applications (Chuvieco, 1993). It can be used to reduce data collection demands by extracting valuable information from existing databases. For example, one important application is in estimating slope steepness from elevation data, which is a critical factor in estimating soil loss (Srinivasan and Engel, 1991).

A simple definition of GIS is that it is an organized collection of computer hardware, software, and geographic data designed to efficiently capture, update, manipulate, analyze, and display all forms of geographically referenced information (Dangermond, 1992). Aronoff (1991) defined a GIS as any manual or computer-based system that provides the following four sets of capabilities to handle geo-referenced data: input, data management (data storage and retrieval), manipulation and analysis, and output. Star and Estes (1990) defined the GIS as an information system that is designed to work with data referenced by spatial or geographic coordinates.

This developing technology offers an extraordinary opportunity to empower and transform the practice of planning (Innes and Simpson, 1992). GIS and closely related technologies are now being applied to many different disciplines and fields of work. Among the most important are watershed monitoring, natural resource management, agriculture, land-use planning, wildlife management, automated mapping, urban planning, geology, ecology, hydrology, geotechnics, archaeology, coastal-zone planning, managing natural and technological hazards[1], and military exercises (Dangermond, 1992).

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[1] A physical situation with a potential for human injury, damage to property, damage to the environment, or some combination of these (Health and Safety Executive, 1989).

In the 1960s, GISs were supported by mainframe computers, which are now found typically in large computer centers. From the mid-1970s to the early 1980s, the dominant type of computers supporting GIS were minicomputers running in a timesharing mode. In the early and middle 1980s there was an explosive growth in the use of personal computers, and by the middle of the decade GIS software became available on these machines. The second fastest growing segment of the GIS hardware has been in the last few years, when 32-bit machines with great computing power and exceptional graphics performance were introduced. Perhaps the most recent hardware development supporting GIS is the interconnection of various hardware devices (computers, storage devices, output devices, etc.) to form a computing network. In addition to the computers, some other kinds of hardware devices are quite important to GIS. Many of these are general-purpose computing devices, such as display terminals, plotters, scanners, and digitizers (Dangermond, 1992).

2.2.2 Geographic data

Geographic information or geographic data usually have three fundamental components which are the phenomenon (like physical dimension or class), the spatial location of the phenomenon, and finally time. Thus, geographic data describe a phenomenon at a location at a specific time. Geographic data may be represented either on a map or in a GIS environment as different features, such as points, lines, and areas.

All spatial data are of limited accuracy. The accuracy of spatial data is often described in terms of positional and attributes accuracy as if these were separable. For example, a spot elevation at a benchmark has a vertical accuracy, which may be quite independent of the accuracy of its position, as different instruments were likely used to determine them. Error is introduced at every step in the process of generating and using geographic information, from collection of the source data to the interpretation of the results of a completed analysis (Aronoff, 1991). Usually, operator, equipment, and geographic feature (such as edges) cause the common sources of error in every step. The objective in dealing with error should not be to eliminate it but to manage it. Achieving the lowest possible level of error may not be the most cost-effective approach. There is a trade-off between reducing the level of error in the database and the cost to create and maintain the database. The level of error in a GIS needs to be managed so that data errors will not invalidate the information that the system is used to provide (Aronoff, 1991).

There are two fundamentally different ways to organize the geographical data inside any information system: the raster model and the vector model. In the raster data structure, the space is regularly subdivided into cells, each grid cell of the array can be referenced by a row and column number and contains a value for the type of attribute being represented. The value stored for each cell indicates the type of object or the value of the attribute it represents. Many of the cells may contain the same value as neighboring cells. There are various methods of data compression for reducing the size of the raster file such as runlength encoding and quadtrees. In the vector data structure, points, lines, and areas represent the features. The position of each object is defined by its placement in a map space that is organized by a coordinate reference system. Each approach tends to work best in situations where the spatial information is to be treated in a manner that closely matches the data model. High spatial variability is efficiently represented in a raster format. It has a simple data structure, and overlay operations are easily and efficiently implemented. But less compactness of its data structure and blocky appearance on its graphics are disadvantages of this model. On the other hand, the vector data model provides a more compact data structure, efficient encoding of topology[1], and the appearance of graphical outputs is close to that of hand-drawn maps. But its complex data structure, difficult implementation in overlay operations, and inefficiency in representation of high spatial variability are disadvantages of this model (Aronoff, 1991).

2.2.3 GIS software

Many companies and universities are developing GIS packages with different level of functionality. Among them, ARC/INFO and ArcView developed by ESRI, IDRISI by Clark University, GRASS by USACERL, and SPANS by TYDAC are the most popular and widely used GIS packages.

ARC/INFO developed by Environmental Systems Research Institute (ESRI), Redlands, CA, manages spatial data in ARC and non-spatial data in INFO. This package commenced by utilizing a vector-based spatial data structure approach (ESRI, 1995). ARC/INFO Version 8 and SDE Version 4 are products built from ESRI's next generation ArcGIS component-based GIS technology. Both software products continue to operate independently, but at version 8, they are also integrated (ESRI, 1999).

ArcView is also made by ESRI and uses geographic data from a variety of sources such as spatial data, image data, and tabular data. ArcView 3.1 is the latest version of desktop GIS package from ESRI (ESRI, 1999).

[1] The mathematical method used to define spatial relationship, like arc-node data model (Burke, 1997).

Ron Eastman developed the raster-based IDRISI geographic information and image-processing package at Clark University in 1988. Since that time, its development was partially supported by the United Nations Environment Program Global Resource Information Database (UNEPGRID), the United Nations Institute for Training and Research (UNITER), and the United States Agency for International Development (USAID). Now, it is only supported by software sales. The latest version of IDRISI for Windows (version 2) couples the extensive analytical capabilities of the IDRISI GIS and Image Processing System with the highly interactive graphical user interface of Microsoft Windows (Clark, 1999).

Geographical Resources Analysis Support System (GRASS) is a GIS package developed by the United States Army Construction Engineering Research Laboratory in the 1980s. The technology was transferred to LAS, Inc. (now Global Geomatics) for commercialization in 1995 and to Baylor University in 1997 to sustain the public domain software versions. Baylor has just released GRASS 5.0, the first major upgrade of public domain GRASS. It has a raster, topological vector, image processing, and graphics production functionality that operates in the UNIX environment through a graphical user interface and shell in X-Windows and is available as source code on the GRASS internet site (GRASS, 1999).

SPANS was developed by TYDAC Technologies, Ottawa, Ontario. It is unique in its adoption of a quadtree spatial data structure. This provides compact raster representation by using a variable-sized grid cell, useful for having a small file size when the data are relatively homogeneous and do not require frequent updating. It provides a wide variety of modules for digitizing, desktop mapping, data importing and exporting (data translation), and image processing. Its modeling language provides the ability of combining multiple layers of spatial data to create desired maps, charts, and tables (Burke, 1997).

2.2.4 GIS and modeling soil erosion

GIS software capabilities are useful in themselves, but they become much more important when they are combined into various kinds of analytical models. These include resource allocation, population forecasting and spatial distribution, land-use forecasting, transportation, and site selection models (Dangermond, 1992).

Modeling in a GIS environment refers to creation of a digital database that can interact with a mathematical model. For example with the use of a GIS, planners can correlate land cover and topographic data with a variety of environmental parameters relating to such indicators as surface runoff, drainage basin area, and terrain configuration. Computer-based information can also be used to refine such models as the USLE. The result is reasonable predictions of agricultural pollutant loads and the potential transport of nonpoint source pollutants based on watershed parameters, such as soil, slope, vegetative cover, and area (Walsh, 1985).

The process of obtaining the terrain (LS) factor from digital elevation models (DEMs) permits quick calculation of soil loss potential for large areas (Blaszczynski, 1992). Logan et al. (1982) used the USLE with the U.S. Army Corps of Engineers Land Resources Information System (LRIS) to estimate soil loss in the U.S. portion of the Lake Erie drainage basin. Blaszczynski (1992), used the RUSLE for regional soil loss prediction utilizing the raster processing capabilities of the Map Analysis and Processing

System (MAPS). Montas and Madramootoo (1991) described and applied a Decision Support System (DSS) for the planning of soil conservation systems on an agricultural watershed in southwestern Quebec. This system consists of a raster-based GIS, the ANSWER model, and Expert System (ES) technologies. Younos et al. (1993) used the USLE with a sediment-yield component to evaluate the comparative effects of alternative reclamation strategies in abandoned mined land located in southwest Virginia. The raster-based Virginia GIS was used to create digital data layers, store, analyze, and display information. Kertesz (1993) used the USLE interfaced with the ARC/INFO GIS for soil loss assessment in Hungary. Rewerts (1992) developed a method to simplify the preparation of information from the GRASS-GIS for use in modeling erosion in the ANSWERS model. Engel et al. (1993) integrated ANSWER with the GRASS GIS to simulate a watershed response to a series of rainfall events. Then the simulated responses were compared with observed runoff and sediment data. The simulated results matched the observed results reasonably well considering model inputs were estimated from base GIS data. Chairat (1993) used the GRASS-GIS to simulate the runoff produced by short-term rainfall events by the physically based, variable source area model.

SPANS is used in different countries around the world mostly for managing and planing in the areas of agriculture, natural resources, water resources, and environment. A smaller but growing number of users are those in the areas of business who perform economic analysis (Tomlinson and Toomey, 1995). Using SPANS, Stempvoort et al. (1993) produced maps by comparing and merging with other GIS spatial data to determine contaminated groundwater along the Saskatchewan-Alberta boundary. Bajjali and Daneshfar (1995) used fuzzy logic modeling in SPANS to investigate the suitability of groundwater resources for drinking purposes in North Jordan. Luo (1995) developed a methodology in the analysis of erosion risk in Snowdonia National Park, U.K. by utilizing the SPANS.

2.2.5 Conclusion

SPANS-GIS is unique in fuzzy logical modeling and is a powerful analytical mapping tool. Its modeling uses customized equations written in the SPANS modeling language to evaluate tables and maps and to create new tables and maps from the resulting data. It is unique in its adoption of a quadtree spatial data structure too. This provides compact raster representation by using a variable-sized grid cell, useful for having a small file size. Before starting this research, a few PC versions of SPANS were prepared by Civil Engineering Department of Concordia University.

2.3 Optimization

2.3.1 Optimization techniques

Optimization theory develops methods for optimal choices of the decision variables. Based on the nature of the problem, one of the mathematical programming techniques such as Linear Programming (LP), Dynamic Programming (DP), and Nonlinear Programming (NLP) could be used to find the best possible solution.

LP models have been applied extensively to optimize resource allocation problems. They define a class of problems with the following characteristics (Lau, 1988):

1. All the decision variables are nonnegative.

2. The objective function is a linear function of the decision variables.

3. The structural constraints are linear inequalities (or equations) in the decision variables.

The standard form of an LP model can be expressed as (Mays and Tung, 1992):

$$Max(or\,Min)x_0 = \sum_{j=1}^{n} c_j x_j \qquad (2.4a)$$

Subject to:

$$\sum_{j=1}^{n} a_{ij} x_j = b_i \text{, for } i = 1, 2, \ldots, m \qquad (2.4b)$$

$$x_j \geq 0 \text{, for } j = 1,2,\ldots,n \qquad (2.4c)$$

where

x_0 = The objective

c_j = The objective function coefficient

x_j = Decision variable

a_{ij} = The technological coefficient

b_i = The right-hand side coefficient

DP is a mathematical technique that can be used to make a sequence of interrelated decisions in order to optimize a given objective. It transforms a sequential or multistage decision problem that may contain many interrelated decision variables, into a series of single-stage problems, each containing only one or a few variables.

Unlike linear programming, there is no standard form for a DP problem and thus there is no standard algorithm that can be used for solving all such problems. Examples that can describe the general philosophy of the DP technique, are resource allocation problems (such as fund allocation to different projects and water allocation to different demands) and the stagecoach problems (such as finding the shortest route from the origin to the destination in a network path).

Although DP possesses several advantages in solving water resources problems, especially for those involving the analysis of multistage processes, it has two disadvantages, which are large computer memory and time requirements (Mays and Tung, 1992).

NLP deals with problems, which have some degree of nonlinearity. These problems come in many different shapes and forms, and no single algorithm that will solve all of these different types of problems exists. Instead, algorithms have been developed for various individual classes of nonlinear programming problems.

2.3.2 Multi-objective programming

Multi-objective programming is concerned with decision-making problems in which there are several conflicting objectives. Multi-objective problems arise in the design, modeling, and planning of many complex resource allocation systems in the areas of industrial production, urban transportation, agricultural and livestock production, and water resources management (Goicoechea et al., 1982).

Multi-objective analysis has been developed in explicit form largely through the work of the Harvard Water Program, a research enterprise supported by the Rockefeller Foundation, the U.S. Army Corps of Engineers, and the Bureau of Land Reclamation. Much of the methodology and research findings were published by Mass et al. in 1962 (cited by Goicoechea et al., 1982). Since that time, multi-objective planning has awakened widespread interest and acceptance, and contributions to its application are being made in many agencies and research centers (Major, 1977).

The general multi-objective optimization problem with n decision variables, m constraints and p objectives is:

$$Max Z(x_1, x_2, \ldots, x_n) = \left[Z_1(x_1, x_2, \ldots, x_n), Z_2(x_1, x_2, \ldots, x_n), \ldots, Z_p(x_1, x_2, \ldots, x_n)\right] \quad (2.5a)$$

Subject to:

$$g_i(x_1, x_2, \ldots, x_n) \leq 0 \text{ for } i = 1, 2, \ldots, m \quad (2.5b)$$

$$x_j \geq 0 \text{ for } j = 1, 2, \ldots, n \quad (2.5c)$$

where

$Z(x_1, x_2, \ldots, x_n)$ = objective function

$Z_1(\ldots), Z_2(\ldots), Z_p(\ldots) = p$ individual objective functions

x_j = Decision variable

The characteristics of the decision-making process that will be used to categorize multi-objective programming methods are the information flows in the process and the decision-making context. The diagram in Figure 2.3 shows the relationships of the different methods, based on the information flows (Cohon, 1978).

Generating techniques emphasize the development of information about a multi-objective problem that is presented to a decision maker in a manner that allows the range of choice and the trade-off among objectives and does not allow preferences to be incorporated into the solution process. Several generating techniques, which are reviewed in the literature, are the Weighting method, Constraint method, and Multi-objective Simplex method. The first two methods transform the multi-objective problem into a single-objective programming format. Then, by parametric variation of the parameters used to effect the transformation, a noninferior set of solutions can be generated.

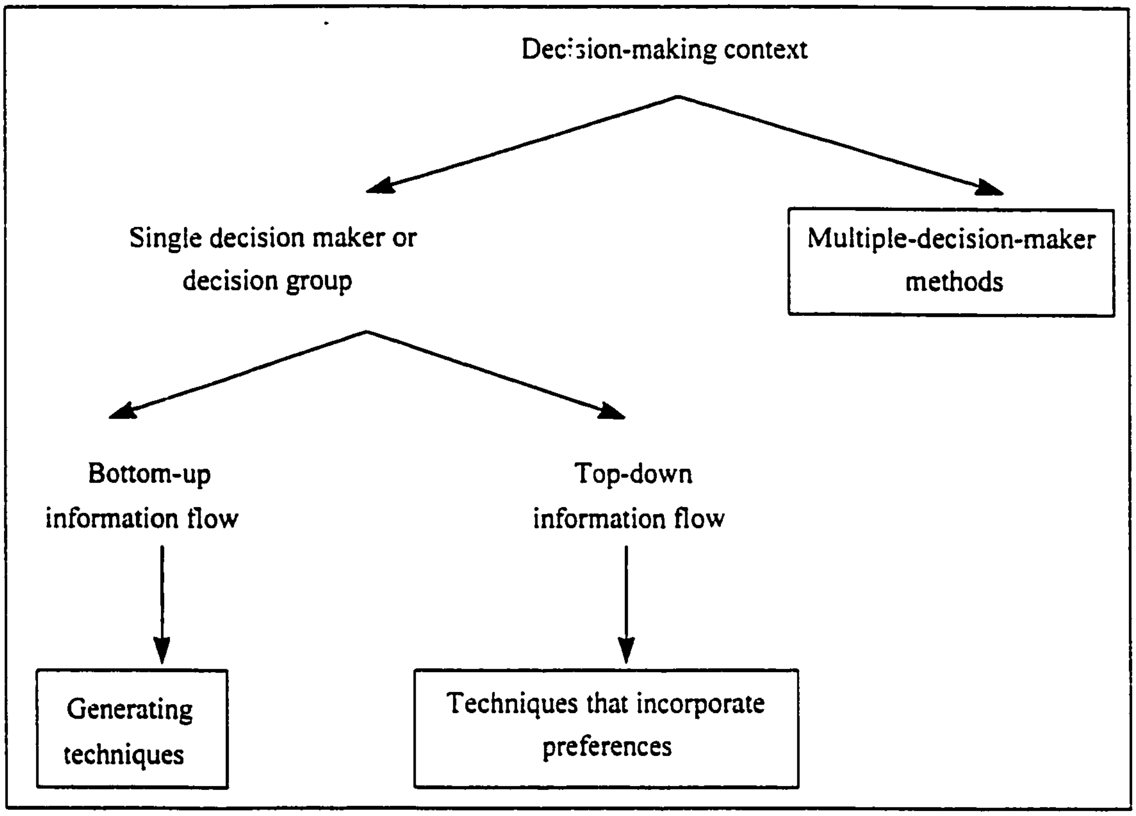

Figure 2.3 Diagram of the multi-objective programming methods

An active research area among mathematical programmers is the development of generating techniques that do not depend on the conversion of a multi-objective optimization problem into a single-objective optimization problem. Those approaches that have been suggested by Philip in 1972, Zeleny (1974), and Steuer (1995) are based on the use of the simplex method for linear programming problems.

A multi-objective simplex tableau for a problem with $n+m$ decision variables (m of them slack variables), m constraints, and p objectives is shown in Table 2.1.

Table 2.1 A multi-objective simplex tableau

	a_1	a_2	a_n	a_{n+1}	a_{n+m}	
c_j^1	c_1^1	c_2^1	c_n^1	0	0	0
c_j^2	c_1^2	c_2^2	c_n^2	0	0	0
⋮	⋮					
c_j^p	c_1^p	c_2^p	c_n^p	0	0	0
a_1						
a_2						
⋮						
a_m						
f_j^1	f_1^1	f_2^1	f_n^1	f_{n+1}^1	f_{n+m}^1	$f_0^1 = Z_1$
f_j^2	f_1^2	f_2^2	f_n^2	f_{n+1}^2	f_{n+m}^2	$f_0^2 = Z_2$
⋮	⋮					⋮
f_j^p	f_1^p	f_2^p	f_n^p	f_{n+1}^p	f_{n+m}^p	$f_0^p = Z_p$

In this table, the symbol c_j^k stands for the coefficient on the decision variable i in objective k. The symbol f_j^k stands for the reduced cost for objective k, and column j. For each variable we now have a set of reduced costs that will be called f_j, i.e.,

$$f_j = \left[f_j^1, f_j^2, \ldots, f_j^p\right]^T \tag{2.6}$$

Chung (1981) used the multi-objective linear programming to trace out a partial trade-off relationship between a soil-loss control policy and an energy-use reduction policy. Batista (1989) used LP and the USLE to minimize the amount of soil loss in a watershed. Chuvieco (1993) presented LP as a promising tool for spatial modeling within an IDRISI-GIS. He used LP in land-use planning with the aim of minimizing rural unemployment. Jacovkis et al. (1989) described a linear programming model for use in analysis and planning of multi-objective water resources systems consisting of reservoirs, hydropower stations, irrigated land, artificial and navigation channels in Argentina.

Benabdallah (1990) applied multi-objective linear programming to the shape of regions allocated to different land uses in a watershed.

2.3.3 Conclusion

As is shown in the technical approach, both objective functions and all constraints of this project are linearly related to decision variables. So the multi-objective linear programming is chosen as solution algorithm. The multi-objective linear programming of Steuer (1995) can be used for all efficient extreme points by moving mathematically from one noninferior extreme point to adjacent points until all noninferior extreme points have been found.

CHAPTER 3

STUDY AREA AND DATABASE

3.1 Study area

Syahrood one of the sub-basins of Damavand watershed in the north-central part of Iran between 35°37′ to 35°46′N latitude and 51°50′ to 52°02′E longitude is chosen as study area. It covers an area of 10 820 ha with average yearly precipitation of 423 mm and temperature of 10°C. Compared to other sub-basins of the watershed, Syahrood covers many different forms of land type, land use, and slope classes, which will be discussed in Section 3.2. Figures 3.1 and 3.2 present the location of the study area on the Iran map and Damavand watershed, respectively.

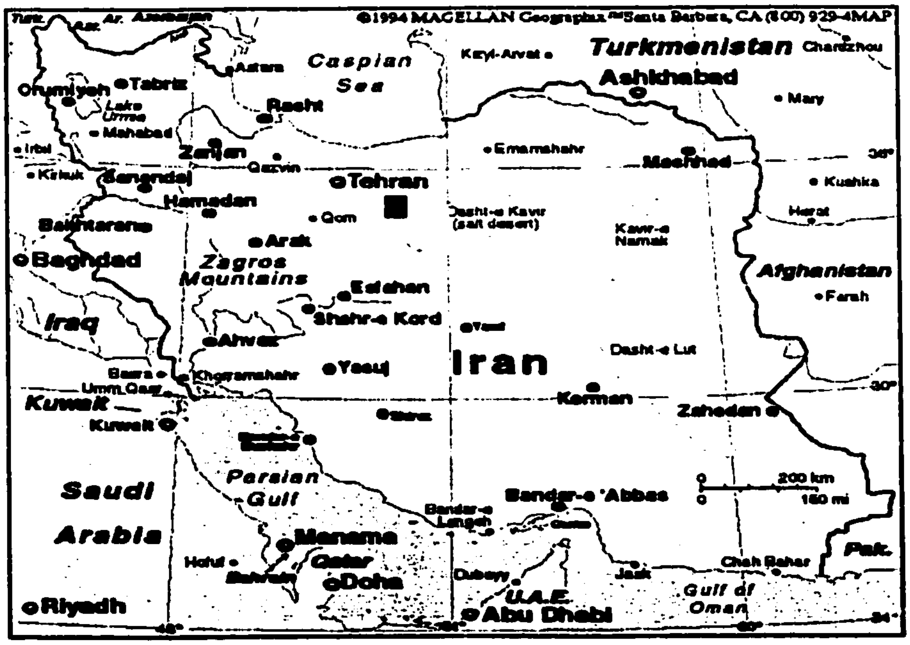

Figure 3.1 Study area (Syahrood sub-basin) on the Iran map (■)

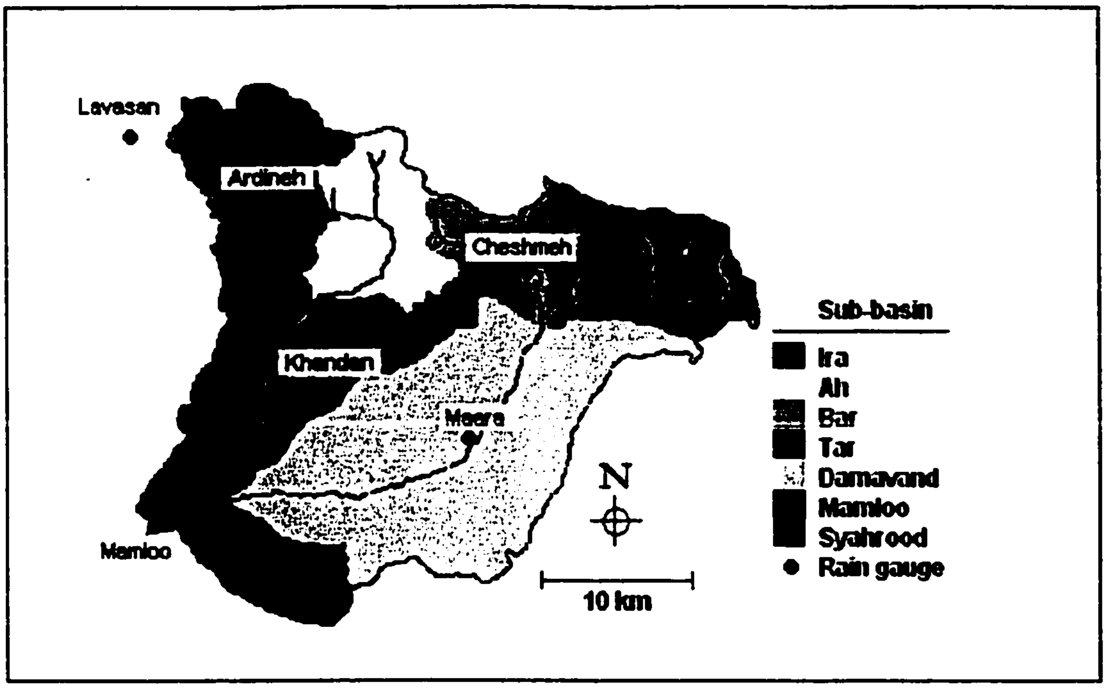

Figure 3.2 Study area (Syahrood) in the Damavand watershed

3.2 Development of database

Most of the necessary field data for modeling soil erosion in a GIS environment are extracted from the "Watershed Management Studies of Damavand". These studies were done by Natural Resources Consulting Engineers (NRCE) for the Construction Ministry of Iran in 1992. The Power Ministry of Iran prepared precipitation data and their consistency are tested in this research. Also, economic data were gathered for this research through the Agricultural and Construction Ministries of Iran, and agricultural offices in the Damavand watershed.

Usually, most of the precipitation in Syahrood sub-basin occurs in February, March, and April with high intensity and in short periods. Based on climatological studies at Homand Ab-sard (an area located 20 km east of Syahrood sub-basin), an 18 mm/h rain intensity has been calculated for a two-year return period and 15 minutes interval (NRCE, 1992). Based on the same source, the area belongs to a cold semi-arid zone. There are no recording rain gauges in the entire region. Instead there are six non-recording rain gauges in Damavand watershed and one of them lays in Syahrood sub-basin. Double-mass analysis was used to test the consistency of eight years precipitation record of six rain gauge stations, i.e., Ardineh, Cheshmeh, Gol Khandan, Lavasan Bozorg, Mamloo, and Maara.

The major land uses in Syahrood are orchard, irrigated land, dryland farming, and rangeland. Wheat, barley, alfalfa, clover, potato, tomato, grape, cucumber, squash, apple, apricot, and fig are the main agricultural products. Figures 3.3 and 3.4 show typical forms of good quality rangelands and degraded drylands in the study area.

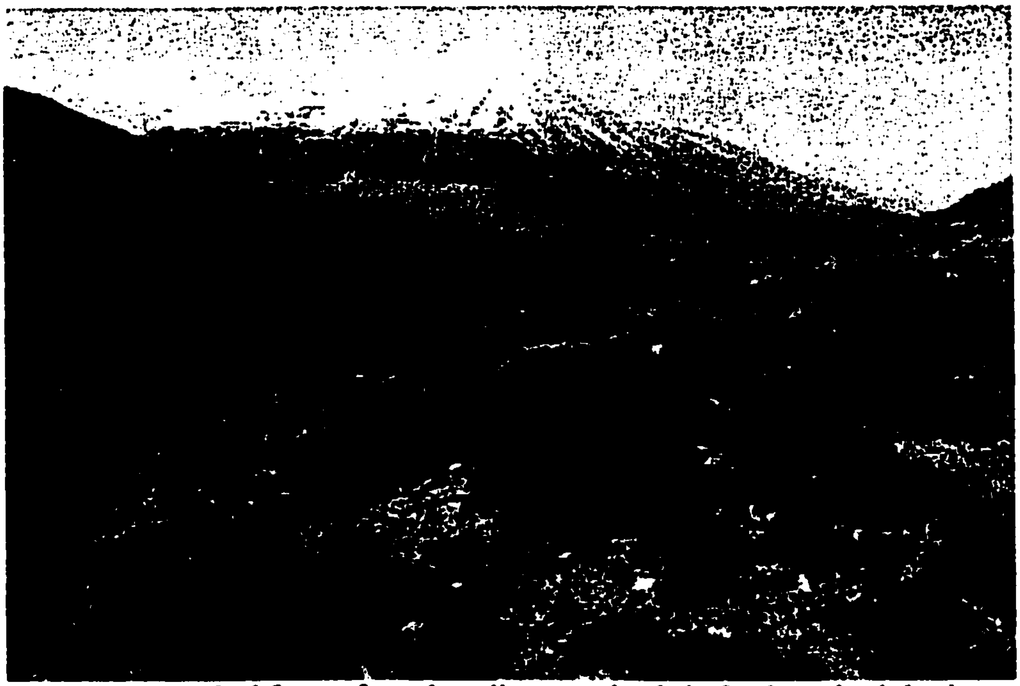

Figure 3.3 Typical form of good quality rangelands in Syahrood sub-basin (The snow-covered crest is not located in the sub-basin)

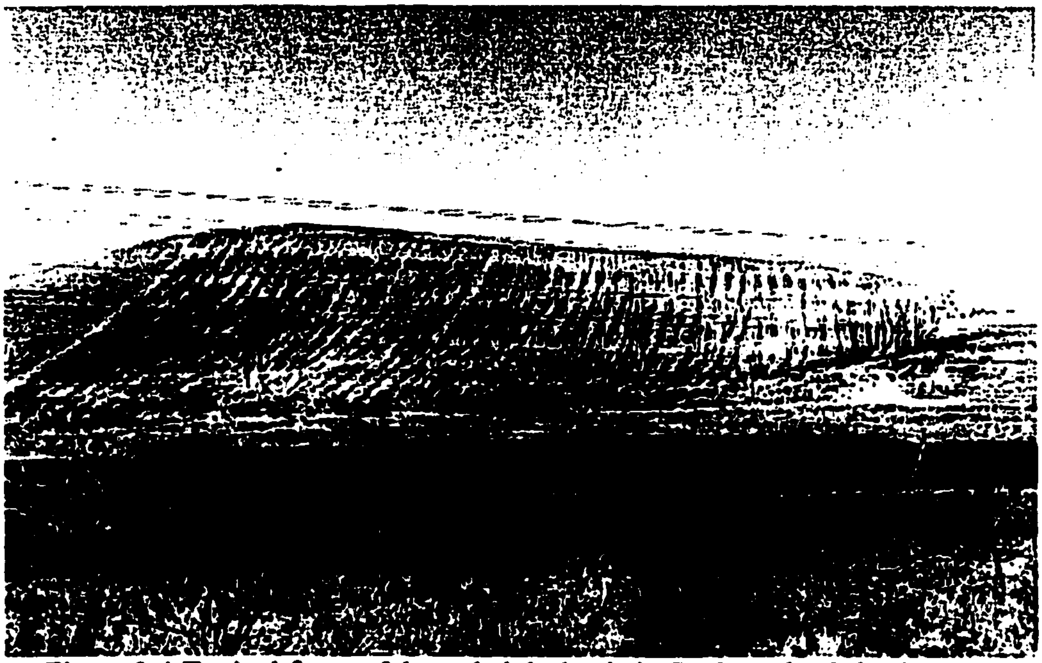

Figure 3.4 Typical form of degraded drylands in Syahrood sub-basin

Usually, drylands are located on steep slopes and are cultivated by many farmers in the slope direction, which causes the concentration of surface runoff and the movement of soil particles. Table 3.1 presents land use classification in Syahrood sub-basin.

Table 3.1 Land use classes in Syahrood sub-basin

Land use	Orchard	Irrigated	Dryland	Rangeland	Municipal	Total
% of total area	1.5	14	15	65	4.5	100
Area (ha)	160	1540	1620	6990	510	10820

There are three kinds of land type in the study area: mountains 43%, hills 43%, and plateaus and terraces 14% of total area. Also, there are 16 different land components (landform classes) in these land types. Table 3.2 presents different land components of the study area (NRCE, 1992).

Table 3.2 Land component classes in Syahrood sub-basin

Land type	Land unit	Land component	Description
1	1	1.1.2	Sharp crests; undeveloped soil profile, very shallow, with gravel, heavy; low vegetation density; used as low production rangelands
		1.1.5	Round crests; undeveloped soil profile, shallow in highs, deeper in low lands, with gravel, heavy; low to medium vegetation density; used as rangelands
	2	1.2.1	Round crests; undeveloped soil profile, shallow, light to medium with gravel; medium vegetation density; used as medium production rangelands and drylands
		1.2.2	Round crests; undeveloped soil profile, slightly deep, heavy; good vegetation cover; used as medium production rangelands and as irrigated lands and orchards
		1.2.3	Round crests; soils slightly deep in highs and deep with gravel in low lands; medium vegetation cover; used as medium to good production rangelands, and as orchards and irrigated lands
2	1	2.1.2	High hills, round and flat crests; undeveloped soil profile, shallow to slightly deep, heavy to very heavy; low to medium vegetation cover; used as medium to good production rangelands
	2	2.2.1	High hills, round crests; undeveloped soil profile, slightly deep, heavy with gravel; medium vegetation cover; used as medium productivity rangelands, also drylands in the slopes
		2.2.2	Low height to high hills, flat crests; undeveloped soil profile, slightly deep to deep, heavy; good vegetation cover; used as rangelands, some parts drylands, irrigated lands, and orchards

Table 3.2 Land component classes in Syahrood sub-basin (continue)

Land type	Land unit	Land component	Description
2	3	2.3.1	Low height hills, round plateaus, too many cuts; undeveloped soil profile, shallow to slightly deep, heavy; good vegetation cover; used as good production rangelands and drylands
		2.3.2	Low height hills and upper plateaus; undeveloped soil profile, slightly deep, heavy; good vegetation cover; used as good production rangelands, drylands, and irrigated lands
	4	2.4.1	High hills with many cuts; developed soil, deep, heavy; medium vegetation cover; used as low production rangelands, and drylands
		2.4.2	High hills; developed soil, deep, heavy; medium to good vegetation cover; used as medium production rangelands, drylands, and irrigated lands
3	1	3.1.2	Round plateaus with high topography; undeveloped soil profile, deep, heavy; medium vegetation cover; used as low production rangelands and drylands
	2	3.2.2	Round plateaus with low topography; developed soil, deep, heavy; medium vegetation cover; used as low to medium production rangelands and drylands
		3.2.3	Upper round plateaus with medium to high topography; undeveloped soil profile, deep, heavy; medium to good vegetation cover; used as good production rangelands and drylands
	5	3.5.2	Medium height plateaus, sedimentary terraces; undeveloped soil profile, medium to deep with gravel, medium to heavy; used as orchards and irrigated lands

Syahrood is a mountainous area with a diversity of slope classes. The elevation on the watershed ranges from 1400 m in the southwest to above 2800 m in the northeast. Table 3.3 shows the existing different slope classes with the area of each class. The method of preparing the slope map and its classification is presented in Chapter 4.

Table 3.3 Slope classes of Syahrood sub-basin

Slope class (%)	0-5	5-10	10-20	20-40	40-60	>60	Total
% of total area	0.0	43.1	28.1	17.2	11.1	0.5	100
Area (ha)	0.0	4668	3045	1859	1195	53	10820

Because of cold weather, high steepness, and high erosion, the soils in the mountainous areas are shallow, but in the lowlands they are very deep. By the Soil Conservation Service (SCS) method, there are four hydrologic soil groups (Singh, 1992).

Group A: Soils in this group have a low-runoff potential (high-infiltration rates) even when thoroughly wetted. They consist of deep, well to excessively well-drained sands or gravels. These soils have a high rate of water transmission.

Group B: Soils in this group have moderate infiltration rates when thoroughly wetted and consist chiefly of moderately deep to deep, well-drained to moderately well-drained soils with moderately fine to moderately coarse textures. These soils have a moderate rate of water transmission.

Group C: Soils have slow infiltration rates when thoroughly wetted and consist chiefly of soils with a layer that impedes the downward movement of water, or soils with moderately fine to fine texture. These soils have a slow rate of water transmission.

Group D: Soils have a high-runoff potential (very slow infiltration rates) when thoroughly wetted. These soils consist chiefly of clay soils with high swelling potential, soils with a permanent high-water table, soils with a clay pan or clay layer near the surface, and shallow soils over nearly impervious material. These soils have a very slow rate of water transmission.

Table 3.4 shows the potential runoff, minimum infiltration rate, percent and area covered by each soil group (NRCE, 1992).

Table 3.4 Characteristics of hydrologic soil groups in Syahrood sub-basin

Soil group	Potential runoff	Min. infiltration (mm/h)	Area (ha)	% of total area
A	low	7.62-11.43	943	8.7
B	medium	3.81-7.62	5818	53.8
C	medium-high	1.27-3.81	3724	34.4
D	high	0.5-1.27	335	3.1
Total	-	-	10820	100

The process of digitizing and developing the necessary database for modeling soil erosion in SPANS-GIS is mentioned later in Sections 3.2.1 and 3.2.2. The following maps were chosen to be digitized and imported to the SPANS-GIS environment.

1. Damavand watershed map showing sub-basins, rivers, and rain gauge stations
2. Elevation map showing contours with 100-m intervals
3. Hydrologic soil group map showing soil classes differentiated by antecedent soil moisture, soil texture, and soil permeability
4. Land-component map defining landform classes

5. Land-use map showing different land uses

These maps were prepared by NRCE at the 1:50 000 scale in 1992. In the first phase all hardcopy maps were digitized by SPANS-TYDIG. In the next phase, digital information was used to provide the necessary layers at the 15th quad level. The SPANS-GIS environment provides a finest grid size of 1.375 m at this level.

3.2.1 Digitizing hardcopy maps by SPANS-TYDIG

SPANS-TYDIG is a digitizing and editing tool designed by INTERA TYDAC Technologies Inc. for manipulation of spatial data. It provides data in digital form from hardcopy maps by using a digitizing table. A digitizing table with a 16-button cursor supporting serial communications and stream mode is needed.

Points, lines (arcs) and areas (whole polygons) are three kinds of spatial data on a hardcopy map, which had to be digitized to develop the database. Every type of geographical feature on a map should be digitized separately and stored in a separate file to build a different layer. Rain gauge locations were digitized as points, while land-use, land-component, elevation, and hydrologic soil group maps were digitized in arc-node polygons. Polygon attributes were assigned to a point digitized inside of each polygon. Digitized files were exported in the TYDIG environment to create appropriate "*.veh/.vec*" file pairs. These two files are used to build different layers when imported in the SPANS environment.

Figures 3.5 and 3.6 show digitized elevation, hydrologic soil group, land-component, and land-use maps within the SPANS-TYDIG.

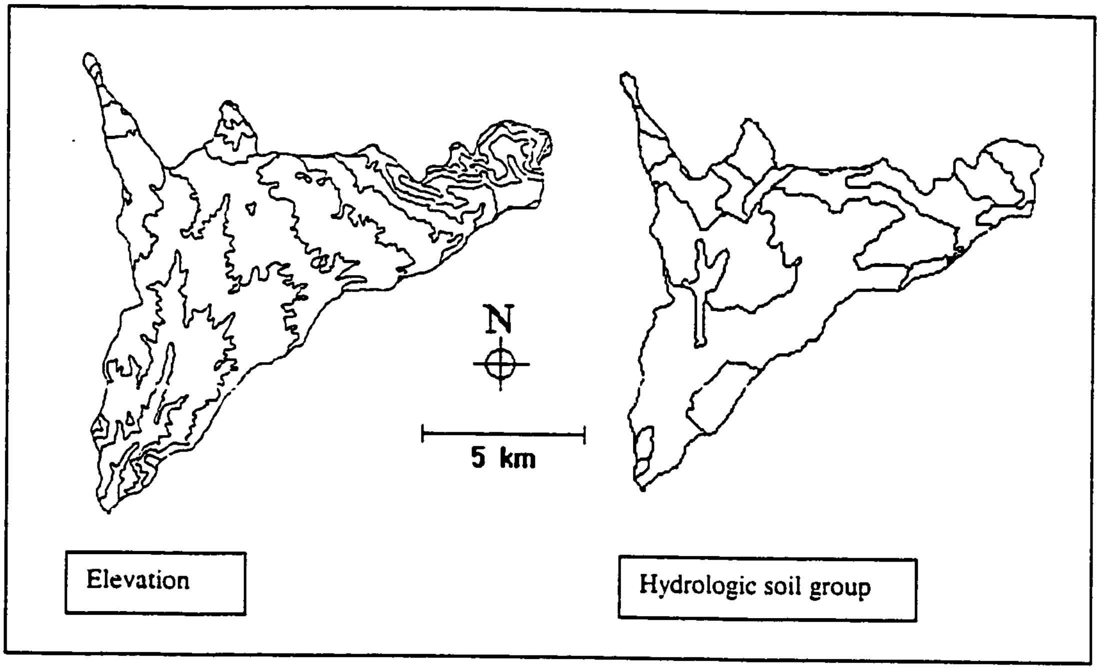

Figure 3.5 Digitized elevation and hydrologic soil group maps of Syahrood

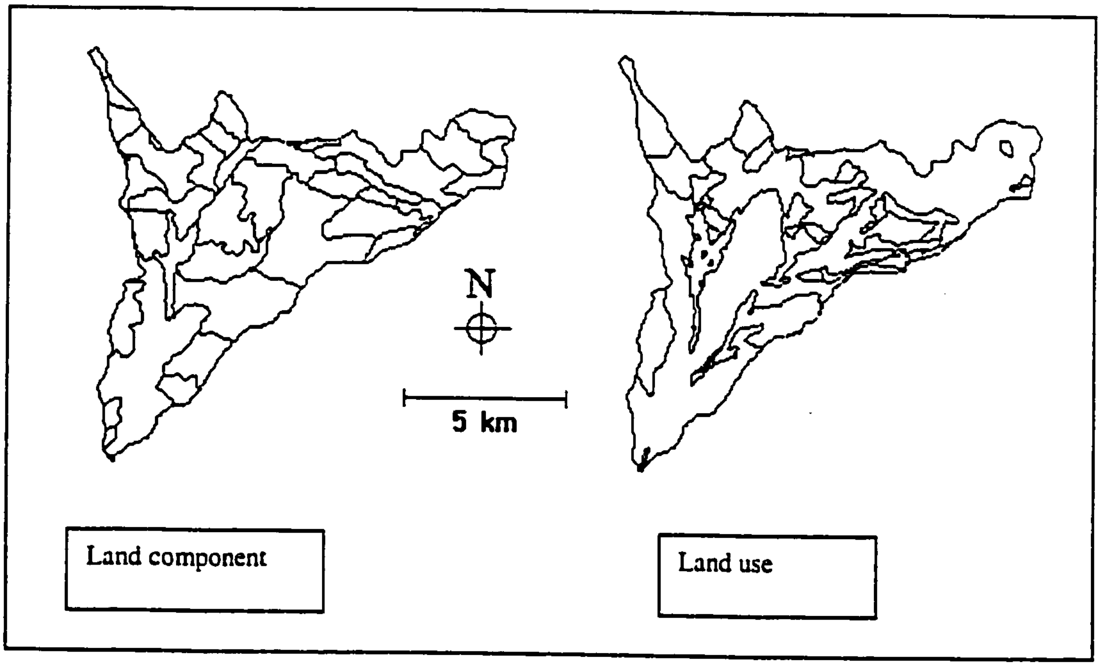

Figure 3.6 Digitized land-component and land-use maps of Syahrood

3.2.2 Development of digitized maps in SPANS-GIS

Exporting digitized files in SPANS-TYDIG successfully created appropriate "*.veh/.vec*" file pairs. These file pairs were imported into the study area, namely Syahrood, to create different data layers within the SPANS-GIS environment. Setting up a study area in SPANS requires the following steps:

1. Creating the study area: Identifying a directory that contains a complete set of files pertaining to a specific, geographic area. Imported "*.veh/.vec*" file pairs, all developing and modeling results will be stored in this directory.
2. Establishing the projection: A projection is a mathematical formula, which is used to reduce the amount of distortion appearing when the three-dimensional, curved surface of the earth is projected onto a flat, two-dimensional surface as a piece of paper or a computer screen. According to these formulas, the geographic coordinates of displaying data are adjusted. The Universal Transverse Mercator (UTM) projection was selected for Syahrood sub-basin.
3. Setting the extents of the study area: The extents define the physical limits (size, position, and rotation angle) of the region to be included in the study area.

Once the study area had been set up, all importing and developing operations were done in the same study area. Digitized arc-node polygons such as elevation, land-use, land-component, and hydrologic soil group were imported as line or vector data. While the attribute data assigned to the points digitized inside each polygon, were imported as point data. Also, digitized rain gauge locations and their attributes were imported as point data.

Developing a map in SPANS requires the following steps:

1. Importing the vector data: Geographical data must always be imported prior to importing and appending the attribute data.
2. Transforming the vector or line data into polygon or area data.
3. Transforming polygon data into a map or quadtree.
4. Importing the point data or attribute data.

Appending classes to points, reclassifications, and map annotations such as title, legend, scale, North arrow, and labels are additional map developing tools in SPANS-GIS. Figures 3.7 through 3.10 show developed maps as databases used for overlay operations in modeling soil erosion in a GIS environment. Slope and Thiessen polygon maps are two other spatial databases, which are to be created by existing databases within the SPANS environment. Therefore, the procedure for developing these two maps will be discussed in the Chapter 4.

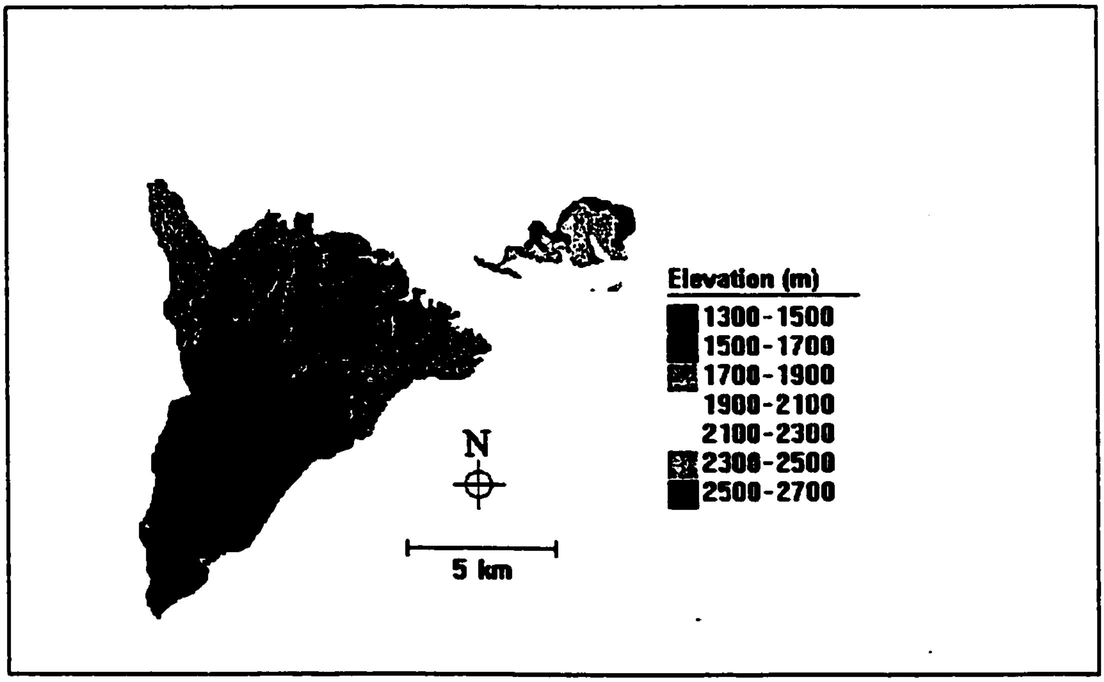

Figure 3.7: Elevation map of Syahrood sub-basin

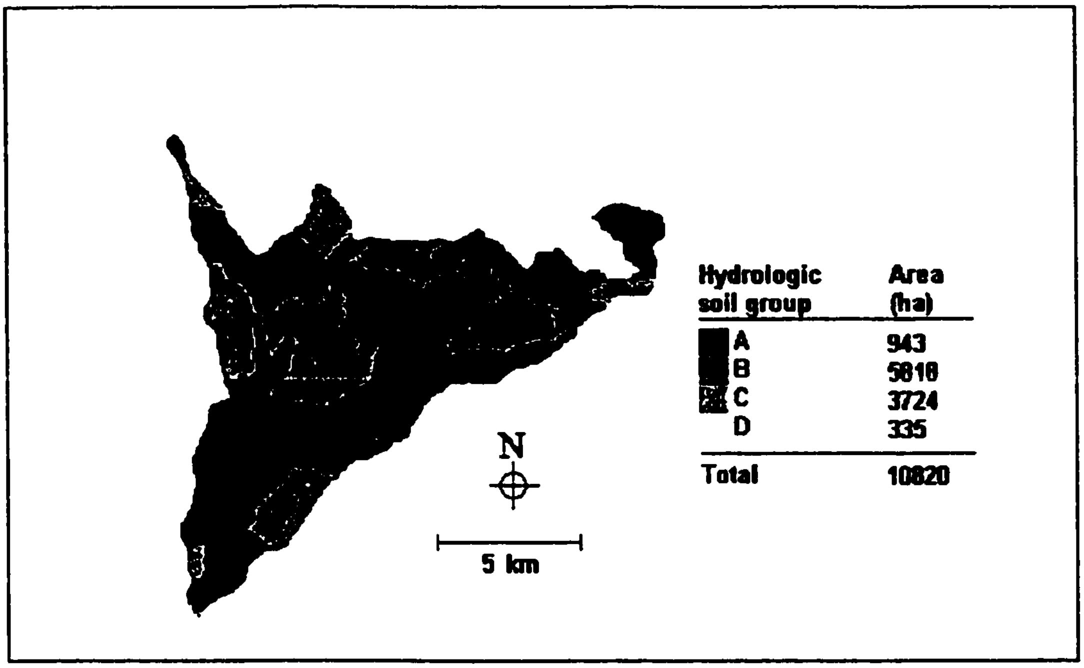

Figure 3.8 Hydrologic soil group map of Syahrood sub-basin. For the meaning of legend see "3.2 Development of database".

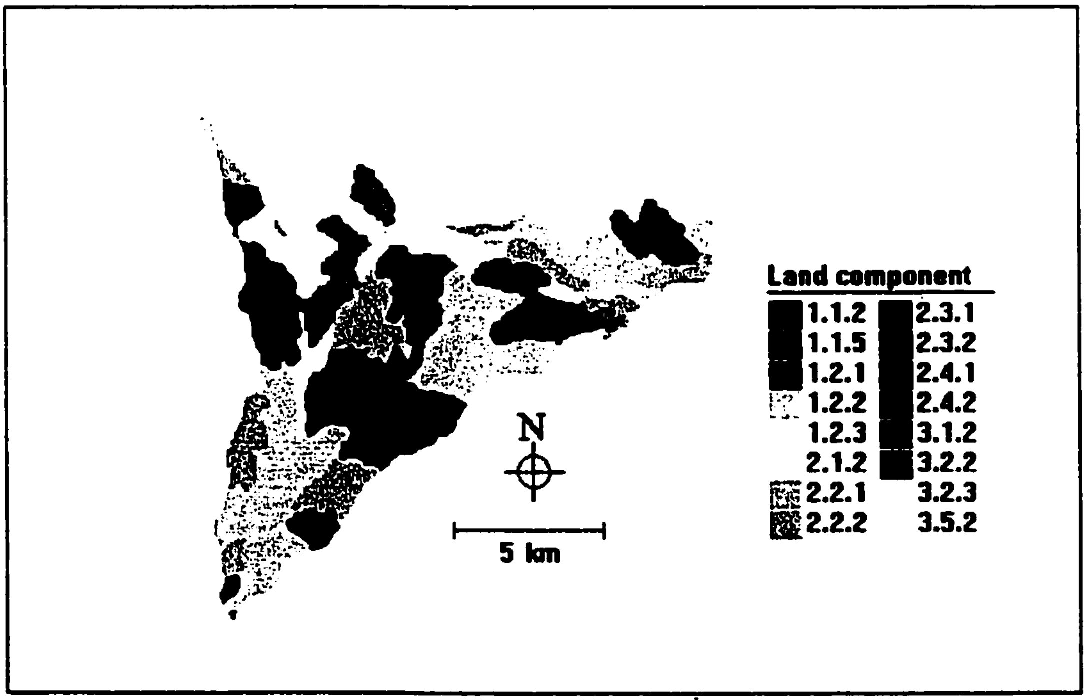

Figure 3.9 Land-component map of Syahrood sub-basin. For the meaning of legend see "3.2 Development of database".

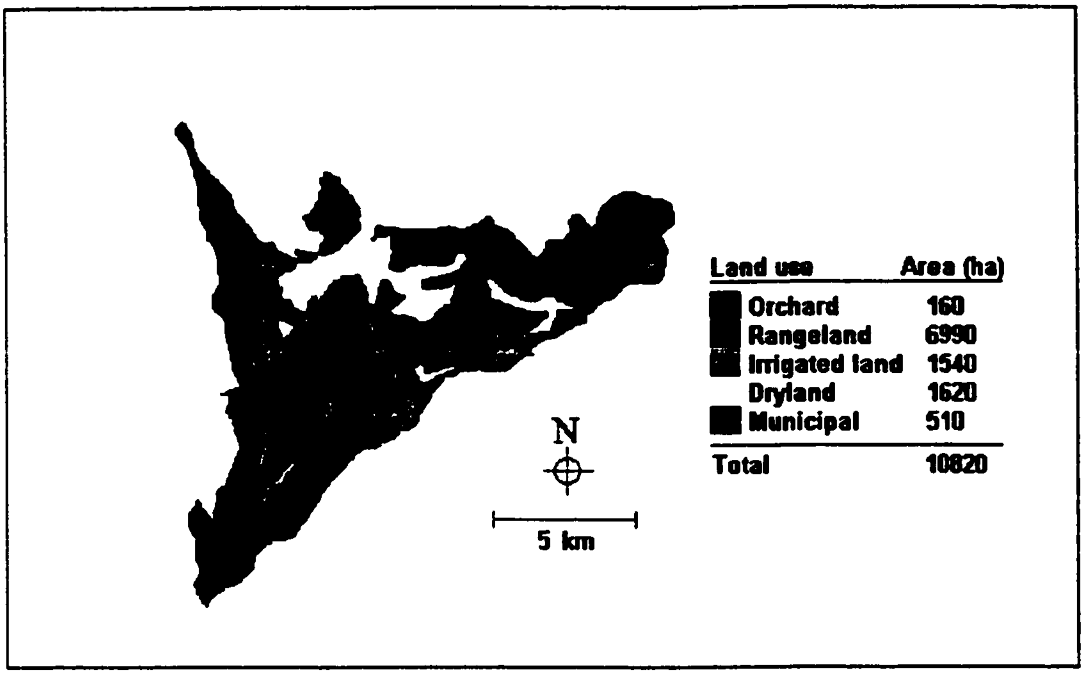

Figure 3.10 Land-use map of Syahrood sub-basin

CHAPTER 4

MODELING SOIL EROSION IN A GIS

The main objective of the study was to examine the effect of different land uses on the sediment yield rate. Two years of data on sediment yield were available for the area, which proved the usefulness of the sediment yield model. As was discussed in Chapter 2, MUSLE was chosen to interface with SPANS-GIS for spatial modeling of sediment yield in the semi-arid zone of Syahrood sub-basin. The selection of the model was based on its simplicity, and its independence from recording rain-gauge data. Equation (4.1a) shows that this model requires seven main variables to be assessed before and during modeling in a GIS environment.

$$S_y = 11.8(QV)^{0.56} KLSCP \tag{4.1a}$$

where

S_y=Sediment yield (t)

Q=The peak flow (m^3/s)

V=The volume of water (m^3) applied to the area

$$Q = 0.042DA / t_p \text{ with } t_p = c_t\left(L_w L_c\right)^{0.0792} \tag{4.1b}$$

$$V = \frac{(P_i - 0.2S_r)^2}{P_i + 0.8S_r} \text{ with } S_r = 25.4(\frac{1000}{CN} - 10) \tag{4.1c}$$

P_i=Daily rainfall (mm)

S_r=Retention parameter (mm)

CN =Runoff curve number depends on land use and management, hydrologic conditions, hydrologic soil group

DA =Drainage area (ha)

t_p =Time from the onset of excess rainfall to peak of the unit hydrograph (h)

c_t =Coefficient based on type of land (1.8-2.2)

L_w =Length of the watershed (m)

L_c =Distance from the outlet to the center of the watershed (m)

K =Soil erodibility factor $\left(\frac{\text{metric ton.hectare.hour}}{\text{hectare.megajoule.millimeter}}\right)$ or $\left(\frac{\text{t.ha.h}}{\text{ha.MJ.mm}}\right)$

L and S =Slope length and steepness (dimensionless).

C and P =Cropping system and supporting practices (dimensionless).

Figure 4.1 illustrates the concept of overlay operation in the GIS environment.

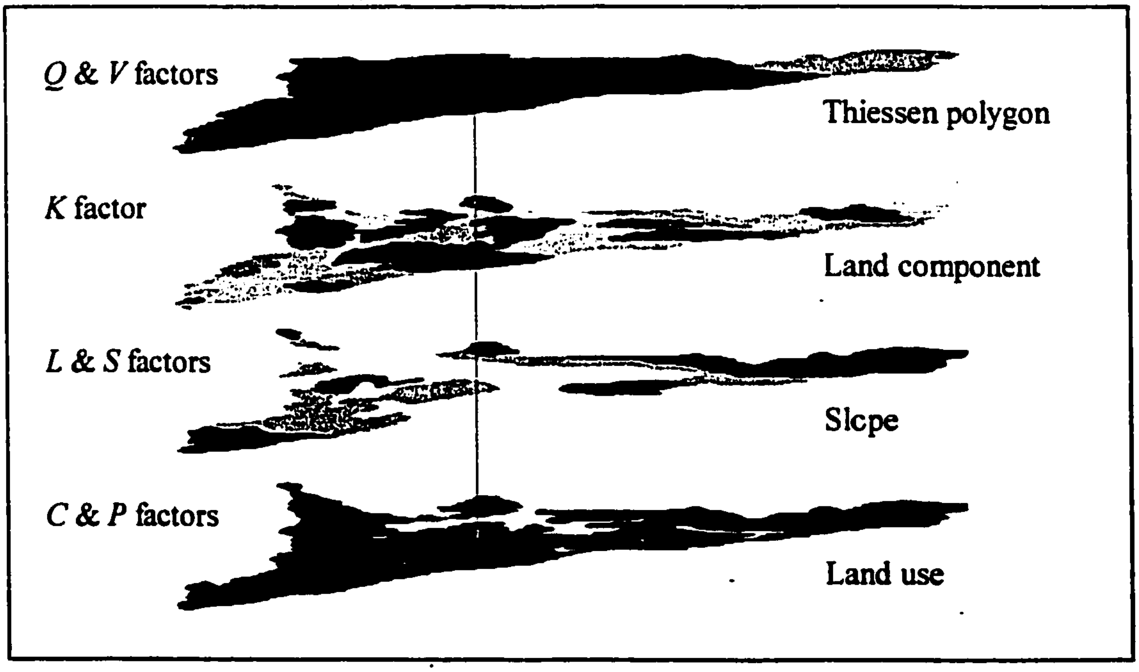

Figure 4.1 Overlay operation in the GIS environment

Sections 4.1 through 4.5 explain the procedure of computing *K, L, S, C,* and *P* factors in the MUSLE.

4.1 Soil erodibility factor *(K)*

Soil fractions[1] such as silt plus very fine sand, sand (except very fine portion), and organic matter as well as soil structure[2] and soil permeability[3] classes were extracted from the existing 26 soil profile data (NRCE, 1992). These data were used on the nomograph (Figure 4.2) of Wischmeier and Smith (1978) to compute *K* factors. Calculated *K* factors were assigned to related class of the land-component map (Figure 3.9). Table 4.1 presents the result of soil profile analysis as well as *K* factors for each land component.

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[1] USDA grain sizes (mm) for differentiating soil fractions.

Sand					Silt	Clay
Very coarse	Coarse	Medium	Fine	Very fine		

2 1 0.5 0.25 0.1 0.05 0.002 0.001

[2] USDA soil structure classes.

Code	Class
1	Very fine or very thin
2	Fine or thin
3	Medium
4	Coarse or thick
5	Very coarse or very thick

[3] USDA soil permeability classes.

Code	Class	Permeability (mm/h)
1	Very slow	1.524
2	Slow	1.524-5.08
3	Moderately slow	5.08-15.24
4	Moderate	15.24- 50.8
5	Moderately rapid	50.8- 152.4
6	Rapid	152.4- 508
7	Very rapid	> 508

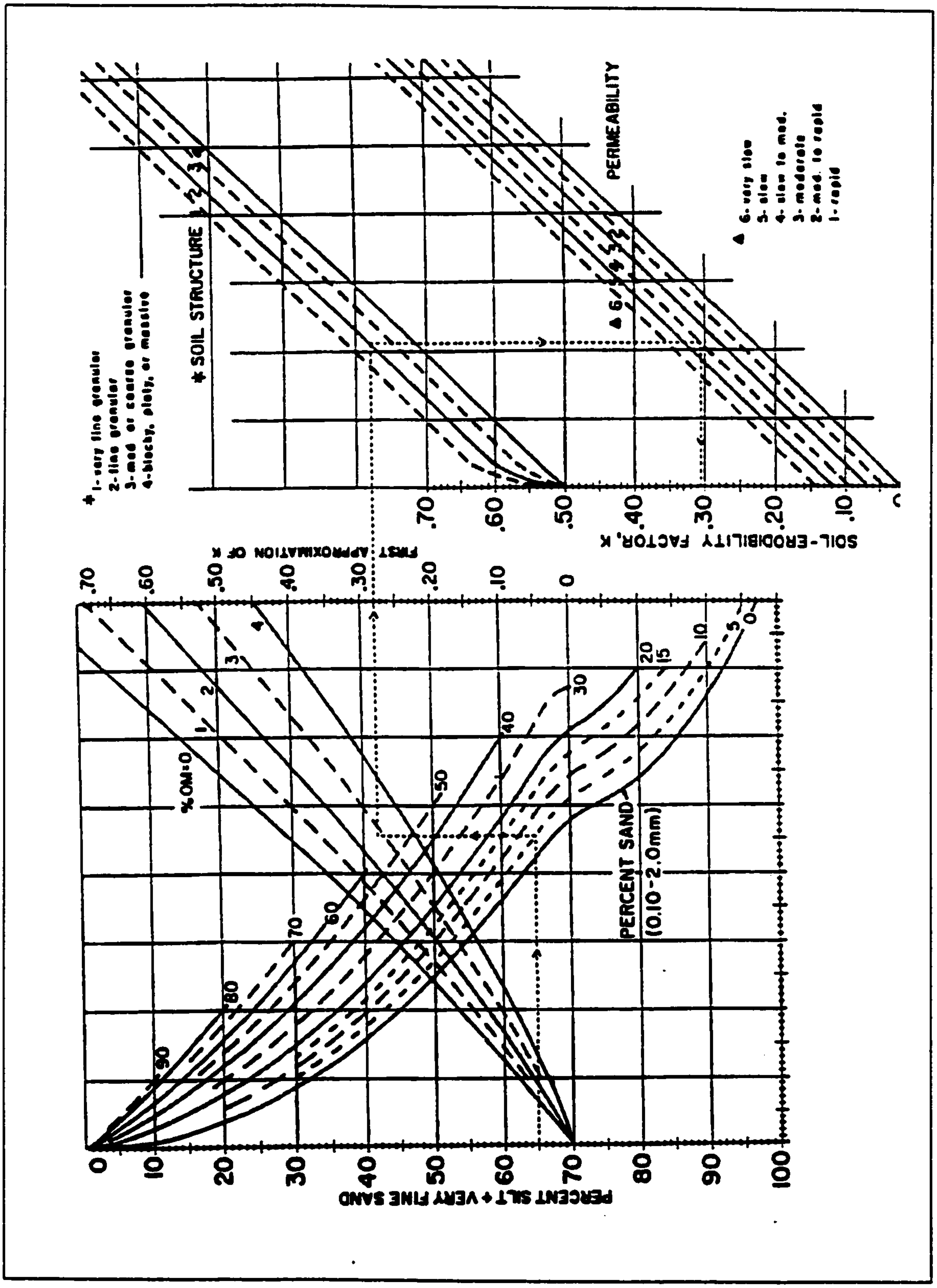

Figure 4.2 Nomograph of Wischmeier and Smith (1978)

Table 4.1 Soil fractions and K factors on each land component of Syahrood

Land component	Silt + very fine sand (%)	Sand (%)	Organic matter (%)	Structure code	Permeability code	K $(\frac{t.ha.h}{ha.MJ.mm})$
1.1.2	50	10	0.43	1	4	0.13
1.1.5	55	10	1.17	2	5	0.32
1.2.1	65	10	0.54	2	3	0.20
1.2.2	55	10	0.81	2	3	0.11
1.2.3	55	5	0.34	2	3	0.17
2.1.2	55	5	0.81	2	2	0.13
2.2.1	55	5	0.55	2	5	0.20
2.2.2	55	5	0.39	3	3	0.18
2.3.1	55	5	0.43	3	3	0.19
2.3.2	55	5	0.31	3	2	0.19
2.4.1	55	5	0.52	2	5	0.20
2.4.2	55	5	0.55	2	5	0.20
3.1.2	65	10	0.54	2	3	0.20
3.2.2	55	5	0.40	2	3	0.15
3.2.3	55	5	0.38	2	3	0.15
3.5.2	60	10	1.60	3	3	0.35

4.2 Slope length and steepness factors *(L and S)*

Computation of L and S factors required preparation of a slope map. SPANS was supposed to compute slope from the elevation map using equation (4.2) and a 3 x 3 neighborhood about each cell location (Burke, 1997).

$$\text{slope} = ((dz/dx/8 * \text{cell size})^2 + (dz/dy/8 * \text{cell size})^2)^{1/2} \tag{4.2}$$

where the cell size is determined by the quad level of the input map.

The templates used to compute x and y partial derivatives are:

dz/dx		
-1	0	1
-2	0	2
-1	0	1

dz/dy		
1	2	1
0	0	0
-1	−2	−1

By testing many points, it was found that this software was not able to produce an accurate slope map for mountainous areas neither from the elevation map nor directly from the digital elevation points. Therefore, a preliminary slope map for the entire area was computed by hand (NRCE, 1992) using equation (4.3) and then slopes were classified in groups of 5-10, 10-20, 20-40, 40-60, and >60 %. As can be noticed, there is no slope class of 0-5 percent in the study area.

$$S_A = (s_1 + s_2 + s_3 + s_4 + 4s_5)/8 \qquad (4.3)$$

where s_1, s_2, s_3, s_4, and s_5 are the slopes of the corners and center and S_A is the average slope of each 1 x 1 km grid on the elevation map. Figure 4.3 shows the computed slope map of the study area.

According to the slope classes and using equations (4.4) to (4.6) from Wischmeier and Smith (1978) the L factors were calculated (Table 4.2).

$$L = (\lambda / 22.128)^m \qquad (4.4)$$

$$m = \beta/(1+\beta) \qquad (4.5)$$

$$\beta = (\sin\theta / 0.0896)/\left[3.0(\sin\theta)^{0.8} + 0.56\right] \qquad (4.6)$$

where

λ =slope length (m)

θ =the angle of slope (degree).

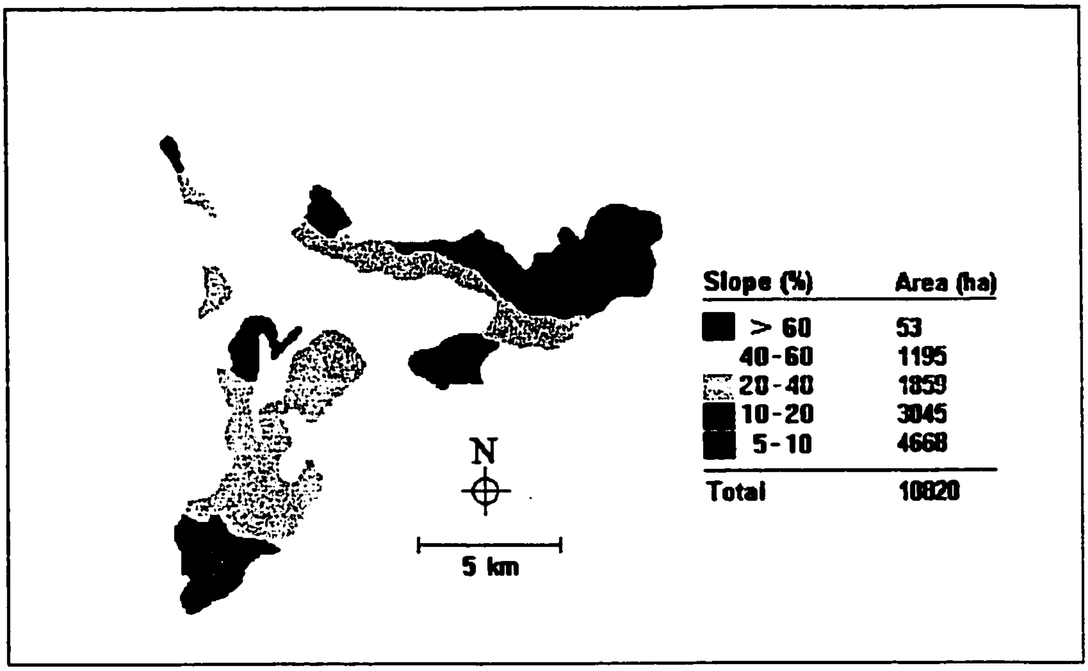

Figure 4.3 Slope map of Syahrood sub-basin

Table 4.2 *L* and *S* factors of each slope class in Syahrood sub-basin

Slope %	λ (m)	β	m	L	S	LS
5-10	61.0	0.8904	0.4710	1.6117	0.84	1.354
10-20	36.4	1.3643	0.5770	1.3364	1.99	2.659
20-40	18.2	1.9174	0.6572	0.8823	4.29	3.785
40-60	13.7	2.3306	0.6998	0.7155	6.96	4.980
>60	13.0	2.4719	0.7011	0.6887	8.14	5.606

For computing the slope length (λ) a few sample areas were randomly chosen on each class of slope map and measured on the field. The measurement started from the point of origin of overland flow to either the point where the slope gradient decreases to the extent that deposition begins or the point where runoff enters a channel. Using equations (4.7) and (4.8), the S factors were calculated according to the same procedure (Table 4.2).

$$S = 10.8\sin\theta + 0.03 \text{ for } \theta < 9 \text{ percent} \quad (4.7)$$

$$S = 16.8\sin\theta - 0.50 \text{ for } \theta \geq 9 \text{ percent} \quad (4.8)$$

Finally, resulting LS factors were assigned to appropriate slope classes on the slope map of Figure 4.3.

4.3 Cropping system factor (*C*)

The C factor is the ratio of soil loss from land cropped under specific conditions to the corresponding loss from clean-tilled, continuous fallow. This factor measures the combined effect of all the interrelated cover and management variables. The C factor was computed for each crop and crop stage and supporting practice information in each land use, using agricultural studies (NRCE, 1992) and Wischmeier and Smith (1978).

4.3.1 Cropping system factor (*C*) for rangelands

Field studies have indicated different canopy covers in rangelands of Damavand watershed (NRCE, 1992). The results of this study are presented in the first two columns of Table 4.3.

Using these data and Table 10 of Handbook 537 (Wischmeier and Smith, 1978), the C factors were calculated for each class of canopy cover and the results are given in the last column of Table 4.3. The weighted average of the C factor was calculated to be 0.0833 for the entire rangelands.

Table 4.3 C factor for rangelands in Syahrood sub-basin

% of rangeland (NRCE, 1992)	Canopy cover (%) (NRCE, 1992)	*C*
13.72	70-100	0.0780
28.29	40-70	0.0820
44.11	20-40	0.0840
13.88	<20	0.0890
Weighted average		0.0833

4.3.2 Cropping system factor (*C*) for croplands

The three main croplands in the Syahrood sub-basin are drylands, irrigated lands, and orchards. In the following sub-sections the *C* factor will be calculated for each kind of crop in each cropland.

The rainfall factor does not completely describe the effects of local differences in rainfall pattern on soil erosion. The erosion control effectiveness of a cropping system on a particular field depends, in part, on how the year's erosive rainfall is distributed among the six crop-stage periods of each crop included in the system. Therefore, expected monthly distribution of erosive rainfall (*EI*) at a particular location is an element in deriving the applicable value of cover and management factor (*C*).

Table 4.4 shows the cumulative percentage of the average annual *EI* that normally occurs between January 1st and indicated dates in existing rain gauges of Damavand watershed. This table is extracted from precipitation data of Damavand watershed, which will be discussed later in this chapter. In general, there are six different crop-stage periods for each kind of crop.

1. Period F (rough fallow), starts from inversion plowing to secondary tillage.

Table 4.4 Cumulative percentage of the average annual *EI* extracted from six rain gauges in Damavand watershed

Month		Ardineh	Cheshmeh	Khandan	Lavasan	Maara	Mamloo	Average
Jan.	1	5.6	4.0	4.9	4.3	6.2	5.1	5.0
	15	11.9	8.1	11.8	11.2	11.2	13.0	11.2
Feb.	1	19.1	13.2	20.5	19.8	19.2	21.0	18.8
	15	23.9	16.2	24.1	24.3	23.9	25.4	23.0
Mar.	1	33.2	20.7	32.1	28.9	31.6	33.2	30.0
	15	41.2	26.9	42.3	40.0	38.7	43.7	38.8
Apr.	1	46.6	31.4	47.6	45.0	43.4	49.2	43.9
	15	51.3	38.2	54.3	49.2	48.1	54.7	49.3
May	1	59.1	45.1	59.2	54.1	54.0	59.4	53.5
	15	63.6	49.1	62.7	57.7	57.8	61.1	58.7
Jun.	1	64.9	50.1	63.0	58.6	59.2	61.4	59.5
	15	65.2	50.2	63.0	58.7	59.2	61.6	59.7
Jul.	1	65.3	50.8	63.4	59.3	59.8	62.2	60.1
	15	67.5	53.7	64.4	61.5	61.9	63.0	62.0
Aug.	1	68.6	54.5	64.7	62.5	63.0	63.2	62.8
	15	68.8	58.3	66.2	65.1	63.6	63.9	64.3
Sep.	1	69.7	58.8	67.1	65.1	64.5	64.4	64.9
	15	69.8	59.0	67.2	65.3	64.7	64.4	65.1
Oct.	1	74.2	71.3	71.4	73.1	69.1	70.2	71.6
	15	77.4	76.9	75.5	76.2	74.4	74.0	75.7
Nov.	1	84.4	83.3	82.3	81.6	80.4	80.4	82.1
	15	90.3	86.9	89.1	86.3	87.6	86.4	88.1
Dec.	1	94.2	94.2	94.4	92.9	92.1	93.6	93.6
	15	100	100	100	100	100	100	100

2. Period SB (seedbed), secondary tillage for seedbed preparation until the crop has developed 10 % of canopy cover.
3. Period 1 (establishment), starts from the end of SB until crop has developed 50 % of canopy cover.
4. Period 2 (development), starts from the end of Period 1 until canopy cover reaches 75 %.
5. Period 3 (maturing crop), the time from the end of Period 2 until the crop is harvested.
6. Period 4 (residue or stubble), covers the time period of harvesting to plowing or new seeding.

4.3.2.1 Cropping system factor (*C*) for drylands

There are 1620 ha of drylands in Syahrood sub-basin with 810 ha under fallow every year. Small grains (wheat and barley), alfalfa, and pea are the most commonly planted crops, which are planted on 758, 37, and 15 ha, respectively. Small grains that cover 46.7 % of drylands and need 270 days to mature are rotationally planted with alfalfa. Table 4.5 shows the calculation of the C factor for areas covered by alfalfa and small grains. Agricultural information about cultivation of the different crops was obtained from NRCE, (1992) and illustrated in table format. Setting up this table is as follow:

Column 1. Chronological sequence of all the land-cover changes that begin a new cropstage period.

Column 2. List of the datės on which each cropstage period begins.

Column 3. The cumulative percentage of *EI* for each date from Table 4.4. The *EI* percentage of the dates not available in this table was obtained by interpolating between available dates.

Table 4.5 *C* factor for drylands (alfalfa and small grains) in Syahrood sub-basin

(1) Event	(2) Date	(3) Cumulative percentage *EI*	(4) Crop-stage period	(5) *EI* in period	(6) Soil loss ratio	(7) Crop-stage *C* value
Plowing	Sep. 23	68.6	F	0.765	0.68	0.520
Planting (alfalfa)	Apr. 4	45.1	SB	0.055	0.70	0.039
10% canopy cover	Apr. 20	50.6	1	0.083	0.55	0.046
50% canopy cover	May 20	58.9	2	0.01	0.43	0.004
75% canopy cover	Jun. 22	59.9	3	0.852	0.11	0.094
Plowing	Apr. 4	45.1	F	0.235	0.68	0.160
Planting (small grains)	Sep. 23	68.6	SB	0.053	0.70	0.037
10% canopy cover	Oct. 9	73.9	1	0.116	0.55	0.064
50% canopy cover	Nov. 9	85.5	2	0.654	0.43	0.281
75% canopy cover	Apr. 21	50.9	3	0.09	0.11	0.009
Harvest	Jun. 22	59.9	4	0.087	0.34	0.029
Plowing	Sep. 23	68.6	F	-	-	-
Sum of 3 years						1.283
Yearly average						0.428

Column 4. The cropstage periods.

Column 5. *EI* in period. These values are obtained by subtracting the number in Column 3 from the number in the next lower line in Column 3. If the cropstage period includes a year-end, the value in Column 3 is first subtracted from 100 and then added to the number in the next lower line. The *EI* in period values are presented as ratios by dividing them by 100.

Column 6. Soil loss ratios is the ratios of soil losses from the cropped plots to corresponding losses from continuous fallow. This ratios were computed for each crop-stage period, for each particular crop, in various combinations of crop sequence and productivity level and gathered in Table 5 of Handbook 537 (Wischmeier and Smith, 1978).

Column 7. The product of values in Columns 5 and 6. The sum of these products is the value of *C* for the entire event period. Because *C* is usually desired as an average annual value, this sum is divided by the number of years in the event periods. Table 4.6 presents the same calculations for pea.

Table 4.6 *C* factor for drylands (pea) in Syahrood sub-basin

Event	Date	Cumulative percentage *EI*	Crop-stage period	*EI* in period	Soil loss ratio	Crop-stage *C* value
Plowing	Oct. 13	78.7	F	0.803	0.68	0.546
Planting	May 22	59.0	SB	0.006	0.70	0.004
10% canopy cover	Jun. 7	59.6	1	0.013	0.55	0.007
50% canopy cover	Jul. 7	60.9	2	0.025	0.43	0.011
75% canopy cover	Aug. 7	63.4	3	0.052	0.11	0.006
Harvest	Sep. 23	68.6	4	0.101	0.34	0.034
Plowing	Oct. 23	78.7	F	-	-	-
Sum						0.608

The calculated C factors for alfalfa and small grains, pea, and fallow are 0.428, 0.608, and 0.50, respectively. By weighting the areas planted to each crop, the average C factor for drylands is 0.47.

4.3.2.2 Cropping system factor (C) for irrigated lands

There are 1540 ha of irrigated croplands in Syahrood sub-basin of which 460 ha are under fallow every year, 581 ha are in small grains (wheat and barely), 225 ha in alfalfa and other forages, 168 ha in potato and vegetables, and 106 ha in legumes (pea and bean). Using the same procedure explained for drylands, Tables 4.7 through 4.10 show the calculations of the C factor for different crops. Weighting for the areas planted to each crop, the average C factor for irrigated lands is 0.26.

Table 4.7 C factor for irrigated lands (small grains) in Syahrood sub-basin

Event	Date	Cumulative percentage *EI*	Crop-stage period	*EI* in period	Soil loss ratio	Crop-stage *C* value
Plowing	Aug. 23	64.6	F	0.040	0.25	0.010
Planting	Sep. 23	68.6	SB	0.053	0.20	0.011
10% canopy cover	Oct. 9	73.9	1	0.116	0.16	0.019
50% canopy cover	Nov. 9	85.5	2	0.654	0.12	0.078
75% canopy cover	Apr. 21	50.9	3	0.090	0.05	0.005
Harvest	Jun. 22	59.9	4	0.047	0.15	0.007
Plowing	Aug. 23	64.6	F	-	-	-
Sum						0.130

Table 4.8 *C* factor for irrigated lands (grains) in Syahrood sub-basin

Event	Date	Cumulative percentage *EI*	Crop-stage period	*EI* in period	Soil loss ratio	Crop-stage *C* value
Plowing	Sep. 23	68.6	F	0.904	0.25	0.226
Planting	May. 22	59.0	SB	0.006	0.20	0.001
10% canopy cover	Jun. 7	59.6	1	0.013	0.16	0.002
50% canopy cover	Jul. 7	60.9	2	0.025	0.12	0.003
75% canopy cover	Aug. 7	63.4	3	0.052	0.05	0.003
Harvest	Sep. 23	68.6	4	0.000	0.15	0.000
Plowing	Sep. 23	68.6	F	-	-	-
Sum						0.235

Table 4.9 *C* factor for irrigated lands (alfalfa) in Syahrood sub-basin

Event	Date	Cumulative percentage *EI*	Crop-stage period	*EI* in period	Soil loss ratio	Crop-stage *C* value
Plowing	Aug. 23	64.6	F	0.040	0.25	0.010
Planting	Sep. 23	68.6	SB	0.053	0.20	0.011
10% canopy cover	Oct. 9	73.9	1	0.116	0.16	0.019
50% canopy cover	Nov. 9	85.5	2	0.654	0.12	0.078
75% canopy cover	Apr. 21	50.9	3	0.090	0.05 (3 yr)	0.005
Harvest (first)	Jun. 22	59.9	4	2 (3 yr)		0.100 (3 yr)
Plowing	Aug. 23 (after 4 yr)	64.6	F			
Sum						0.130

Table 4.10 C factor for irrigated lands (potato and vegetable) in Syahrood sub-basin

Event	Date	Cumulative percentage *EI*	Crop-stage period	*EI* in period	Soil loss ratio	Crop-stage C value
Plowing	Sep. 23	68.6	F	0.864	0.25	0.216
Planting	May 5	55.0	SB	0.040	0.20	0.008
10% canopy cover	May 21	59.0	1	0.009	0.16	0.001
50% canopy cover	Jun. 21	59.9	2	0.046	0.12	0.006
75% canopy cover	Aug. 21	64.5	3	0.197	0.05	0.009
Harvest	Nov. 6	84.2	4	0.844	0.15	0.127
Plowing	Sep. 23	68.6	F	-	-	-
Sum						0.367

4.3.2.3 Cropping system factor (*C*) for orchards

There are 160 ha of orchards in Syahrood sub-basin. Using agricultural studies (NRCE, 1992) and Table 12 of Handbook 537 (Wischmeier and Smith, 1978) with fair soil condition, no live ground vegetation, and 40% mulch cover, the C factor for orchards is 0.17.

4.4 Supporting practices factor (*P*)

The P factor is the ratio of soil loss with a specific support practice to the corresponding loss with up-and down-slope culture. The P factor was computed for each supporting practice information in each land use, using agricultural studies (NRCE, 1992) and Wischmeier and Smith (1978). In the study area irrigated lands and orchards are terraced and contoured by farmers. These kinds of supporting practices are used partially in drylands and rangelands. Due to heavy grazing on the rangelands, narrow terraces built by animal movement are plainly visible. Therefore, using Tables 13 and 15 of Handbook 537 (Wischmeier and Smith, 1978), the P factors were calculated for orchards, rangelands, irrigated lands, and drylands (Table 4.11). This table summarizes C, P, and consequently CP factors for each land use.

Table 4.11 *CP* factors for each land use in Syahrood sub-basin

Land use	C	P	CP
Orchard	0.17	0.50	0.085
Rangeland	0.08	0.60	0.048
Irrigated land	0.26	0.50	0.130
Dryland	0.47	0.70	0.329

4.5 Computing runoff peak flow (Q)

Calculation of time from the onset of excess rainfall to peak of the unit hydrograph, t_p, in Snyder's method (equation 4.1b) is necessary for computing Q. For this purpose Handbook 537 (Wischmeier and Smith, 1978) is used to determine the coefficient based on type of land, c_t, for each slope class. Table 4.12 shows the amount of c_t for each slope class as well as its weighted average for Syahrood sub-basin.

The length of the watershed, L_w, and the distance from the outlet to the center of the watershed, L_c, were measured on Syahrood sub-basin by tracing the main river and streams on the 1:50 000 topographic map of the area. Table 4.13 shows the procedure for calculating runoff peak flow (Q) for the Syahrood sub-basin by Snyder's method (equation 4.1b).

Table 4.12 c_t for each slope class of Syahrood sub-basin

Slope (%)	5-10	10-20	20-40	40-60	>60
Area (ha)	4668	3045	1859	1195	53
c_t	2.14	2.08	2.00	1.92	1.80
Weighted average c_t	2.07				

Table 4.13 Computing Q for Syahrood sub-basin

Area (ha)	c_t	L_w (m)	L_c (m)	t_p (h)	Q (m^3/s)
10820	2.07	16016	12109	9.39	48.43

4.6 Computing the volume of runoff water (V) applied to each polygon

Distribution of precipitation data due to distribution of rain gauge stations in any watershed obliges consideration of the zones affected by each rain gauge. For this reason it is necessary to compute V factor for such influenced areas.

A Thiessen polygon, also known as a Voronoi diagram, defines an area about a point (rain gauge station) such that all locations within that area are closer to that point than to any other point. SPANS-GIS can analyze the point location of such rain gauges and produce the Thiessen polygon map. The point attribute data of Figure 3.2 was used to produce Thiessen polygon map for Damavand watershed (Figure 4.4). For soil erosion modeling there was no need to use other sub-basins of Damavand watershed except Syahrood. Figure 4.5 presents the Thiessen polygon map of Syahrood sub-basin.

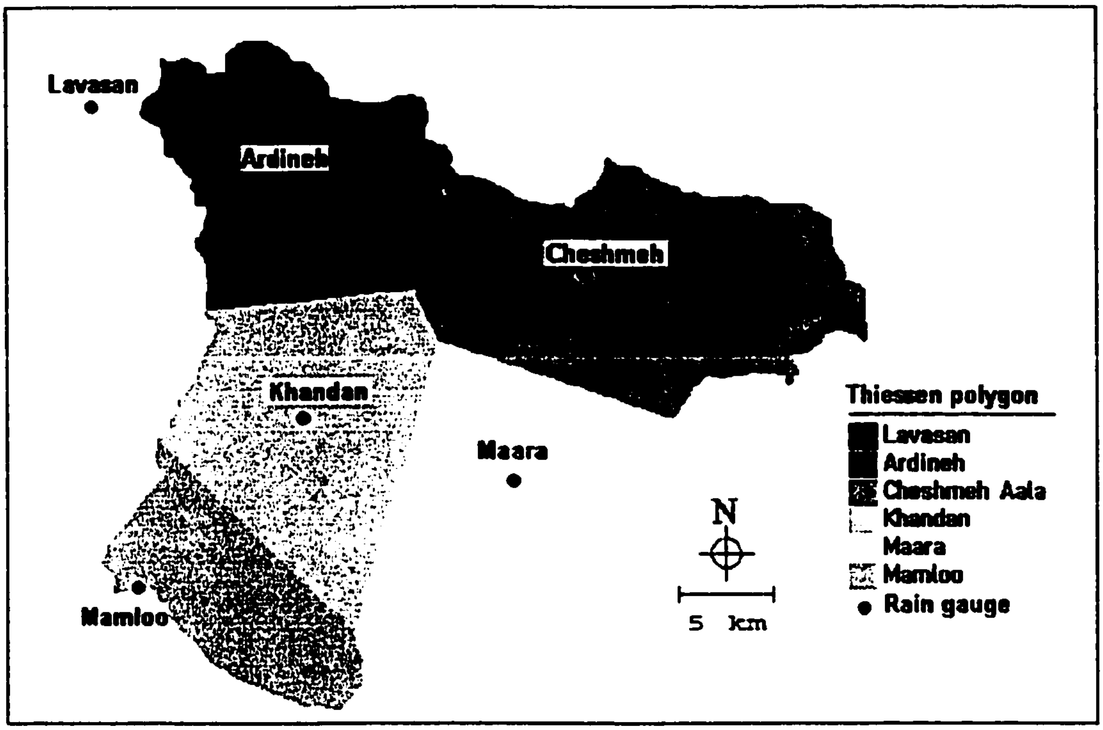

Figure 4.4 Thiessen polygon map of Damavand watershed

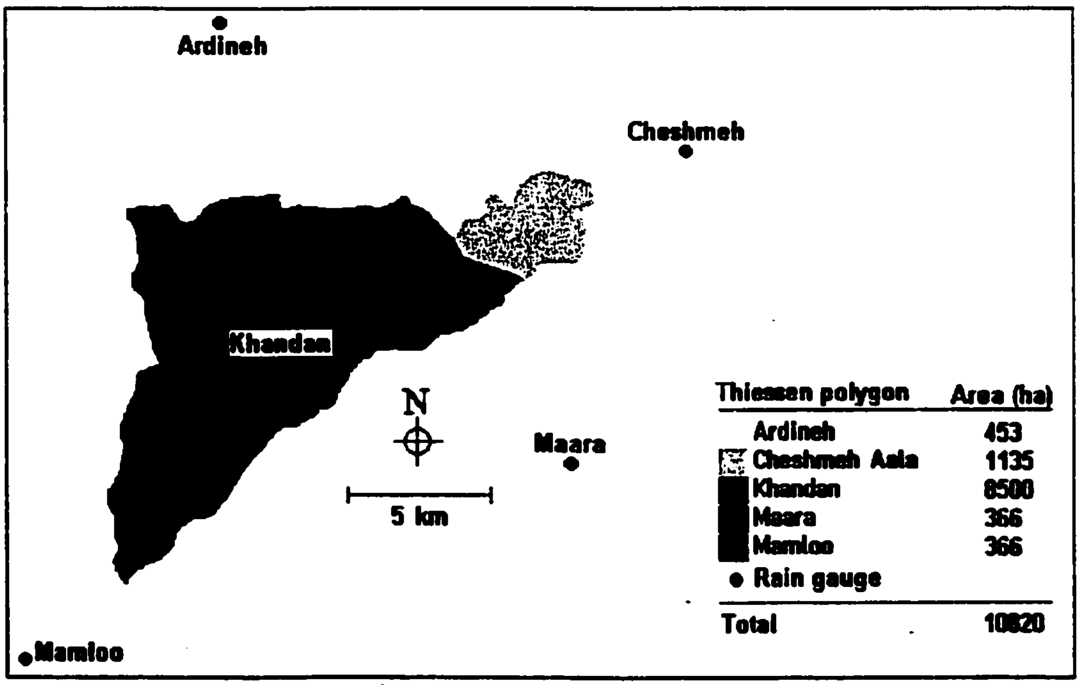

Figure 4.5 Thiessen polygon map of Syahrood sub-basin

Before computation of the volume of runoff water (V) applied to each Thiessen polygon area, the consistency of precipitation data for all rain gauge stations was tested. In double-mass analysis method, the accumulated annual precipitation record at a given station is compared with that of the accumulated annual precipitation mean values of other nearby stations. When a change greater than 10% in the slope of the relationship occurs, it indicates that the gauge was moved or some other occurrence caused the gauge to receive a different amount of precipitation. In this case it is necessary to adjust the record by the ratio of the slope to make the record consistent (Singh, 1992).

Figures 4.6.a through 4.6.f show no significant change in the slope of the regression lines. Based on these tests, the precipitation data of all stations are acceptable.

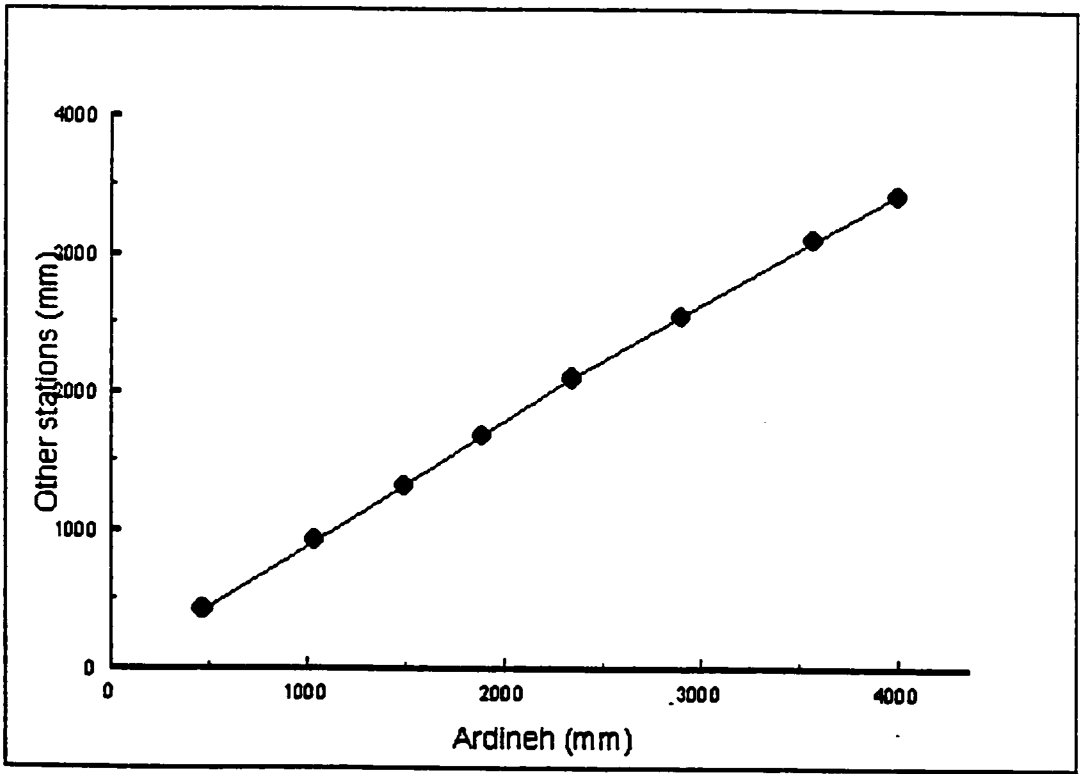

Figure 4.6.a Consistency analysis of Ardineh station

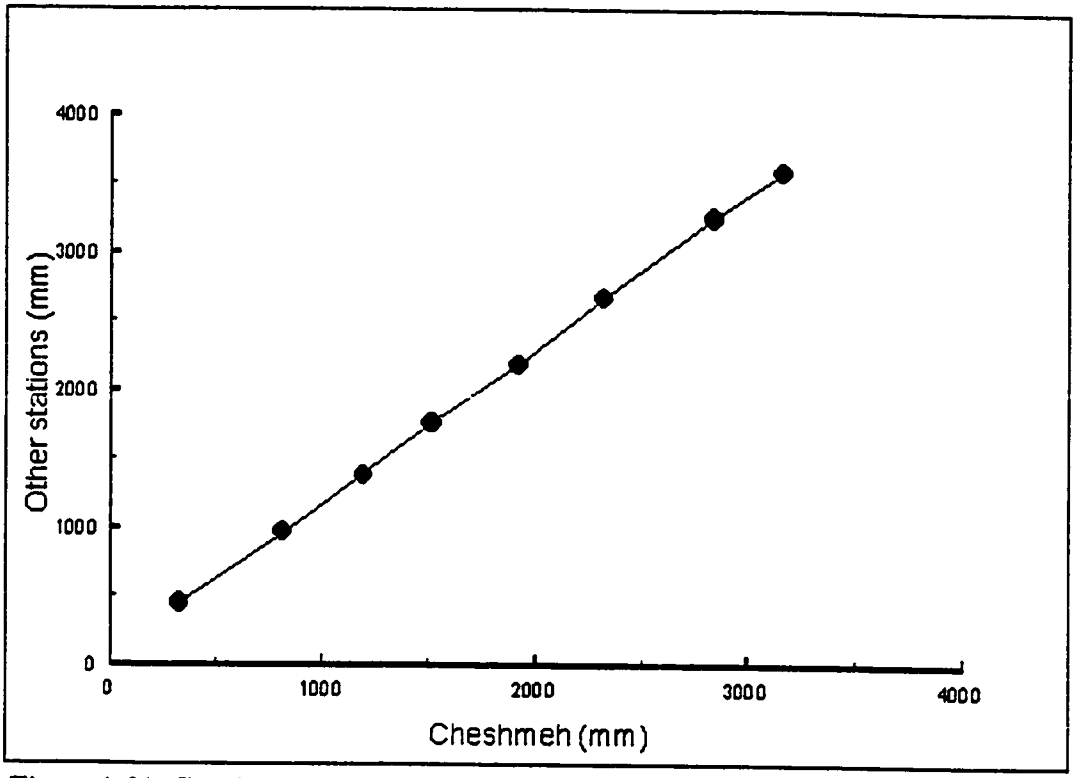

Figure 4.6.b Consistency analysis of Cheshmeh station

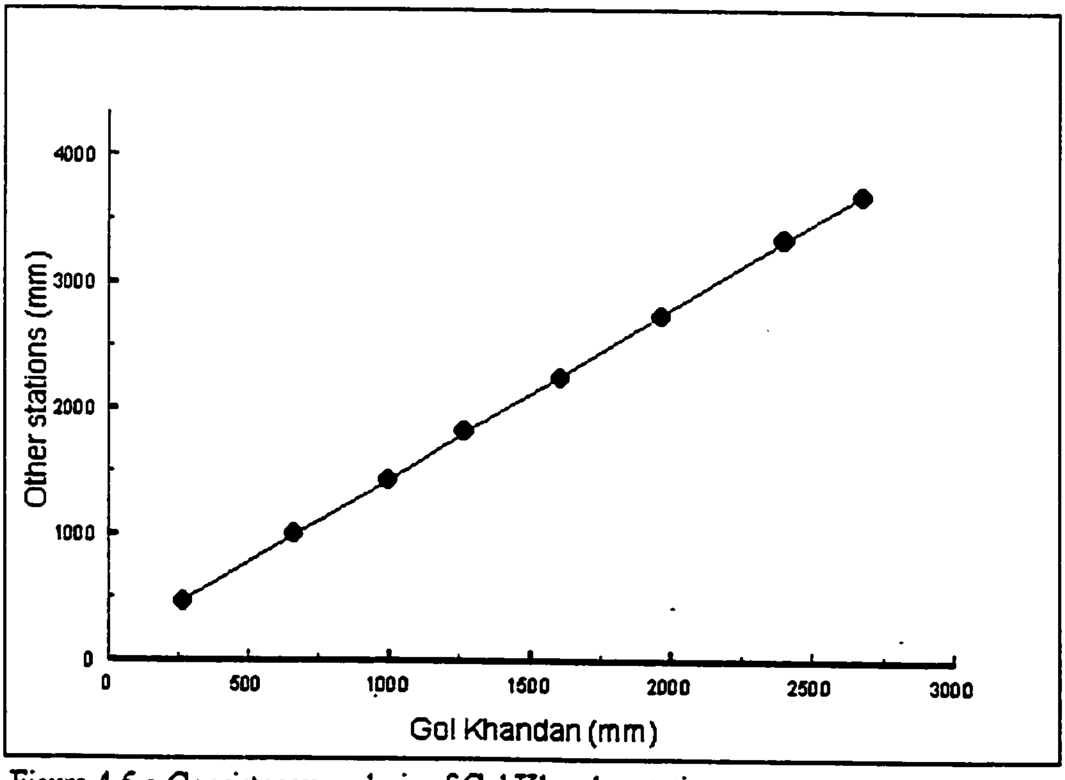

Figure 4.6.c Consistency analysis of Gol Khandan station

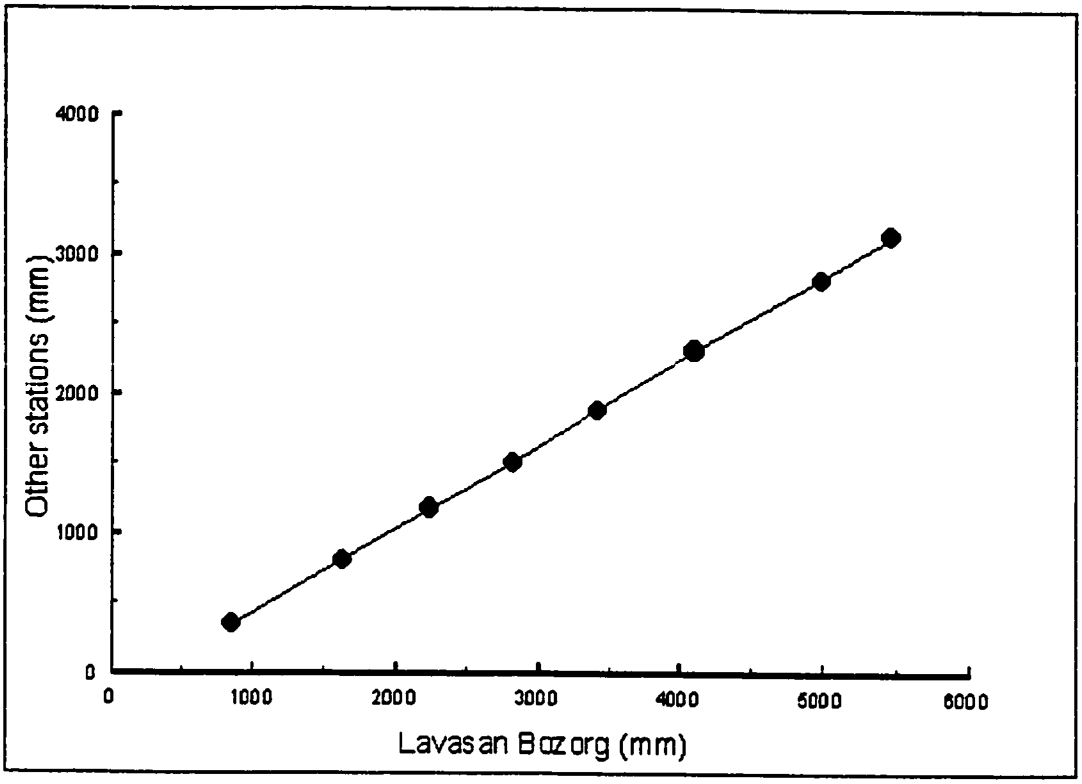

Figure 4.6.d Consistency analysis of Lavasan Bozorg station

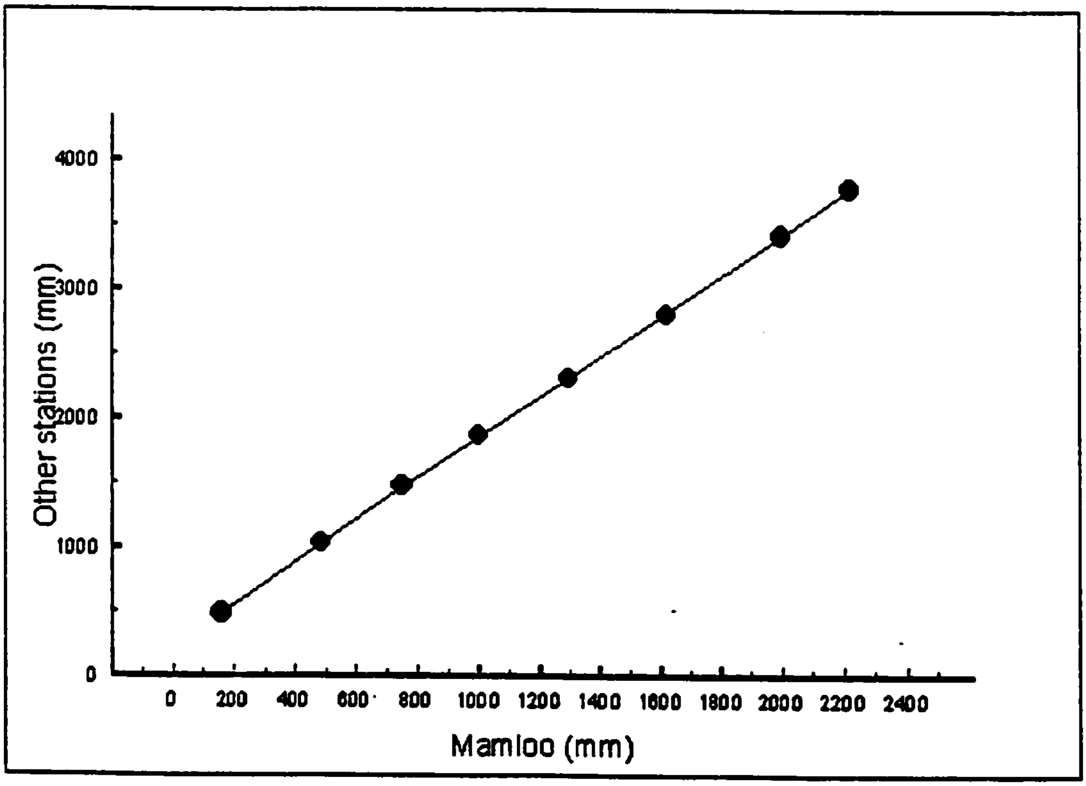

Figure 4.6.e Consistency analysis of Mamloo station

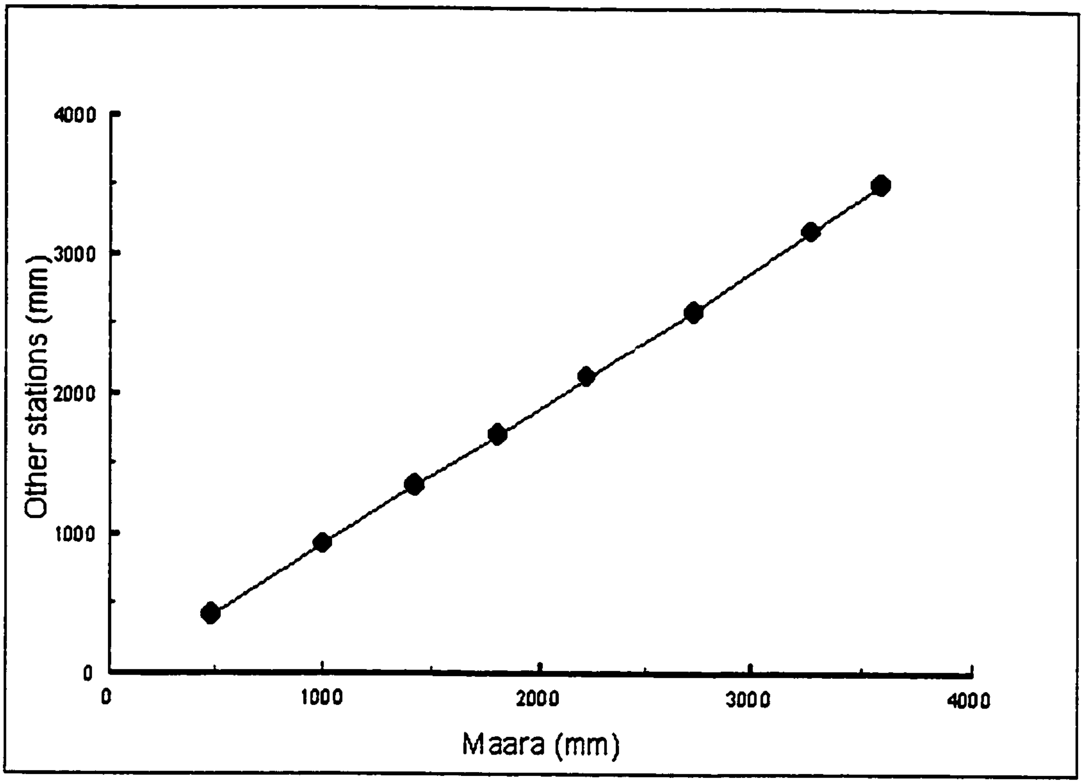

Figure 4.6.f Consistency analysis of Maara station

Computation of the volume of runoff water (V) applied to each Thiessen polygon area requires the following steps:

1. Calculation of the retention parameter (S_r) in each Thiessen polygon area: First, hydrologic soil group and land-use maps were overlaid and using equation (4.1c), S_r is calculated for each combination of the above overlay results (Table 4.14). In this table, Curve Numbers (CN) are calculated based on the cropland condition from the CN table of SCS (Singh,1992). Second, the Thiessen polygon map is overlaid with the result of the last overlay (hydrologic soil group and land-use). The results are given in Table 4.15 showing S_r for each Thiessen polygon.

Table 4.14 S_r for each combination of land-use and hydrologic soil group

Land-use and hydrologic soil group	Area (ha)	*CN*	S_r (mm)
Rangeland-A	147	62	156
Irrigated land-A	348	65	137
Dryland-A	223	72	99
Municipal-A	225	59	177
Orchard-B	140	66	131
Rangeland-B	3694	76	80
Irrigated land-B	865	76	80
Dryland-B	1017	81	60
Municipal-B	102	74	89
Orchard-C	20	77	76
Rangeland-C	2823	84	48
Irrigated land-C	323	84	48
Dryland-C	384	88	35
Municipal-C	173	82	56
Rangeland-D	330	87	38
Irrigated land-D	1	88	35
Municipal-D	5	86	41
Total	10820	-	-

Table 4.15 S_r for each Thiessen polygon area in Syahrood sub-basin

Thiessen polygon	S_r (mm)
Ardineh	58.89
Cheshmeh	72.77
Khandan	73.15
Maara	69.46
Mamloo	50.22

2. Computing V for each rainfall event: Neglecting precipitation less than $0.2S_r$ in the record to avoid negative values of $P_t - 0.2S_r$ in equation (4.1c), the amount of V for each rainfall event and in each Thiessen polygon is calculated and stored.

3. Finally, the results are multiplied by the related Q factors in Table 4.13 and then raised to the power 0.56.

4.7 Computing sediment yield

1. Overlaying land-use and slope maps: To compute the $LS.CP$ products land-use and slope maps are overlaid. Figure 4.7 and Table 4.16 present the results of this overlaying.

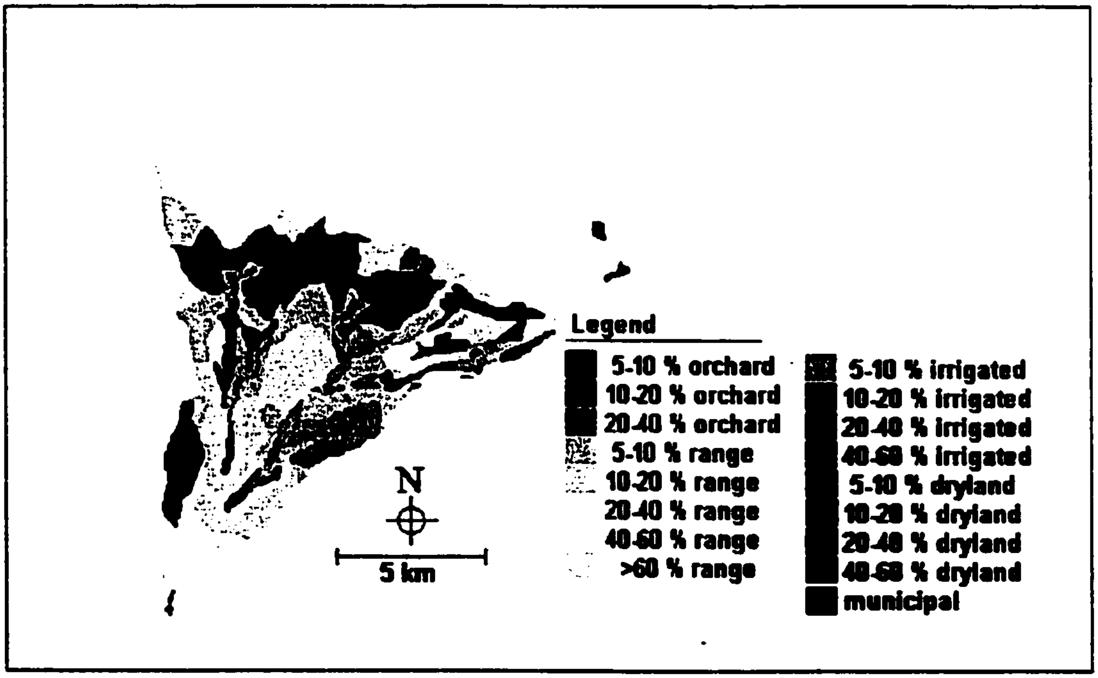

Figure 4.7 Overlaid land-use and slope maps of Syahrood sub-basin

Table 4.16 *LS.CP* for each land use in Syahrood sub-basin

Land use	*CP*	Slope classes (%)					Total land use area (ha)	Weighted *LS.CP*
		5-10	10-20	20-40	40-60	>60		
		LS						
		1.35	2.66	3.78	4.98	5.61		
		Area (ha)						
Orchard	0.08	134	1	25	-	-	160	0.323
Rangeland	0.05	1810	2391	1557	1179	53	6990	0.589
Irrigated	0.13	1143	178	214	5	-	1540	0.334
Dryland	0.33	1254	323	33	10	-	1620	0.737
Total							10820	-

2. Overlaying land-use and land-component maps: To compute the *K.LS.CP* combination, the land-use map with new values of *LS.CP* is overlaid on the land-component map with 16 classes. The result is presented in Table 4.17.

Table 4.17 *K.LS.CP* for each land use of Syahrood sub-basin

Land use	*K.LS.CP*
Orchard	0.01991
Rangeland	0.0231
Irrigated land	0.0493
Dryland	0.1041

3. Computing the amount of sediment yield in each land use: As was noted in Figure 3.2, the locations of eight rain gauge stations are distributed uniformly in the area. Therefore, to compute the amount of sediment yield in each land use, Thiessen polygon and land-use maps are overlaid. In this overlaying, the result of part 3 in Section 4.6 is multiplied by a constant (11.8) and by the appropriate value of *K.LS.CP* in Table 4.17. Figure 4.8 presents the amount of sediment yield in each land use.

The average sediment yield based on the model was 4.75 t/ha.y over the entire Syahrood sub-basin. The higher sediment yields are in the drylands, which are usually found on steep slopes and are cultivated in rows parallel to the slope direction. This causes higher concentration of runoff that removes soil particles.

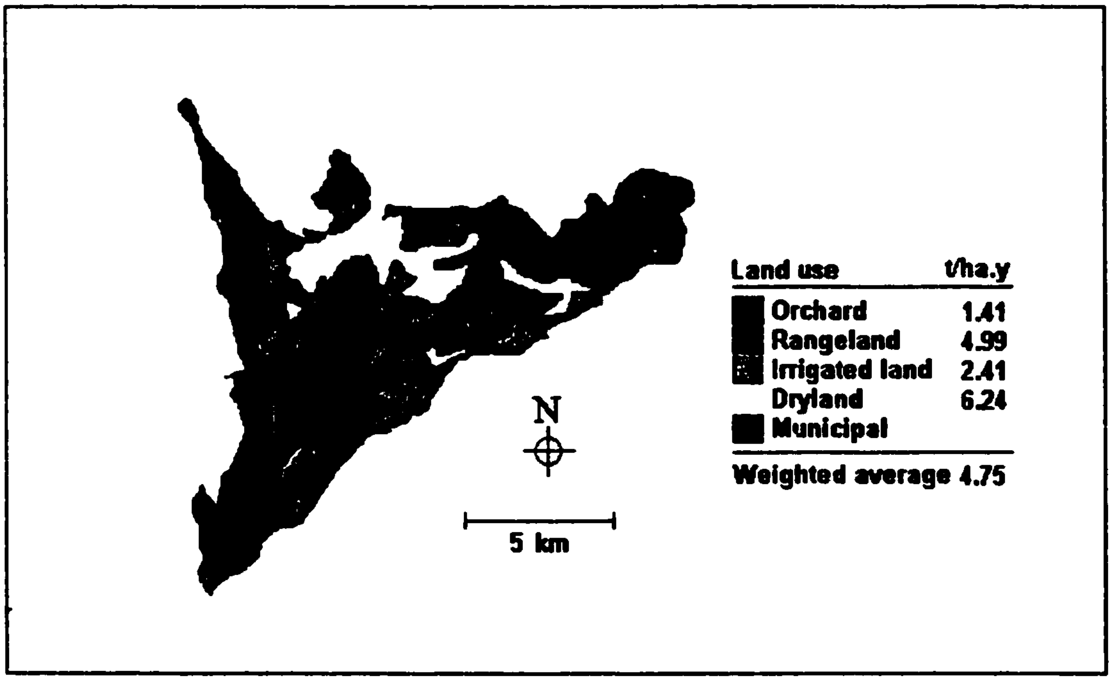

Figure 4.8 Sediment yield in each land use of Syahrood sub-basin

CHAPTER 5

OPTIMIZING THE MANAGEMENT OF SOIL EROSION

The second important objective of the study was to optimize the management of soil erosion. In other words, minimize the sediment yield and maximize the farm income in the watershed.

5.1 Formulation of the problem

As was described in Chapter 2, based on linearity of objective functions in the study area problem, multi-objective linear programming is chosen. Also, the simplex method does not depend on the conversion of a multi-objective optimization into a single-objective one. Therefore, this method was chosen to solve the multi-objective linear programming problem of the Syahrood sub-basin.

The general multi-objective optimization problem with n decision variables, m constraints and p objectives is as given in equation (2.5a) through (2.5c). Using these equations, the general form of the existing problem in Syahrood sub-basin can be written as:

$$Max(Z_1) = \sum_{i=1}^{n}[(A_i^1 - (A_i^2 + A_i^3))X_i] \qquad (5.1a)$$

$$Min(Z_2) = \sum_{i=1}^{n} C_i X_i \qquad (5.1b)$$

Subject to:

$$\sum_{i=1}^{n} X_i = B \tag{5.1c}$$

$$X_i \geq 0 \tag{5.1d}$$

where

Z_1 = Annual net farm income of whole watershed (10^6 Rial/y)

Z_2 = Annual sediment yield of whole watershed (t/y)

X_i = Surface area of each land use (ha)

C_i = Annual sediment yield per unit area in each land use (t/ha.y)

A_i^1 = Amount of net farm income per unit area of each land use (10^6 Rial/ha)

A_i^2 = Production cost per unit area of each land use (10^6 Rial/ha)

A_i^3 = Cost due to soil loss per unit area of each land use (10^6 Rial/ha)

B = Total land area (ha)

The problem can be written in detail in the following form:

$$Max(Z_1) = [(A_1^1 X_1 - (A_1^2 X_1 + A_1^3 X_1)) + (A_2^1 X_2 - (A_2^2 X_2 + A_2^3 X_2)) +$$

$$(A_3^1 X_3 - (A_3^2 X_3 + A_3^3 X_3)) + (A_4^1 X_4 - (A_4^2 X_4 + A_4^3 X_4))] \tag{5.2a}$$

$$Min(Z_2) = C_1 X_1 + C_2 X_2 + C_3 X_3 + C_4 X_4 \tag{5.2b}$$

Subject to:

$$X_1 \leq B_1 \tag{5.2c}$$

$$X_3 \leq B_2 \tag{5.2d}$$

$$X_4 \leq B_3 \tag{5.2e}$$

$$X_1 + X_3 \leq B_4 \tag{5.2f}$$

$$X_1 + X_2 + X_3 + X_4 = B_5 \tag{5.2g}$$

$$X_1 \geq B_6 \tag{5.2h}$$

$$X_2 \geq B_7 \tag{5.2i}$$

$$X_1, X_2, X_3, X_4 \geq 0 \tag{5.2j}$$

where

X_1 = Area allocated to orchard (ha)

X_2 = Area allocated to rangeland (ha)

X_3 = Area allocated to irrigated land (ha)

X_4 = Area allocated to dryland (ha)

A_1^1 = Amount of net farm income per unit area of orchard (10^6 Rial/ha)

A_1^2 = Production cost per unit area of orchard (10^6 Rial/ha)

A_1^3 = Erosion cost per unit area of orchard (10^6 Rial/ha)

A_2^1 = Amount of net farm income per unit area of rangeland (10^6 Rial/ha)

A_2^2 = Production cost per unit area of rangeland (10^6 Rial/ha)

A_2^3 = Erosion cost per unit area of rangeland (10^6 Rial/ha)

A_3^1 = Amount of net farm income per unit area of irrigated land (10^6 Rial/ha)

A_3^2 = Production cost per unit area of irrigated land (10^6 Rial/ha)

A_3^3 = Erosion cost per unit area of irrigated land (10^6 Rial/ha)

A_4^1 = Amount of net farm income per unit area of dryland (10^6 Rial/ha)

A_4^2 = Production cost per unit area of dryland (10^6 Rial/ha)

A_4^3 = Erosion cost per unit area of dryland (10^6 Rial/ha)

C_1 = Annual sediment yield per unit area of orchard (t/ha.y)

C_2 = Annual sediment yield per unit area of rangeland (t/ha.y)

C_3 = Annual sediment yield per unit area of irrigated land (t/ha.y)

C_4 = Annual sediment yield per unit area of dryland (t/ha.y)

B_1 = Maximum limit of orchard surface area (ha)

B_2 = Surface area of irrigated land (ha)

B_3 = Surface area of dryland (ha)

B_4 = Surface area of orchard plus irrigated land (ha)

B_5 = Total area (ha)

B_6 = Minimum limit of orchard surface area (ha)

B_7 = Surface area of rangeland (ha)

5.2 Estimation of constants

Estimation of the A_i^j, B_i, and C_i constants is necessary to be able to solve equations (5.2a) through (5.2j). The procedure for estimating these constants is described in the following sub-sections.

5.2.1 Estimation of each land use area ($B_1, B_2, B_3, B_4, B_5, B_6, B_7$)

Due to not being able to make any changes in the use of municipal lands, these areas were excluded from land-use optimization. Therefore, municipal lands are subtracted from the total area in Table 5.1 and the remaining of 10310 ha is considered as B_5 or the total area of the Syahrood sub-basin in equation (5.2g).

Table 5.1 Sediment yield in each land use of Syahrood sub-basin

Land use	Area (ha)	Sediment yield (t/ha.y)	Sediment yield (t/y)
Orchard	160	1.41	226
Rangeland	6990	4.99	34880
Irrigated land	1540	2.41	3711
Dryland	1620	6.24	10109
Total	10310	4.75	48926

According to the results of the overlay operation of land-use and slope maps within the GIS environment, the distribution of land use activities in different slope classes is illustrated in Table 5.2. For proper management of agricultural lands, it is not wise 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 avoiding soil erosion and reduction of crop yield.

Therefore, irrigated farms on more than 10% slopes and drylands on more than 20% slopes were deducted in the optimizing formulations. According to Table 5.2, the values of B_1 through B_7 in equations (5.2c) through (5.2i), were 557, 1143, 1577, 1700, 10310, 160, and 6990 ha, respectively.

Table 5.2 Distribution of land use activities in different slope classes of Syahrood

Slope (%)	Orchard (ha)	Rangeland (ha)	Irrigated land (ha)	Dryland (ha)	Total (ha)
5-10	134	1810	1143	1254	4341
10-20	1	2390	178	323	2892
20-40	25	1556	214	33	1828
40-60	-	1180	5	10	1195
>60	-	54	-	-	54
Total	160	6990	1540	1620	10310

5.2.2 Estimation of soil erosion in each land use (C_1, C_2, C_3, C_4)

From the GIS results in Chapter 4, and from Figure 4.8, soil erosion in orchard, rangeland, irrigated, and dryland areas (C_1 through C_4) in equation (5.2b) was 1.41, 4.99, 2.41, and 6.24 t/ha.y, respectively.

5.2.3 Estimation of benefit and cost in orchards (A_1^1, A_1^2)

There are 160 ha of orchards in Syahrood sub-basin. The major crops that are included in this model are given in Table 5.3. The area of each crop, yield, net benefit and cost from farm crop production were detailed in studies by NRCE (1992). By taking the municipal area into account, and dividing the total cost and benefit values in the last row of Table 5.3, the weighted average of benefit (A_1^1) and cost (A_1^2) of orchard crops are 11.444 and 0.899 million Rial/ha.

In 1992, 1 $US was equal to 70 and 1500 Rial (Iranian currency) in the Central Bank of Iran and in the open market, respectively. At the time of writing this thesis, conversions changed to 4950 and 9100 Rial per US $, respectively.

Table 5.3 Major orchard crops and their cost/benefit information in Syahrood

Crop	Area (ha)	Yield (t/ha)	Cost (Rial/t)	Benefit (Rial/t)	Total cost (10^6 Rial/y)	Total benefit (10^6 Rial/y)
Apple	78.20	19.00	47,370	500,000	70.38	742.90
Cherry	30.25	8.50	105,880	750,000	27.22	192.84
Fig	1.00	5.50	163,640	450,000	0.90	2.47
Grape	6.25	6.00	150,000	430,000	5.62	16.12
Pineapple	31.50	13.00	69,230	500,000	28.35	204.75
Walnut	12.80	7.50	120,000	7000,000	11.52	672.00
Total	160	-	-	-	143.99	1831.08

5.2.4 Estimation of benefit and cost in rangelands (A_2^1, A_2^2)

Through range management studies (NRCE, 1992), three types of condition[1] were studied in 6990 ha of rangelands in Syahrood sub-basin. These conditions were classified by comparing the rangelands at the time of study with its potential situation regarding vegetation canopy cover, vegetation combination, soil conservation, and residue

[1] Range condition is an ecological measure to compare current plant species composition of a rangeland to its potential (often called "climax") and is determined by totaling the condition scores for all present species. Poor, fair, good, and excellent conditions have 0 to 25%, 26 to 50%, 51 to 75%, and 76 to 100% of the climax community, respectively (McGinty and White, 1996).

condition. Table 5.4 differentiates these rangelands by condition types, area, and production.

Using Table 5.4, the weighted average dry-forage[1] production in Syahrood sub-basin is calculated as 0.14 t/ha. Assuming 55% of produced forage is Total Digestible Nutrients (TDN), the total produced TDN is 0.08 t/ha. Considering that 230 kg/y TDN is required for each animal unit (sheep), 0.35 animal units per hectare are fed by rangelands every year. Also, the average weight of each animal unit in the area is 32 kg (NRCE, 1992). Therefore, the total weight of live animal units is 11.2 kg/ha.

Table 5.4 Differentiation of rangelands by type, area, and production in Syahrood

Rangeland condition	Area		Average dry-forage (t/ha)	Total dry-forage (t)
	ha	%		
Medium	2290	32.7	0.240	550
Poor	3400	48.7	0.103	350
Very poor	1300	18.6	0.085	110
Total	6990	100	-	1010

Considering the price of live sheep in 1992, which was 4,230 Rial/kg, the total economic production of rangelands (A_2^1) amounts to 0.047 million Rial/ha. On the other hand, due to governmental ownership of rangelands in the study area, there is no cost (A_2^2) for meat production. Also, other animal productions such as milk, wool, and animal fertilizer are not taken into account.

[1] All browsed and herbaceous foods that are available to grazing animals. Forages are cut and dried in the field for later use (Trottier, 1992).

5.2.5 Estimation of benefit and cost in irrigated lands (A_3^1, A_3^2)

From the total 1540 ha of irrigated croplands in Syahrood sub-basin, 458 ha is under fallow condition every year. Table 5.5 gives crop production data in irrigated lands. By taking the fallow area into account, and dividing the total cost and benefit values in the last row of Table 5.5, the weighted average of benefit (A_3^1) and cost (A_3^2) in irrigated lands are 1.523 and 0.926 million Rial/ha, respectively.

Table 5.5 Major irrigated land crops and their cost/benefit information in Syahrood

Crop	Area (ha)	Yield (t/ha)	Cost (Rial/t)	Benefit (Rial/t)	Total cost (10^6 Rial/y)	Total benefit (10^6 Rial/y)
Alfalfa	225	5.00	130,000	300,000	146.25	337.50
Barley	175	2.00	267,000	296,000	93.45	103.60
Onion	52	7.00	325,000	350,000	118.30	127.40
Pea	106	1.20	2,142,000	2,630,000	272.46	334.54
Potato	116	18.00	225,000	500,000	469.80	1044.00
Wheat	408	3.00	266,000	326,000	325.58	399.02
Fallow	458	-	-	-	-	-
Total	1540	-	-	-	1425.84	2346.06

5.2.6 Estimation of benefit and cost in drylands (A_4^1, A_4^2)

There are 1620 ha drylands in Syahrood sub-basin with 812 ha under fallow condition every year. Small grains (wheat and barley), alfalfa, and pea are the most popular crops. Table 5.6 indicates crops, area, yield, and benefit/cost data of each crop in drylands. By taking the fallow area into account, and dividing the total cost and benefit values in the last row of Table 5.6, the total benefit (A_4^1) and cost (A_4^2) in drylands are 0.095 and 0.073 million Rial/ha, respectively.

Table 5.6 Major dryland crops and their cost/benefit information in Syahrood

Crop	Area (ha)	Yield (t/ha)	Cost (Rial/t)	Benefit (Rial/t)	Total cost (10^6 Rial/y)	Total benefit (10^6 Rial/y)
Alfalfa	36	1.50	130,000	300,000	7.02	16.20
Barley	214	0.50	256,000	296,000	28.67	33.15
Pea	16	0.40	2,142,000	2,630,000	13.71	16.83
Wheat	544	0.50	252,000	326,000	68.54	88.67
Fallow	810	-	-	-	-	-
Total	1620	-	-	-	117.94	154.85

5.2.7 Estimation of erosion cost in different land uses ($A_1^3, A_2^3, A_3^3, A_4^3$)

There is no research on the evaluation of economic losses due to sediment yield in the study area. Therefore, it is difficult to evaluate it directly. However, these losses can be estimated indirectly by the evaluation of fertile soil loss. For example, based on data relating topsoil loss to yield reductions, just 2.5 cm of topsoil loss is enough to reduce U.S. wheat yields an average of 60 million bushels (bushel = 35.21 liter)/year (Dregne, 1982). Another way to estimate economical losses due to sediment yield is to apply lost soil to the eroded area based on the depth of root zone in each land use (NRCE, 1992).

The depth of the lost soil in each land use is calculated by considering the amount of sediment yield in that land use, the appropriate rooting depth of vegetation (root zone), and soil bulk density (NRCE, 1992). Table 5.7 presents the land use, the amount of sediment yield, root zone, soil bulk density, total area lost due to erosion, and the estimated cost due to soil erosion in each land use. Estimated lost areas in this table (column 5) were multiplied by the economic net income of each land use to estimate economic cost due to sediment yield (column 6) in each land use.

Table 5.7 Estimated economical losses due to sediment yield in Syahrood

Land use	Erosion (t/ha.y)	Root zone (cm)	Soil bulk density (g/cm^3)	Lost area (m^2/ha)	Cost (Rial/ha)
Orchard	1.41	100	1.4	1.01	1062
Rangeland	4.99	15	1.6	20.79	98
Irrigated land	2.41	50	1.4	3.44	205
Dryland	6.24	15	1.5	27.73	61

Table 5.8 summarizes the production of each land use activity in the study area. The annual average of net farm income in the area is 0.288 million Rial/ha.

Table 5.8 Current land uses and production of Syahrood sub-basin

Land use	Area (ha)	Production (10^6 Rial/ha)	Cost (10^6 Rial/ha)	Net income (10^6 Rial/ha)	Total net income (10^6 Rial)
Orchard	160	11.444	0.899	10.545	1687.20
Rangeland	6990	0.047	-	0.047	328.53
Irrigated land	1540	1.523	0.926	0.597	919.38
Dryland	1620	0.095	0.073	0.022	35.64
Total	10310	0.452	0.164	0.288	2969.28

5.3 Solution to the problem

According to the computations in the last few sections, the general form of the optimization problem can be written as follow.

$$Max(Z_1) = [(11.444X_1 - (0.899X_1 + 0.00106X_1)) + (0.047X_2 - (0X_2 + 0.00010X_2)) +$$
$$(1.523X_3 - (0.926X_3 + 0.00021X_3)) + (0.095X_4 - (0.073X_4 + 0.00006X_4))] \quad (5.3a)$$

$$Min(Z_2) = 1.41X_1 + 4.99X_2 + 2.41X_3 + 6.24X_4 \quad (5.3b)$$

By simplifying the first objective function, and changing the minimization to maximization form in the second objective, these equations change to the following simpler forms.

Objective 1. $Max(Z_1) = 10.544X_1 + 0.047X_2 + 0.597X_3 + 0.022X_4$

Objective 2. $Max(-Z_2) = -1.41X_1 - 4.99X_2 - 2.41X_3 - 6.24X_4$

There are seven constraints of the land-use optimization model. The constraints and their justifications are discussed below.

Constraint 1. $X_1 \leq 557$

The first constraint indicates that the present area under orchard, which is 160 ha could be increased up to 557 ha. The reason for these constraints is that the areas of irrigated lands with slope classes of 10-20, 20-40, and 40-60 % are not suitable for irrigating cropland. These lands could be changed to other land uses especially orchards, by terracing, if necessary, and planting permanent vegetation.

Constraint 2. $X_3 \leq 1143$

The second constraint is that the area under irrigated lands, which is 1540 ha, after subtracting high slope classes, as described in constraint 1, should not be more than 1143 ha.

Constraint 3. $X_4 \leq 1577$

Slopes more than 20% are not suitable for dryland farming. The third constraint indicates that the area under dryland farming, which is 1620 h, after subtracting high slope classes, should not be more than 1577 ha. Other reasons for this constraint are as follows.

A. The government owns the rangelands and people cannot change their use of these lands.

B. Due to lack of sufficient rainfall in the area, dryland farming is not suitable for most areas in this watershed.

C. People seldom use supporting practice systems in drylands, which causes large amounts of soil erosion in this form of land use.

Constraint 4. $X_1 + X_3 \leq 1700$

Based on the limitation of irrigation water, the forth constraint implies that the area under orchard and irrigated croplands could not be more than 1700 ha.

Constraint 5. $X_1 + X_2 + X_3 + X_4 = 10310$

The fifth constraint is simple and it is the area limitation of the Syahrood 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 10310 ha of the available lands in the watershed.

Constraint 6. $X_1 \geq 160$

Base on the reasons in Constraint 1, the sixth constraint shows the present area under orchards.

Constraint 7. $X_2 \geq 6990$

The seventh constraint indicates that the area under rangeland should be at least 6990 ha. The reason for this constraint is that the government owns the rangelands and people cannot change their form of land use. Many rangelands have been illegally converted to improper drylands, which could be changed back to rangelands.

Constraint 8. $X_1, X_2, X_3, X_4 \geq 0$

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

Socioeconomic conditions in the study area do not allow converting all the irrigated lands to orchards. Also, limited detail data on suitability of croplands to different crops or combination of crops as well as the lack of cost/benefit information limits the objectives and constraints to those explained.

Simplified objective functions and their constraints discussed above are entered in Table 5.9 as a revised linear multi-objective simplex tableau. In this table, variables and their units are as follows:

Table 5.9 Linear multi-objective simplex tableau of Syahrood sub-basin problem

(1) Equation	(2) X_1	(3) X_2	(4) X_3	(5) X_4	(6) Type	(7) RHS
Objective 1	10.544	0.047	0.597	0.022	Max	0
Objective 2	-1.41	-4.99	-2.41	-6.24	Max	0
Constraint 1	1	0	0	0	≤	557
Constraint 2	0	0	1	0	≤	1143
Constraint 3	0	0	0	1	≤	1577
Constraint 4	1	0	1	0	≤	1700
Constraint 5	1	1	1	1	=	10310
Constraint 6	1	0	0	0	≥	160
Constraint 7	0	1	0	0	≥	6990

Columns 2 through 5 in this table present decision variables, which in rows 2 and 3 have currency and sediment yield units, respectively. Numbers 1 and 0 in the remaining rows show the presence or absence of the decision variables in constraints, respectively. Rows 2 and 3 of column 6 indicate the maximization or minimization form of the objective functions while 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 represent land availability in ha.

After solution of the revised simplex tableau in Table 5.9 by the computer program of Steuer (1995), the proposed areas for orchards (X_1), rangelands (X_2), irrigated lands (X_3), and drylands (X_4) are revealed in Table 5.10. Using the proposed land-use values, the annual net income (Z_1) and sediment yield (Z_2) are calculated as 6.96 billion Rial/y and 46504 t/y, respectively.

Table 5.10 Land-use optimization output of Syahrood sub-basin

Land use	Allocated area (ha)	Sediment yield (t/ha.y)	Sediment yield (t/y)	Net income (10^6 Rial/ha.y)	Total net income (10^6 Rial/y)
Orchard	557	1.41	785	10.545	5873.56
Rangeland	8610	4.99	42964	0.047	404.67
Irrigated land	1143	2.41	2755	0.597	682.37
Dryland	-	6.24	-	0.022	-
Total	10310	-	46504	0.675	6960.6

CHAPTER 6

DISCUSSION, CONCLUSIONS, AND SUGGESTIONS

The main objective of present study was to develop a new methodology and associated tools to predict the sediment yield with greater reliability in watersheds with deficiency of recorded rain gauge data. A subsequent objective was to optimize land-use activities of a watershed in such a way that soil erosion is minimized while maximizing the agricultural economic income for the Syahrood sub-basin which drains directly into the Damavand river in Northeastern Tehran, the capital city of Iran. The high sediment yield and serious flooding due to faulty land practices in the area provided the initiative for using that area as a study site. It was hoped that the results of the study would have the potential for application in other watersheds.

The study describes the development of two models, the integration of a sediment yield model with a GIS and a land-use optimization model. The sediment yields are predicted by Modified Universal Soil Loss Equation using daily precipitation as input. Seven factors were computed and assigned to related land-component, slope, land-use, and Thiessen polygon maps. SPANS-GIS modeling tools were used to provide necessary database and assist soil loss estimation.

The output results of the sediment yield model along with the net income of each land-use were used as input in the land-use optimization model for minimizing the sediment yield and maximizing farm production of each land-use. The multi-objective linear programming simplex method was used to solve the problem. This method can be used to generate an exact representation of the noninferior set by moving mathematically from one noninferior extreme point to adjacent points until all noninferior extreme points have been found. Figures 6.1 through 6.3 compare the area, sediment yield, and total net farm income of different land uses of Syahrood sub-basin before and after optimization.

6.1 Accuracy of sediment yield modeling within SPANS-GIS

For estimation of sediment yield the Modified Universal Soil Loss Equation was integrated by a GIS. The selection of the MUSLE was due to its advantage of easy estimation of the runoff factor from the peak flow volume and total flow volume. Also, the estimation of the rainfall erosivity factor for the original USLE requires the intensity of rainfall, which is impossible to obtain from the daily precipitation record.

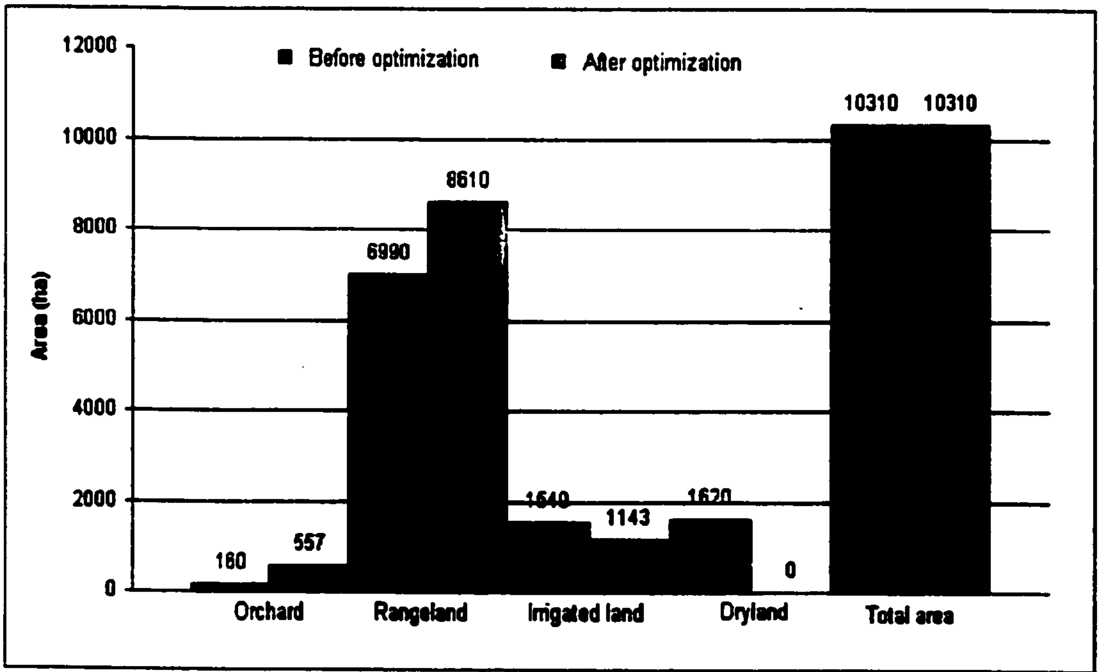

Figure 6.1 Land use area in Syahrood before and after optimization

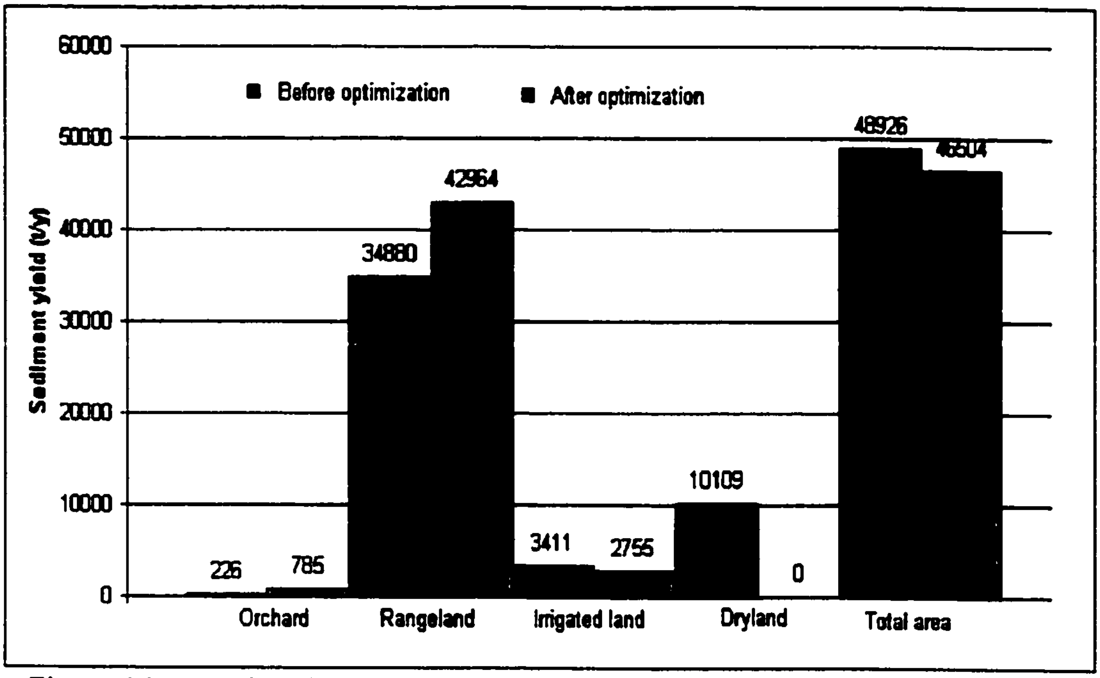

Figure 6.2 Annual sediment yield in Syahrood before and after optimization

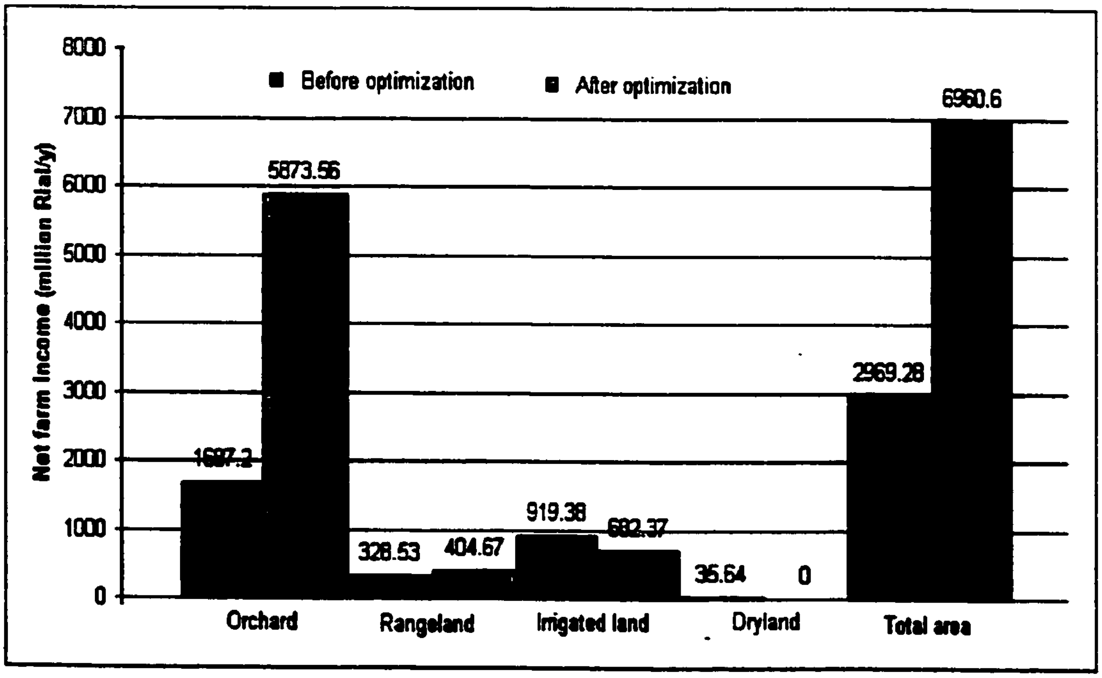

Figure 6.3 Annual net income in Syahrood before and after optimization

In addition, the runoff erositivity factor gives more accurate estimates of sediment yield as compared to the rainfall erosivity factor, because runoff is more closely related to erosion than is rainfall.

Accuracy is the degree of likelihood that the information provided is correct. This definition focuses on two components of accuracy. The first and more familiar aspect of accuracy is that it predicts the proportion of information that is expected to be correct or the magnitude of error to be expected. The second and often ignored aspect of accuracy is that it involves a probability. When a map or other data set is asserted to be 80% accurate it means that when the data set is used, it can be expected that on average 80% of the information will be correct. The measure of this probability of having a higher or lower accuracy than expected is termed the level of confidence. So, when a map is rated 80% accurate with a 90% level of confidence it means that if a large number of accuracy tests were done on the map, then 80% or more of the test points would be correct in 9 out of every 10 tests.

The level of accuracy depends on the information to be provided and the level of detail required. For example a road map with an accuracy of one km may be suitable to estimate the driving time between cities. However engineering drawings of a city street are required to have accuracy on the order of centimeters. Accuracy can usually be improved by expending more resources. More money can be spent on the field investigations, more time can be spent on analysis, and more quality control can be exercised in assembling the data. An acceptable level of accuracy is that level where the costs of making the wrong decision are equal to the costs of acquiring more accurate information.

The accuracy of predicted sediment yield in the study area depends on two major resources. First, the soil erosion prediction model (MUSLE) and the parameters used with it. Second, the GIS environment and the components used to model soil erosion with it.

6.1.1 Accuracy of soil erosion model

The MUSLE model is an experimental model whose parameters are gathered by field studies at a proposed scale. The accuracy of a model in an expected scale depends on the precision of the model parameters and the skill of the people working on the project. If assuming all the parameters gathered to model soil erosion are precise, still the model should be calibrated in the study area before using it. The MUSLE model was used to predict sediment yield in many similar watersheds by the Forests and Range Research Institute of Iran. Two years of sedimentary data were collected from the rivers of Damavand watershed (NRCE, 1992). Based on these data, sediment load caused by channel erosion was calculated on non-rainy days and subtracted from the sediment data. According to this study, 4.73 t/ha.y of sediment yield was reported for Syahrood sub-basin. Comparing the estimated sediment yield (4.75 t/ha.y) with this later value shows that the present research goals were achieved.

6.1.2 Accuracy of modeling in GIS environment

In the GIS environment, map accuracy depends on many factors. At the micro level, there are components such as positional accuracy, attribute accuracy, logical consistency, and resolution. At the macro level, there are components such as completeness, time, and lineage. Finally, usage components are accessibility and direct or indirect costs. There are also different sources of errors associated with all geographic information. Some of the more common errors are related to data collection, data input, data storage, data manipulation, data output, and the way of using and understanding results.

Paper data such as different maps and associated geographic attributes and data are used as one of the sources of input data to the GIS environment. In this process the paper data are converted to digital data. The level of accuracy of the digital data will be the same as paper data if they are correctly converted to the digital form with a suitable package in an acceptable resolution. Once the data are converted, the accuracy of the output data resulting from different manipulations depends on the resolution power of the software along with the skill of the operator.

SPANS-GIS utilizes a quadtree data structure, which provides a more compact raster representation by using a variable-sized grid cell. Instead of dividing an area into cells of one size, finer subdivisions are used in those areas with finer details. In this way, a higher level of resolution is provided only where it is needed. For a thematic map, the fine grid is only needed in the vicinity of lines, points, and polygon boundaries. A large area of a single class would be just as accurately encoded with one large cell as with many small cells because they all have the same attribute value. At the quad level of 15, the finest grid size is 1.375 m for 1:50 000 scale maps of the study area. It means that the output maps have a resolution of 1.375 m, which is a very good resolution for this scale. For positional and attribute accuracy tests of the prepared maps with TYDIG and SPANS-GIS, 25 points were selected on each of four digitized elevation, land-use, land-component, and hydrologic soil group maps of Syahrood sub-basin. Their longitude, latitude, and class attributes were compared with the ones on paper maps by the query tool in SPANS. All tested points had exactly the same positional and attribute data as the paper maps.

6.2 Sensitivity analysis of the optimization model

Post-optimality analysis involves conducting sensitivity analysis to determine which parameters of the model are the most critical in determining the solution. Some or all of the parameters generally are an estimate of some quantity whose exact value will become known only after the solution has been implemented. Therefore, after identifying the sensitive parameters, special attention is given to estimating each one more closely, or at least its range of likely values.

Sensitivity analysis often begins with the investigation of the effect of changes in the B_i, the amount of resource i being made available for the activities under consideration. The reason is that there generally is 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 prices is extremely useful for deciding which changes should be considered. The shadow price (y_i^*) for resource i measures the marginal value of this resource, that is, the rate at which Z could be increased by slightly increasing the amount of this resource being made available. In particular, if $y_i^* > 0$, then the optimal solution changes if B_i is changed, so B_i is a sensitive parameter.

The sensitivity analysis for checking all sensitive parameters of the problem started with B_i. Then the investigation continued on A_i^1 and C_i parameters. It was found that B_1, which refers to the restriction of area under orchard was the most sensitive parameter. Increasing the area in orchards by 1 ha increases y_1^* by 10 million Rial/y and decreases y_2^* by 1 t/y, which means the most attention should be toward allocating areas to orchard under the present conditions. Tables 5.11 through 5.13 show the results of sensitivity analysis for all problem parameters.

6.3 Conclusion

Measures are being taken to improve the watershed conditions to reduce the sediment yield while maximizing production. To achieve these goals, the objective functions for maximizing watershed production were designed in such a way that the cost of sediment yield from each land-use practice was counted towards its cost of production. A multi-objective linear program was used for land-use optimization for maximizing watershed production and minimizing sediment yield. After taking allocated areas into account, average annual sediment yield and average annual income for the entire study area were 46504 t/y and 6.96 billion Rial/y, respectively. Compared with the values before optimization, the annual sediment yield would have decreased by 2422 t/y (or by 5%) and the annual net income increased by 3.99 billion Rial/y (or by 134%).

The results indicate that the objectives of the study were achieved. The models used for prediction of sediment yield and optimization of land use in the Syahrood sub-basin gave reasonable results. The encouraging results of these models allow the scope of their applicability to extend to other watersheds. The watershed manager or planner can use land-use optimization for making decision in allocating watershed area for different land uses to achieve specific objectives.

Table 6.1 Sensitivity analysis of land resources (B_i) in Syahrood

B_1 (ha)	B_2 (ha)	B_3 (ha)	B_4 (ha)	B_5 (ha)	B_6 (ha)	B_7 (ha)	X_1 (ha)	X_2 (ha)	X_3 (ha)	X_4 (ha)	Z_1 (10^6 Rial/y)	Z_2 (t/y)
557	1143	1577	1700	10310	160	6990	557	8610	1143	0	6960	46504
558	1143	1577	1700	10310	160	6990	558	8610	1142	0	6970	46503
559	1143	1577	1700	10310	160	6990	559	8610	1141	0	6980	46502
557	**1144**	1577	1700	10310	160	6990	557	8610	1143	0	6960	46504
557	**1145**	1577	1700	10310	160	6990	557	8610	1143	0	6960	46504
557	1143	**1578**	1700	10310	160	6990	557	8610	1143	0	6960	46504
557	1143	**1579**	1700	10310	160	6990	557	8610	1143	0	6960	46504
557	1143	1577	**1701**	10310	160	6990	557	8610	1143	0	6960	46504
557	1143	1577	**1702**	10310	160	6990	557	8610	1143	0	6960	46504
557	1143	1577	1700	**10311**	160	6990	557	8611	1143	0	6960	46509
557	1143	1577	1700	**10312**	160	6990	557	8612	1143	0	6960	46514
557	1143	1577	1700	10310	**161**	6990	557	8610	1143	0	6960	46504
557	1143	1577	1700	10310	**162**	6990	557	8610	1143	0	6960	46504
557	1143	1577	1700	10310	160	**6991**	557	8610	1143	0	6960	46504
557	1143	1577	1700	10310	160	**6992**	557	8610	1143	0	6960	46504

Bold numbers represent a new iteration in sensitivity analysis.

Table 6.2 Sensitivity analysis of A_i^1 in optimizing land use activities in Syahrood

A_1^1 (10^6 Rial/ha)	A_2^1 (10^6 Rial/ha)	A_3^1 (10^6 Rial/ha)	A_4^1 (10^6 Rial/ha)	X_1 (ha)	X_2 (ha)	X_3 (ha)	X_4 (ha)	Z_1 (10^6 Rial/y)	Z_2 (t/y)
10.544	0.047	0.597	0.022	557	8610	1143	0	6960	46504
11.544	0.047	0.597	0.022	557	8610	1143	0	7517	46504
12.544	0.047	0.597	0.022	557	8610	1143	0	8074	46504
10.544	**1.047**	0.597	0.022	557	8610	1143	0	15570	46504
10.544	**2.047**	0.597	0.022	557	8610	1143	0	24180	46504
10.544	0.047	**1.597**	0.022	557	8610	1143	0	8103	46504
10.544	0.047	**2.597**	0.022	557	8610	1143	0	9246	46504
10.544	0.047	0.597	**1.022**	557	8610	1143	0	6960	46504
10.544	0.047	0.597	**2.022**	557	8610	1143	0	6960	46504

Table 6.3 Sensitivity analysis of C_i in optimizing land use activities in Syahrood

C_1 (t)	C_2 (t)	C_3 (t)	C_4 (t)	X_1 (ha)	X_2 (ha)	X_3 (ha)	X_4 (ha)	Z_1 (10^6 Rial/y)	Z_2 (t/y)
1.41	4.99	2.41	6.24	557	8610	1143	0	6960	46504
2.41	4.99	2.41	6.24	557	8610	1143	0	6960	47061
3.41	4.99	2.41	6.24	557	8610	1143	0	6960	47618
1.41	**5.99**	2.41	6.24	557	8610	1143	0	6960	55114
1.41	**6.99**	2.41	6.24	557	8610	1143	0	6960	63724
1.41	4.99	**3.41**	6.24	557	8610	1143	0	6960	47647
1.41	4.99	**4.41**	6.24	557	8610	1143	0	6960	48790
1.41	4.99	2.41	**7.24**	557	8610	1143	0	6960	46504
1.41	4.99	2.41	**8.24**	557	8610	1143	0	6960	46504

The study also recognizes that before making any decision for implementing land-use optimization, the objectives and the constraints should be clearly recognized and realistic estimates of constants of the objective function made.

The estimated sediment yield from orchards, rangelands, irrigated lands, and drylands in the Syahrood sub-basin was 1.41, 4.99, 2.41, and 6.24 t/ha.y, respectively. Annual weighted average of sediment yield for the entire area amounts to 4.75 t/ha.y. Compared with Europe, Australia, North America, and Asia with 0.84, 2.73, 4.91, 6.10 t/ha.y of soil erosion, respectively (NRCE, 1992), it is clear that the lands are improperly managed in the study area.

In general, the high erosion rate in the Syahrood sub-basin is related to the following reasons.

1. 244 400 animal units (sheep) are grazing on the rangelands of Damavand watershed, which need 29 100 t of dry forage (NRCE, 1992). The produced dry forage in the area is 8 640 t, which provides 1/3 of the needs. Therefore, decreasing vegetation cover of rangelands by heavy grazing causes lower soil fertility, greater soil compaction, and eventually more surface runoff, which easily removes soil particles.
2. Table 5.2 indicates that 323 ha of drylands are on the 10-20% slopes and 43 ha on slopes greater than 20%. Based on steep slopes and low precipitation (423 mm/y), crop yield of these drylands is often so low that the farmers do not attempt to harvest. They leave these lands for one or two years fallow without any vegetation cover, which causes more erosion in these periods. As it can be noticed (Figures 3.3 and 3.4), rangelands with permanent vegetation

cover on steep slopes are converted to drylands with seasonal vegetation cover and cultivated in rows parallel to the slope direction. Converting these lands back to rangeland, reduces annual sediment yield from 6.24 to 4.99 t/ha.y and increases the annual net income from 0.022 to 0.047 million Rial/ha.y.

3. Lack of proper erosion control practices cause high values of the supporting practices factor (*P*) in many lands. Utilizing proper supporting practice systems such as contour furrowing, strip cropping, terracing, and pitting accompanied with planting permanent or annual plants will further decrease the value of *P* and subsequently annual erosion and increase annual net income.
4. Cutting trees and shrubs from the rangelands by farmers to use as fuel causes the same problems discussed above, in parts 1 and 2.

6.4 Suggestions for future work

The present work could be further developed in the following aspects:

1. SPANS-GIS is not capable of producing an accurate slope map for mountainous areas. The slope module of this package needs to be improved in new versions. In addition work is necessary to make the modeling environment more user friendly.
2. MUSLE does not take gully and channel erosion into account. Further investigations are recommended in this area.
3. To maximize the benefits from the study area, the combination of different crops should be considered in the optimization procedure.

4. Taking other animal products such as wool, milk, and fertilizer into account increases the precision of the optimization problem. This information was not available for this research.
5. There are some costs associated with transforming land uses (like seeding in drylands to convert them to rangelands). They should be computed and taken into account. Further investigations are necessary in this matter.
6. Continued monitoring and gathering of precipitation and sedimentary data are the essential tools for validating proposed models. In Syahrood sub-basin, there were just two years of sedimentary data available to this research.
7. The relationship between erosion and crop yield in different croplands is another topic, which needs to be investigated further. This later suggestion is valid for all areas of the world and is not specific to the Syahrood sub-basin.
8. Investigation on water availability, supply, and quality, is also recommended. Converting appropriate drylands to productive irrigated lands or orchards significantly increases total net income and decreases annual sediment yield of whole area.

REFERENCES

Agassi, M. (1996). *Soil Erosion, Conservation, and Rehabilitation.* Marcel Dekker, Inc., New York, NY.

Aina P.O., R. Lal, and G.S. Taylor, (1976). *Soil and crop management in relation to soil erosion in the rainforest of western Nigeria.* Soil erosion: Prediction and control. The proceedings of a national conference on soil erosion, Purdue University.

Aronoff Stan, (1991). *Geographic Information Systems: A Management Perspective.* second printing, WDL Publications, Ottawa, Canada.

Bajjali, W. and B. Daneshfar, (1995). Determining the suitability of the groundwater resources for drinking purposes in North Jordan by using a fuzzy logic model in a GIS environment. TYDAC Technologies Inc., Proceeding of the 1995 International SPANS workshop. Ottawa, Canada.

Bashier Hussain Shah, (1985). *Land use optimization and sediment yield model for Siran Watershed (Pakistan),* Ph.D. dissertation, The University of Arizona.

Batista, Jose A.H., (1989). *Optimal Research Allocation for Development planning and policy Formation in the Ocoa Watershed, Dominican Republic.* Ph.D. dissertation, Michigan State University.

Beasley D.B. and Larry F. Huggins, (1982). *Areal Nonpoint Source Watershed Environment Response Simulation (ANSWERS).* Agricultural Engineering Department, Purdue University.

Benabdallah Salah, (1990). *Allocation Models in Spatial Optimization.* Ph.D. dissertation, Purdue University.

Birkeland P.W., (1974). *Pedology, weathering, and geomorphological research.* Oxford University Press, New York.

Blaszczynski, J., (1992). *Regional Soil Loss Prediction Utilizing the RUSLE/GIS Interface.* Geographic Information Systems(GIS), Mapping-practices and Standards. ASTM STP 1126, A.I. Johnson, C.B. Pettersson, and J.L. Fulton, Eds., American Society for Testing and Materials, Philadelphia.

Brooks Frank L., (1976). *Use of the universal soil loss equation in Hawaii.* Soil erosion: Prediction and control, The proceedings of a national conference on soil erosion, Purdue University.

Browning George M., (1979). *Development for and of the Universal Soil Loss Equation.* Universal Soil Loss Equation: Past, present, and future, Soil Science Society of America, Inc., Medison, WI.

Burke Diane, (1997). *SPANS Explorer, The Future of Geographic Analysis Defined.* TYDAC Research Inc., Ottawa, Ontario.

Canali Gilberto Ernesto, (1992). *The Impact of Watershed Dynamics and Homogeneity on Sedimentation.* Ph.D. dissertation, Colorado State University.

Chairat Sihem, (1993). *Adapting a physically Based Hydrologic Model with a Geographic Information System for Runoff Prediction in a small Watershed.* Ph.D. dissertation, Purdue University.

Chung Pil-Kwon, (1981). *The trade-off relationship between energy use and environmental quality in U.S. agriculture: A multi-objective linear programming analysis.* Ph.D. dissertation, Iowa State University.

Chuvieco Emilio, (1993). *Integration of linear programming and GIS for land-use modeling.* Int. J. Geographical Information Systems, 7: 71-83.

Clark, (1999). Internet site of Graduate School of Geography at Clark University, Worcester, Massachusetts. http://www.clarklabs.org.

Cohon Jared L., (1978). *Multi-objective Programming and Planning.* Academic Press, Inc., New York.

Cook H.L., (1936). *The nature and controlling variables of water erosion process.* Soil Sci. Soc. Am. Proc., 1: 487-493.

Dangermond J., (1992). *What is a Geographic Information System (GIS)?* Geographic Information Systems (GIS) and Mapping- Practices a Standards, edited by A.I. Johnson, C.B. Pettersson, and J.L. Fulton, American Society for Testing and Materials, Philadelphia, pp. 11-17.

Dregne H.E., (1982). *Historical Perspective of Accelerated Erosion and Effect on World Civilization.* Determinants of Soil Loss Tolerance, ASA, No. 45.

Ekern P.C., (1950). *Raindrop impact as the force initiating soil erosion.* Soil Sci. Soc. Am. Proc., 15: 7-10.

Ellison W.D., (1946). *Soil detachment and transportation.* US SCS, Soil Conservation Service, 11: 179.

Engel B.A., R. Srinivasan, J. Arnold, and C. Rewerts, (1993). *Nonpoint Source (NPS) Pollution Modeling Using Models Integrated with Geographic Information Systems(GIS).* Wat. Sci. Tech. 28: 685-690.

ESRI, (1995). *Understanding GIS, the ARC/INFO Method.* Environmental Systems Research Institute, Inc. Redlands, CA.

ESRI, (1999). Internet site of Environmental Systems Research Institute, Inc. http://www.esri.com.

Evans William R. and George Kalkanis, (1976). *Use of the universal soil loss equation in California.* Soil erosion: Prediction and control, The proceedings of a national conference on soil erosion, Purdue University.

Farmer E.E. and Joel E. Fletcher, (1976). *Highway erosion control systems: An evaluation based on the Universal Soil Loss Equation.* Soil erosion: Prediction and control, The proceedings of a national conference on soil erosion, Purdue University.

Fogel M.M.L.H. Hekman, and L. Duckstein, (1976). *A Stochastic Sediment yield Model Using the Modified Universal Soil Loss Equation.* The proceedings of a National Conference on Soil Erosion. May 24-26, Purdue University.

Foster G.R., (1979). *Sediment yield from Farm Fields: The Universal Soil Loss Equation and farm 208 Plan Implementation.* Universal Soil Loss Equation: Past, Present, and Future, Soil Science Society of America.

Foster G.R., D.K. McCool, K.G. Renard, and W.C. Moldenhauer, (1981). *Conversion of the universal soil loss equation to SI units.* Journal of Soil and Water Conservation, November-December: 355-359.

Foster G.R., (1988). *Modeling soil erosion and sediment yield.* Soil erosion research methods, R.Lal, Soil and water conservation society, U.S.A.

Frederick R. Troeh, J. Arthur Hobbs, and Roy L. Donahue, (1991). *Soil and water conservation.* Second edition, Prentice-Hall, Inc., New Jersey.

Glymph Louis M., (1972). *Evolving emphases in sediment-yield predictions.* Present and Prospective Technology For Predicting Sediment Yields and Sources, Proceedings of the Sediment-Yield Workshop, USDA Sedimentation Laboratory, Oxford, Mississippi.

Goicoechea Ambrose, Don R. Hansen, and Lucien Duckstein, (1982). *Multi-objective Decision Analysis With Engineering and Business Applications.* John Wiley and Sons Inc., Toronto, Canada.

GRASS, (1999). Internet site of US Army Corps of Engineers, Construction Engineering Research Laboratory.
http://www.cecer.army.mil/grass/GRASS.main.html

Hayes W.A., (1976). *Estimating water erosion in the field.* Soil erosion: Prediction and control, The proceedings of a national conference on soil erosion, Purdue University.

Health and Safety Executive, (1989). *Risk Criteria for Land-Use Planning in the Vicinity of Major Industrial Hazards,* HMSO, London.

Huxhold William E., (1991). *An Introduction to Urban Geographic Information Systems.* Oxford University Press Inc., New York.

Innes Judith E. and David M. Simpson, (1992). *Implementing Geographic Information Systems for Planning: Lessons from the History of Technological Innovation.* Working paper 585, University of California at Berkeley.

Jacovkis P.M., H. Gradowczyk, A.M. Freisztav, and E.G. Tabak, (1989). *A Linear Programming Approach to Water-Resources Optimization.* Estudio Gradowczyky, Asociados S.A.T., Tres Sargentos 401, 1054 Buenos Aires, Argentina.

Kertesz Adam, (1993). *Application of GIS Methods in Soil Erosion Modeling.* Comput., Environ., and Urban Systems, 17: 233-238.

Kirby P.C. and G.R. Mehuys, (1986). *The seasonal variation of soil erosion by water in southwestern Quebec.* Can. J. Soil Sci. 67: 55-63.

Kirby P.C. and G.R. Mehuys, (1987). *Seasonal variation of soil erodibilities in southwestern Quebec.* Journal of Soil and Water Conservation, 42: 211-215.

Kreyszig E., (1993). *Advanced Engineering Mathematics.* John Wiley and Sons Inc., Toronto, Canada.

Krishna J.H., J.G. Arnold, and C.W. Richardson, (1988). *Predicting Water and Sediment Yields From Agricultural and Grassland Watersheds.* Modeling Agricultural, Forest, and Rangeland Hydrology, Proceedings of the 1988 International Symposium, Chicago, Illinois, Published by ASAE.

Laflen John M., Leonard J. Lane, and George R. Foster, (1991). *WEEP, A new generation of erosion prediction technology.* Journal of Soil and Water Conservation, No. 34.

Lal R., (1988). *Erodibility and erosivity.* Soil Erosion Research Methods, Soil and Water Conservation Society.

Lau K.K., (1988). *Linear Programming; A Computational Approach.* Chartwell-Bratt (Publishing and Training) Ltd, Sweden.

Logan T.J., Urban D.R., Adams J.R., and Yaksich S.M., (1982). *Erosion Control Potential with Conservation Tillage in the lake Erie Basin: Estimates Using the Universal Soil Loss Equation and the Land Resource Information System(LRIS).* Reprinted with permission of Journal of Soil and Water Conservation 37: 50-55.

Lowdermilk W.C., (1948). *Conquest of the land through seven thousand years.* Soil Conservation Service, U.S. Department of Agriculture, S.C.S. MP-32, 33p.

Luo, X., (1995). Erosion Risk Modeling in Mountain Environments. TYDAC Technologies Inc., Proceeding of the 1995 International SPANS workshop. Ottawa, Canada.

Major David C., (1977). *Multi-objective water resource planning.* American Geographical Union, Washington D.C.

Mays Larry W. and Yeou-Koung Tung, (1992). *Hydrosystems Engineering and Management.* McGraw-Hill Inc., New York.

McCool D.K., Myron Molnau, R.I. Papendick, and F.L. Brooks, (1976). *Erosion research in the dryland grain region of the Pacific Northwest: Recent developments and needs.* Soil erosion: Prediction and control, The proceedings of a national conference on soil erosion, Purdue University.

McGinty Allan and Larry D. White, (1996). *Range condition key to sustained ranch productivity.* TEXNAT (Texas Natural Resource Web Site), http://texnat.tamu.edu/index.htm.

Moldenhauer W.C., (1979). *Erosion Control Obtainable Under Conservation Practices.* Universal Soil Loss Equation: Past, Present, and Future, Soil Science Society of America.

Montas and Madramootoo, (1991). *A Decision Support System for soil conservation planning. Comput.*, Electron., Agric., 7: 187-202.

Morgan R.P.C., (1979). *Soil Erosion.* Longman Group Limited, London.

Morgan R.P.C., (1986). *Soil Erosion and Conservation.* Longman Scientific and Technical, UK.

Natural Resources Consultation Engineers (NRCE), (1992). *Watershed Management Studies of Damavand.* Ministry of Construction, Tehran, Iran.

Nering Evar D. and Albert W. Tucker, (1993). *Linear Programs and Related Problems.* Academic Press Inc., San Diego, CA.

Niknam F., and B. Ahranjani, (1976). *Dunes and development in Iran.* Forestry and Range Organization, Ministry of Agriculture and Natural Resources, Teheran, Iran, 21p.

Osborn H.B., J.R. Simanton, and K.G.Renard, (1976). *Use of the universal soil loss equation in the semiarid southwest.* Soil erosion: Prediction and control, The proceedings of a national conference on soil erosion, Purdue University.

Pearse C.K., (1970). *Range deterioration in the Middle East.* Proceeding of XI International Grassland Congress, M.J.T. Norman, University of Queensland Press, St. Lucia, Australia.

Pratt P.F., (1979). *Universal soil Loss Equation: Past, present, and future.* Soil science society of America Inc.

Renard K.G., G.R. Foster, and G.A. Weesies, (1989). *Predicting soil erosion by water- a guide to conservation planning with the Revised Universal Soil Loss Equation (RUSLE).* USDA-ARS.

Rewerts C. Charles, (1992). *ANSWERS on GRASS; Integrating a Watershed Simulation with a Geographic Information System.* Ph.D. dissertation, Purdue University.

Robinson A.R., (1979). *Sediment Yield as a Function of Upland Erosion.* Universal Soil Loss Equation: Past, present, and future, Soil science society of America Inc.

Roose E.J., (1976). *Use of the universal soil loss equation to predict erosion in West Africa.* Soil erosion: Prediction and control, The proceedings of a national conference on soil erosion, Purdue University.

Schwab Glenn O., R.K. Frevert, T.W. Edminster, and K.K. Barnes, (1981). *Soil and Water Conservation Engineering.* Third edition, John Wiley & Sons Inc.

Segarra Eduardo, (1992). *A Dynamic Analysis of the Crop Productivity Impacts of Soil Erosion: An Application to the Piedmont Area of Virginia.* Ph.D. dissertation, Virginia Polytechnic Institute and State University.

Singh Vijay P., (1992). *Elementary hydrology.* Prentice-Hall Inc., New Jersey.

Soil Science Society of America (S.S.S.A), (1998). *Internet Glossary of Soil Science Terms.* http://www.soils.org/sssagloss/index.html.

Srinivasan R. and Engel B.A., (1991). *Effect of Slope Prediction Methods on Slope and Erosion Estimates.* American Society of Agricultural Engineers, 7: November 1991.

Star Jeffrey and John Estes, (1990). *Geographic Information Systems, An Introduction.* Prentice-Hall Inc., New Jersey.

Stempvoort D., L. Ewert, and L. Wassenaar, (1993). *Aquifer Vulnerability Index: A GIS-Compatible Method for Groundwater Vulnerability Mapping.* Canadian Water Resources Journal, 18(1): 25-37.

Steuer Ralph E., (1995). Multiple Objective Linear Programming. University of Georgia, Athens, Georgia.

Sukresno M.S., (1991). *Evaluation of USLE, RUSLE, and MUSLE on steep watersheds in Java, Indonesia.* Ms.C. dissertation, University of Nebraska.

Tomlinson R.F. and M.A.G. Toomey, (1995). GIS and LIS in Canada. TYDAC Technologies Inc., Proceeding of the 1995 International SPANS workshop. Ottawa, Canada.

Trottier Garry C., (1992). *A Landowner's Guide, Conservation of Canadian Prairie Grasslands.* Ministry of the Environment – Canadian, Wildlife Service. http://www.mb.ec.gc.ca/ENGLISH/LIFE/WHP/PRGRASS/index.html

Walsh S.J., (1985). *Geographic Information Systems for Natural Resources Management.* Journal of Soil and Water Conservation 40: 202-205.

Wanielista Martin P. and Yousef A. Yousef, (1993). *Storm water Management.* John Wiley and Sons Inc., Toronto, Canada.

Williams J.R. and Roy W. Hann, (1973). *Problem-Oriented Computer Language For Hydrologic Modeling. Users Manual.* ARS, U.S. Department of Agriculture in cooperation with Texas Agricultural Experiment Station, Texas A&M University.

Williams J.R., (1975). *Sediment yield prediction with Universal equation using runoff energy factor. In present and prospective technology for predicting sediment yields and sources.* ARS-S-40, USDA, pp. 244-252 Washington D.C.

Wischmeier W.H., (1976). *Use and misuse of the Universal soil loss equation.* Soil erosion: Predicting and control, The proceeding of A National conference on Soil Erosion, May 24-26, 1976, Soil Conservation Society of America.

Wischmeier W.H., and D.D. Smith, (1965). *Predicting rainfall-erosion losses from cropland east of the Rocky Mountains-a guide for selection of practices for soil and water conservation.* Agricultural Handbook No. 282, 47pp.

Wischmeier W.H., and D.D. Smith, (1978). *Predicting rainfall erosion losses-a guide to conservation planning.* USDA, Agricultural Handbook, No. 537, 58pp.

Younos T.M., Yagow E.R., Zipper C.E., and Diplas P., (1993). *Modeling Mined Land Reclamation Strategies In a GIS Environment.* American Society of Agricultural Engineers, 9: 22 January.

Zeleny Milan, (1974). *Linear Multi-objective Programming.* Springer-Verlag, Berlin, Germany.