Rainfall, Runoff and Soil Degradation in the Hindu Kush-Himalayas - A Case Study in Hilkot Watershed Pakistan

by

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Abstract

Surface runoff and sediment transport are often considered as the two most important hydrological parameters in water resources engineering. Surface soil erosion from most of the areas is a serious threat to sustainable agriculture and sediment accumulation in reservoirs. An extensive runoff and soil erosion study was conducted in Hilkot watershed, Pakistan. The watershed consists of four major land uses including degraded, forests, agricultural, and pasture lands. The main objective of this dissertation was to provide a better understanding of the hydrologic and land use behavior of the watershed. Moreover, the goals were: 1) to calculate and compare annual rainfall, runoff and soil losses with their seasonal distribution from different land uses; 2) to establish rainfall, runoff and soil loss relationships; and 3) to develop a calibrated mathematical model for runoff and soil loss estimation.

Overall, the results obtained from this research demonstrated that the Hilkot watershed falls in the monsoon region with about 38% rainfall occurred in the monsoon period (July to September). The average annual rainfall found in the study area was 1160 mm. In all the erosion plots, almost 50% of the runoff and soil loss occurred during the monsoon period. The mean maximum runoff was from the degraded plot (674 m^3/ha/y), while the minimum was observed at the pasture plot (310 m^3/ha/y). The average runoffs on other land uses were 529 and 460 m^3/ha/y from the forest and agriculture plots, respectively. The average maximum soil loss was recorded from the degraded plot (6.5 t/ha/y) and the average minimum (1.8 t/ha/y) was on the pasture plot. Similarly, the average soil losses were 3.3 and 3.4 t/ha/y measured from the forest and agricultural plots, respectively.

Polynomial regression analyses were developed for predicting rainfall, runoff and soil loss relationships and showed a reasonable correlation among the parameters. A mathematical model was also developed and calibrated with field data (using a genetic algorithm approach) to estimate the total runoff and soil loss for various land uses. The model reproduced the measured field data reasonably well and it indicated the highest and lowest runoff and soil loss for degraded and pasture lands, respectively.

Preface

This dissertation was conducted by analyzing a seven-year data set for the Hilkot watershed, Pakistan. The required data were collected for the People and Resource Dynamics Project (PARDYP) in a catchment of Terbala Dam from 1999 to 2005. I was involved with PARDYP as a hydrologist and was responsible for monitoring the network and field data collection. All data were analyzed on monthly and annual basis and a numerical model was developed and calibrated with field data at the University of British Columbia.

Three papers were submitted for publication in different journals. Chapter 4 is based on submitted journal paper for publication. Zokaib, S. and Naser, B. 2010. Impacts of Land Use on Runoff and Soil Degradation in Hilkot Watershed in Pakistan. Submitted for publication in the International Journal of Sediment Research. I was involved in data collection, data analysis and paper writing. Dr. Bahman Naser was involved in editing.

Chapter 5 is based paper submitted to journal for publication. Zokaib, S. and Naser, B. 2011. A Study on Rainfall, Runoff, and Soil Loss Relationships at Different Land Uses – A Case Study in Hilkot Watershed in Pakistan. Submitted to the Journal of Hydrological Research. . I was involved in data collection, data analysis and paper writing. Dr. Bahman Naser was involved in editing

Chapter 6 has also been submitted to the Journal of Hydrology. Zokaib, S. and Naser, B. 2011. A New Approach on Modeling Soil Erosion and Surface Runoff in a Watershed. Submitted to the Journal of Hydrology. I was involved in development of mathematical model and model calibration with field data. Dr. Bahman Naser was involved in editing.

Table of Contents

List of Figures

List of Tables

Acronyms and Abbreviations

GBPIHED	G. B. Pant Institute for Himalayan Environment and Development
HKH	Hindu Kush Himalaya
ICIMOD	International Centre for Integrated Mountain Development
IDRC	International Development Research Centre
KIB	Kunming Institute of Botany
m^3	meter cube
m^3/ha	meter cube /hectare
MASc	Master of Applied Science
mm	milli meter
MONENCO	Montreal Engineering Company
MSc	Master of Science
PARC	Pakistan Agricultural Research Council
PARDYP	People and Resources Dynamics Project
PCRWR	Pakistan Council of Research in Water Resources
PFI	Pakistan Forest Institute
RF	Rainfall
RO	Runoff
SCEA	Strategic Country Environmental Assessment Report
SDC	Swiss Agency for Development and Cooperation
SL	Soil loss
t/ha:	ton/hectare
UBC	University of British Columbia
UoB	University of Bern
USDA	United States Development Agency
WAPDA	Water and Power Development Authority

Mathematical Notations

A	cross-sectional area
A_p	Area
C	concentration
c_s	cohesive strength ,
h	depth of water
m_s	mass
m_w	mass of the flowing water
$\dot{m}_{s_{in}}$	inflow rates from control volume
$\dot{m}_{s_{out}}$	outflow rates from control volume
Q	flow discharge
Q_{in}	inflow
Q_{out}	outflow
R_h	hydraulic radius
S_f	slope of energy grade line
S_t	rate of the released eroded material
V	volume
W_p	wetted perimeter
γ_w	specific weight of water
ρ_w	density of water
σ	effective normal stress
τ_a	available shear stress
τ_s	shear strength
τ_s	erosion yield strength
φ	angle of repose.

Acknowledgements

First and for most I am very grateful to the Almighty ALLAH, without his support and blessings, this piece of work would never have been accomplished.

My sincere gratitude goes to my supervisor Dr. Bahman Naser for his sympathy, encouragement, endless patience, and valuable guidance. He has been sensitive and softhearted; he always tried to take care of every problem I had during my entire study and research period. He was more like a friend than just a professor. Due to his coaching and encouragement, I have been able to finish my M.A.Sc. dissertation successfully and it is my privilege to acknowledge his guidance.

I would like to extend gratitude to my committee members, Dr. Kasun N. Hewage, and Dr. Shahriar Alam for their advice and input. The author gratefully acknowledges the input of Dr. Rehan Sadiq, M. Shafiqul Islam, Rehan Ahmed, Mike Cresswell, and Saheb Mansour Rezaei.

I would also like to thank my family for the unconditional love and support they provided me throughout my life and in particular during study period. I would acknowledge the contributions of my parents, wife, children, brother and sisters for their continuous support, enthusiasm, and encouragement to accomplish my goals. Without their love, support and encouragement, none of my achievements would have been possible. I would like to express my gratitude to all my friends and colleagues, who have been helping and encouraging me during study and thesis writing periods.

Finally, I am thankful to my colleagues in the People and Resource Dynamics Project, Pakistan Forest Institute Peshawar and International Centre for Integrated Mountain Development, especially Hakim Shah, Mohammad Jehangir and all field staff for their cooperation, guidance and hard work in data collection and processing.

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DEDICATED

TO

MY PARENTS, WIFE AND CHILDRENS

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Chapter 1: Introduction

"Only 2.5% of the world's water is not salty, and two-thirds of that is trapped in the icecaps and glaciers. Of what is left, about 20% is in remote areas and most of the rest comes at the wrong time and in the wrong place, as with monsoons and floods. The amount of fresh water available for human use is less than 0.08% of all the water on the planet. About 70% of the fresh water is already used for agriculture, and the report says the demands of industry and energy will grow rapidly. The World Water Council report estimates that in the next two decades the use of water by humans will increase by about 40%, and that 17% more water than is available will be needed to grow the world's food. The commission concludes that only rapid and imaginative institutional and technological innovation can avoid the crisis."

(BBC News, "Water arithmetic doesn't add up", 13 March 2000)

As the above quotation implies, fresh-drinking water reserves are scarce; consequently, ensuring a safe, reliable, and sustainable water resources to supply water to various users is a key priority for all water authorities. Amongst all the natural resources, water is perhaps the most precious but globally misused one. This exigency highlights the quest for a more realistic understanding of water resources systems and predicting their responses to various changes.

While Pakistan is blessed with adequate water resources, its rapid population growth and lack of planning in water resources management have placed a massive pressure on quantity as well as quality of the water in the country. Pakistan's current population of 170 million is growing at an annual rate of 1.5%, and it is expected to reach approximately 221 million by 2025. Water availability per capita in Pakistan has decreased from 5000 m^3 in 1951 to 1100 m^3 per annum in 2006 and expected to reach at 850 m^3 in 2013 (Pak-SCEA, 2006). The minimum water requirement per capita for a country not to be a "water shortage country" is 1000 m^3. Decreasing trend of water resources in the country shows that Pakistan may reach the stage of "acute water shortage country" in 2012, if proper actions are not taken (WAPDA, 2002). Pakistan, once a water surplus country, is heading toward becoming a water-deficit country due to lack of management and future planning. WAPDA (2002) reported that water availability and quality is currently unable to meet the economic, social, and environmental needs of Pakistan.

This is largely due to the inefficient irrigation practices in agriculture, which consume more than 90% of the water extracted from the Indus basin.

About 51% of Pakistan (404195 km^2) is part of Hindu Kush Himalayan (HKH), while around 23% of the country's population (40 millions) live in the Hindu Kush Himalayas region (Banskota and Sharma, 1994). Water, a fundamental need for survival of human, has already become scare in the Hindu Kush Himalayas region. Based on an opinion poll conducted in July 2002, Merz (2003) indicated water scarcity, floods, water pollution, erosion and sedimentation, unequal access to safe water, water resources availability, biodiversity decline, and wetlands destruction as the key water related issues in Hindu Kush Himalayas region. Lack of water resources management and catchment degradation may also affect water availability (Chalise and Sial, 2000). In low rainfall areas, water availability problem is more acute. Due to depletion of groundwater, the degree of desertification is also feared in some parts of Hindu Kush Himalayas (e.g., Baluchistan, Pakistan). Recent studies (Tahir, 1994 and Pak-SCEA, 2005) showed that pollution in groundwater is also increasing. The crisis of decreasing water availability is not only seriously effecting the economic development of the region but also threatening the survival of rural mountain people who are directly depending on rainwater (ICIMOD, 2000). Rodda (2001) illustrated that densely populated Hindu Kush Himalayas region is a home to millions of people who rely on the water resources directly coming from the Ganges-Brahmaputra and the Indus rivers in the Indian subcontinent and the Yangtze and Yellow Rivers in China. This region is projected as increasingly water scarce in years to come. Increase in population growth (and thus water demand for agriculture, industries, and sanitation) on one hand and decrease in water resources on the other hand widen the demand and supply gap.

Water is life; too little and too much water are issues that are both prevalent in the Hindu Kush Himalayas region on an annual basis during the monsoon and dry seasons. Merz (2000) indicated that a large quantity of water is available during the monsoon season (July to September), while insufficient water is present in the winter season (December to February). High intensity monsoon rainfalls are major cause of floods and sediment loss in the region. The sediment load in the Hindu Kush Himalayas rivers are amongst the highest in the world, resulting in reservoir siltation, water quality and blockage of river channels. The major sources of sediment loads are landslides, overgrazing, and intensive cultivation in hilly slopes (ICIMOD, 1999).

Stoddart (1969) reported that the Asian rivers deliver about 80% of the total sediments to the oceans, with the Himalayan Rivers being major contributors. Due to poor land management, sediments continue to deposit in rivers causing damage in infrastructures, loss of topsoil (a key issue in agriculture), blockage of water channels, and water quality for drinking and agriculture purposes.

The increasing population in Pakistan demands steep land cultivation in hilly areas and construction of new reservoirs to meet agricultural and energy demands. Unfortunately, for all development and research projects in the country, base line data are not available, which is very important for planning and designing, are not available. The lack of adequate data and reliable information at planning stage can lead a hydrologic/hydraulic system to fail, unless otherwise unnecessary conservative safety factors are considered at the design stage (USDA-SCS, 1942). There is an increasing need of awareness to protect the natural resources in order to meet present and future requirements. Since the economies and environments are dependent on healthy soil and water, it is essential to ensure the sustainable use of the resources to meet growing demand of population and protect our natural resources for future generations. Carver (1997) reported that no matter how good the economy is and no matter how many additional resources can be brought in from external sources, if erosion is excessive, site degradation will put the entire system into decline and ultimate failure.

As water resources and sediment transport issues continue to grow scarcely, the demand intensifies for innovative approaches that provide better understanding and management of the available water resources. Thus, it becomes necessary to have a better understanding of the natural processes causing runoff and sediment generation and to identify the influence of human activities on the watersheds in these areas. To fully understand the system and the involved hydrological and soil erosion processes, continuous monitored data is important. Unfortunately, little reliable climatic and hydro meteorological data is available in the Himalayan region and the existing monitoring networks are not adequate and often poorly maintained. This leaves very small amount of good quality data available in the Hindu Kush Himalayas region. Therefore, long-term database is needed for the assessment and planning of resource dynamics and its impacts on human life. Even in intensively monitored watersheds, the data for all parameters are not often available. Therefore, there is a need to take alternative methods for different parameters prediction using available information. In the absence of reliable field data, demand for alternative methods such as mathematical models and different relationships among the involving parameters are increasing. Therefore, investigation of the relationships between vegetative cover, rainfall, runoff, and soil loss is important. Moreover, the establishment of relationships between all of these parameters is challenging due to large number of factors involved and also the stochastic nature of the processes being studied (Bultot et al., 1990). Over the years, several hydrological models have been developed for the runoff and soil loss prediction at plot as well as watershed level (Raghuwansh, 2006). Marsh and Marsh (1995) reported that in the absence of reliable data for specific area, different relationships are most effective and reliable tools to estimate water flow in a watershed. Sophisticated hydrologic models and parameters relationships will help the water authorities to make more informed decisions at design and operation stage.

The depletion of natural resources such as land, water, and forest in the Hindu Kush Himalaya region is a serious concern. This study will attempt to fill some of the gaps and contribute to a better understanding of runoff and soil erosion processes in the region. The research was based on an extensive field study in the Hilkot watershed conducted by the People and Resource Dynamics Project (PARDYP) from 1999 to 2005 at plot and the watershed scales for different land uses (i.e. degraded, forests, agricultural, and pasture lands) in the region. Important parameters like rainfall, runoff, soil loss, and discharge were measured, while discovering their relationships and behaviors on different land uses. In this study, the focus was on the Hilkot watershed containing almost all representative land uses.

1.1 Thesis Objectives

This dissertation was an attempt to contribute to a better understanding of the runoff and soil erosion process in the Hilkot watershed by studying some of the key factors that are essential for optimum operation of local water resources. The primary objective of this research was to provide a more realistic decision-making tool for local water authorities in Hindu Kush Himalayas region. Such a tool will help them to have more reliable estimates towards the surface runoff and sediment transport and land use impacts on runoff and soil loss in the Hindu Kush Himalayas region. The primary objectives were achieved through the following goals:

1. to investigate monthly, annual runoff and sediment losses from different land uses;

2. to estimate and compare seasonal distribution of rainfall, runoff, and soil loss on different land uses;
3. to develop rainfall, runoff, and soil loss relationships for different land uses; and
4. to create a calibrated mathematical model for runoff and soil loss for different land uses in the watershed.

1.2 Thesis Organization

The structure of this thesis was based on journal articles (submitted). Thus, small overlaps may occasionally be noticed among the chapters. Figure 1.1 represents a schematic flowchart illustrating the thesis structure in terms of the division of the thesis into various chapters. As the figure indicates, the thesis includes the following seven chapters:

Chapter 1 provides an introduction and general overview of the problem, highlighting research significance, as well as the research objectives. This Chapter also discusses some key issues in the region, scope, and research contributions and thesis structure.

Chapter 2 discusses the research area, measurement networks, methodology, and data collection techniques. This chapter also explains the base line information of the research area such as watershed characteristics, land uses, population, and climatic information of the study area.

Chapter 3 reviews the related previous studies in the literature providing an overview of water crises in Pakistan, runoff and soil loss issues in the region, seasonal distribution, land use impacts on runoff and soil loss, and runoff-sediment transport mathematical models. This chapter emphasizes on different approaches for runoff and soil loss estimation and their impacts.

Chapter 4 contains the impacts of land uses on runoff and soil degradation in the Hilkot watershed. The main emphasis of this chapter is on the 1^{st} and 2^{nd} research objectives. This chapter marks the completion of runoff and soil loss data analysis and detail study of land use impacts on runoff and soil loss generation.

Chapter 5 includes a study on rainfall, runoff, and soil loss relationships at different land uses. The chapter addresses the 3^{rd} objective of the dissertation for investigating rainfall, runoff and soil loss relationships. The chapter discusses polynomial regression models for runoff and soil loss different land uses.

Chapter 6 accounts for a mathematical modeling of surface runoff and soil erosion for the Hilkot watershed. This chapter also discusses a genetic algorithm approach to calibrate the model.

Chapter 7 summarizes and concludes all the findings of the thesis. This chapter also makes some recommendations for future research.

References This section contains a list of all references used in thesis.

Appendices This section includes raw data used in this thesis.

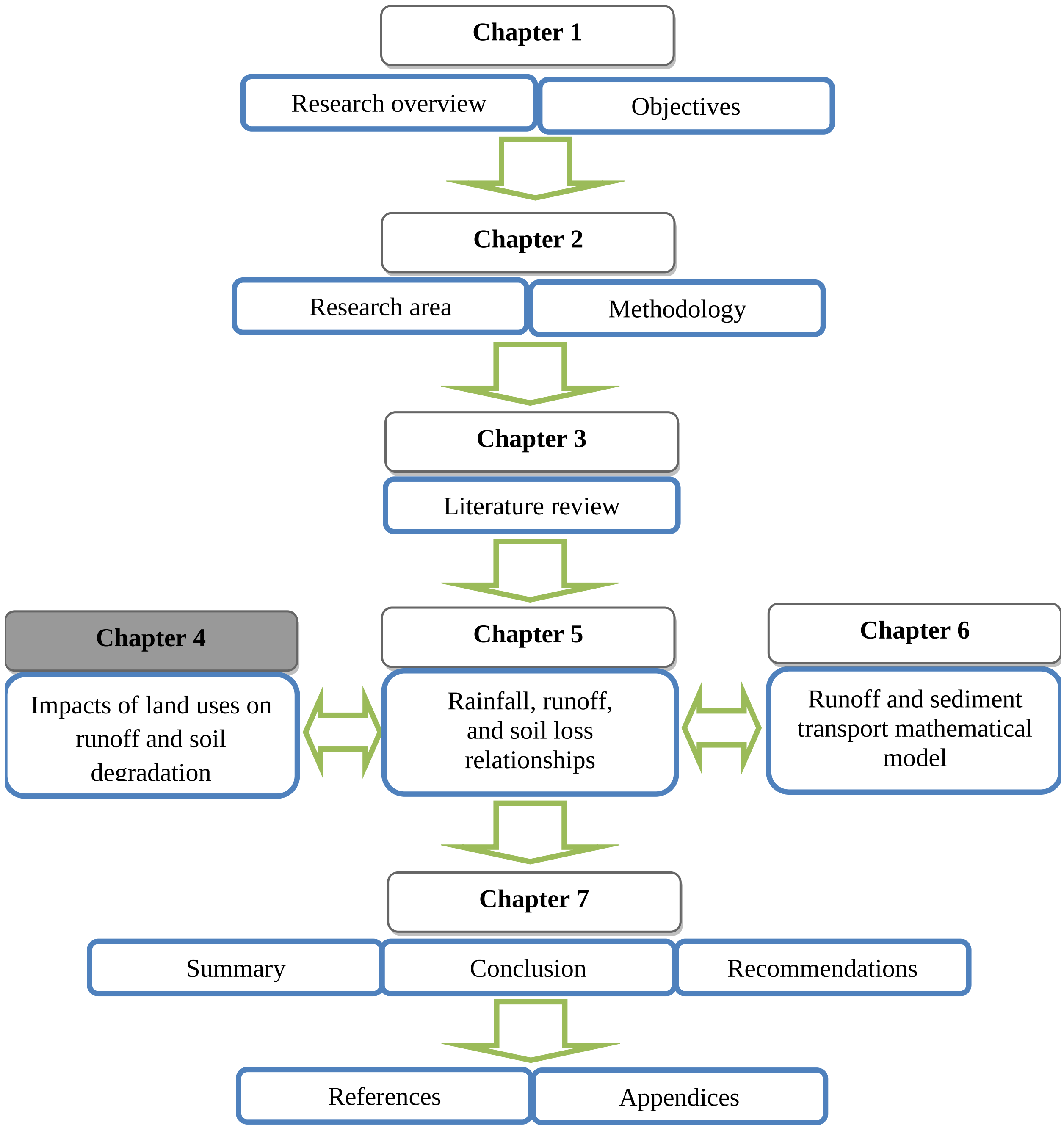


Figure 1.1 – Thesis organization

Chapter 2: Research Area and Methodology

"It is a capital mistake to theorize before one has data. Insensibly one begins to twist facts to suit theories instead of theories to suit facts."

(Sherlock Holms)

This chapter introduces the Hilkot watershed and its hydrological/meteorological characteristics, land uses, population and some climatic information of the research area. The chapter also explains the research methodology and field data collection techniques and devices. Some part of this chapter appeared in the journal publications.

2.1 Research Area – Hilkot Watershed

The research was conducted on the hilly area of Hilkot watershed (Figure 2.1), district Mansehara, Pakistan. The Hilkot watershed with an area of 1600 ha (located in the northern part of Pakistan on 34.5°N and 73°E) lies in the catchment area of Siran River; an important tributary of the river Indus draining directly into the Tarbela reservoir. The geology was roughly mapped, whereby granite, mica schist, slate, loess and alluvium were discovered (PARDYP, 2004). In contrast to the other regions in the Himalaya and Karakoram, this area lies outside the influence of glaciers and their melted waters. Therefore, only precipitation and natural spring water brings available water into the catchment. The tract falls in humid temperate climatic region; however, within the region, the altitude and aspects create great climatic variations. Average rainfall of the area is more than 1000 mm. The research area is in the monsoon region and receives about 40-50 percent of precipitation in summer months (July to September). Winters are normally severe and dry with very low precipitation. The average temperature is 10^{o}C or above for four to seven months.

2.2 Operational Background of the Study

From 1999 to 2005, a 7-year field study was conducted by People and Resource Dynamic Project (PARDYP) in Hilkot watershed Pakistan. PARDYP was a multidisciplinary regional watershed management, research and development project, involved in the fields of meteorology, hydrology, soil erosion, and fertility studies. This project operated in five watersheds in the middle mountains of Hindu Kush Himalayas in four partner countries including Pakistan, India, Nepal, and China. As Figure 2.2 shows these watersheds are Hilkot watershed in Pakistan, the Bhetagad watershed in India, Xi Zhuang watershed in China, the Jhikhu Khola and Yarsha Khola watersheds in Nepal (ICIMOD, 1999). Although the PARDYP project involved four countries, the current research focused only on the Hilkot watershed in Pakistan.

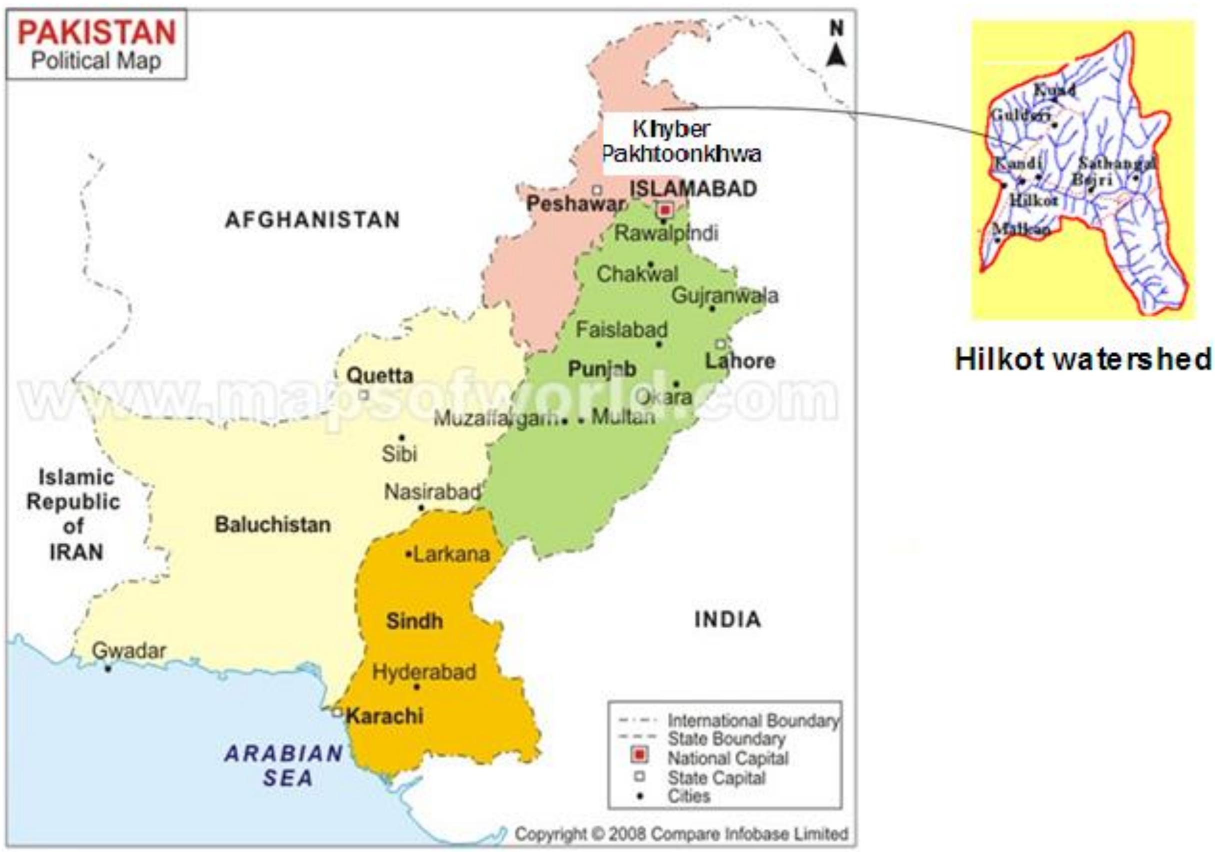


Figure 2.1 – Schematic position map

Selected national research institutions implemented, managed, and supervised with the assistance of international partners and collaborators. International Centre for Integrated Mountain Development (ICIMOD) provided the overall coordination and guidance. The required activities were carried out by local teams in each country i.e. the Kunming Institute of Botany (KIB) in China, the G. B. Pant Institute for Himalayan Environment and Development (GBPIHED) in India, ICIMOD in Nepal, and the Pakistan Forest Institute (PFI) in Pakistan.

Two international collaborators supported PARDYP including the University of British Columbia/Canada in the fields of resource management and soil fertility studies, and the Hydrology Group of the University of Bern/Switzerland in the field of water and soil erosion studies. The project was funded by the Swiss Agency for Development and Cooperation (SDC), International Development Research Center (IDRC) Canada, and contributions from all collaborating partners. In order to be able to share and utilize the data for regional database, a network of hydrology, meteorology and erosion plots was set up in all the five watersheds of the four countries along with similar equipments and technologies of data collection (PARDYP, 1999).

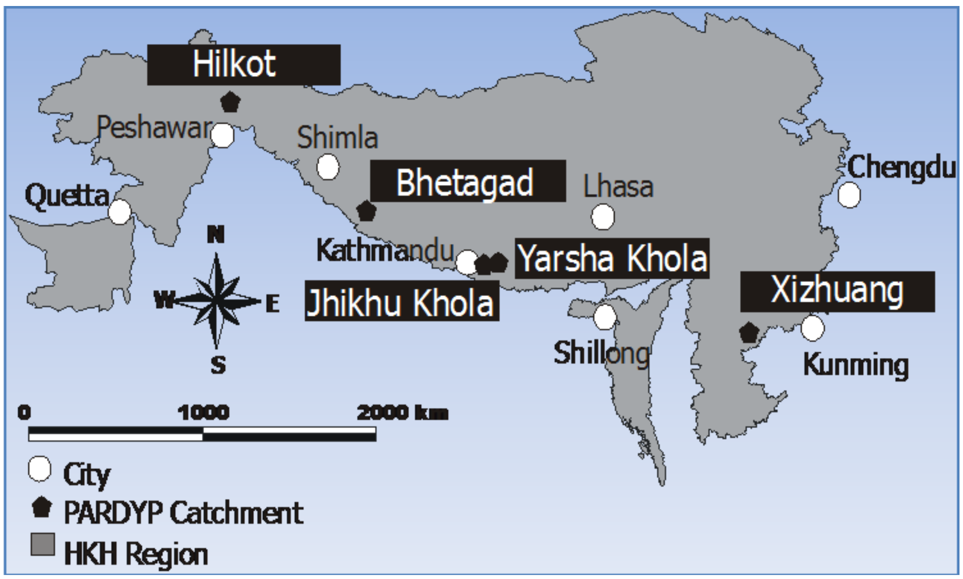


Figure 2.2 – Location of PARDYP watersheds in the Hindu Kush Himalayas (ICIMOD, 1999)

2.3 Hilkot Watershed – Base Line Information

2.3.1 Population

Hilkot is a small village, six kilometers away from the Karakoram Highway, connected through a small road entering at Battal. A livelihood survey conducted by PARDYP (1999) indicated a population of 6630 living in the Hilkot watershed. This made it a densely populated area with around 414 persons per square kilometer with an average of 7.74 persons per household with 51% male and 49% female. The statistical bureau of the Khyber Pukhtoonkhwa

Province showed an annual growth rate of 2.4% for the population of the district Mansehara (NWFPSTAT, 2005).

2.3.2 Land Use

In the Hilkot watershed, the major land uses (Figure 2.3) include forestland (20%), rangeland (34%), irrigated (6%) and rainfed agriculture (40%) with small patches of degraded land (Zokaib, 2000). This diversity was associated with scarcity of irrigation water. The dominant forest species in the area were *Pinus wallinchina, Ilenttaaus altisima* and *Robinia pseudocacia*. Rangeland is steep used for animal grazing and forage production. Due to increase in demand of agricultural products, steep rangelands are being converted into agriculture land by making small terraces. Water scarcity and difficulty in transportation due to topography leaves only 6% of the area under irrigation (PARDYP, 1999).

Agriculture is the main source of income and priority sector of the people in the Hilkot watershed. The majority of the people living in the catchment are primarily involved in agriculture practices on small land holdings. Most of the agriculture system is mono cropping. Maize on rainfed agriculture and rice on irrigated fields during the summer season are main crops. In winter, people normally leave the fields bare.

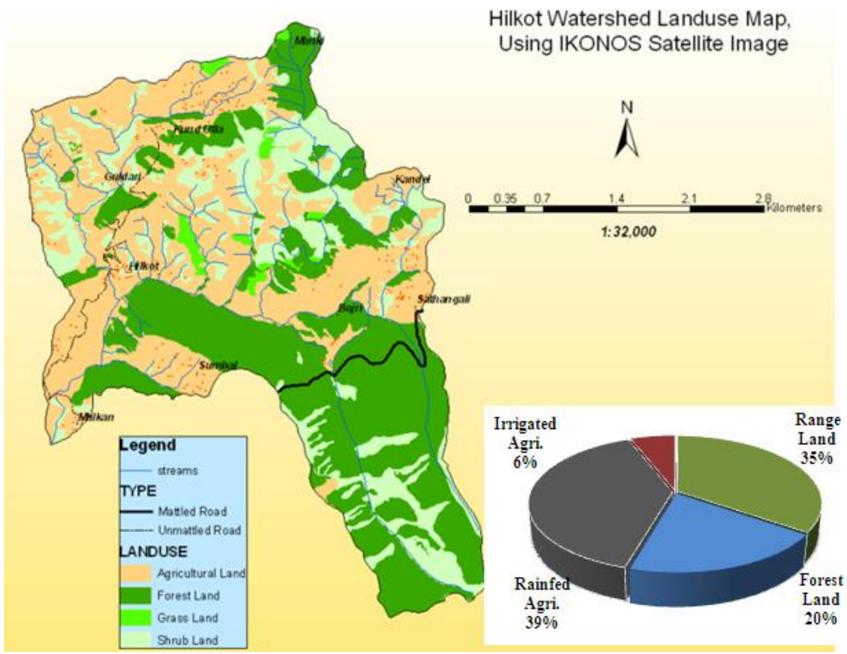


Figure 2.3 - Land uses in Hilkot watershed (PARDYP, 2001)

2.3.3 Local Climate and Seasons

Pakistan enjoys all four seasons. The mountainous ranges of northern Pakistan are extremely cold in winter (December to February) while the summer months (July to September) are very pleasant. The plain area of the Indus Valley have cold weather in winter but are very hot in summer, while coastal strip in south has a temperate climate (Ali, 2007). In general, annual rainfalls vary significantly from area to area and low in amount to meet the country needs. The annual rainfall in the country ranges from 150 mm (plains) to 1500 mm (in northern part). Rains are monsoonal (July to September) in the region and fall late in summer (Banskota and Sharma, 1994). In general, there are two well-defined mechanisms producing precipitation in the Hindu Kush Himalayas including Hilkot watershed. These include the summer monsoon and western disturbances in early springs (March) and late winter. In summer (July to September), large part of Pakistan is strongly affected by the monsoon system. The monsoon rains are normally frequent short spells with high intensity, which results in flash flooding and soil erosion. The main seasons experienced on the study area are pre-monsoon (March to June), monsoon (July to September), and post-monsoon (October to February).

Local climate of the study area is humid temperate. Hilkot watershed receives most of the rainfall in the monsoon season lasting from July to September with very little rainfall in autumn (October to February). During the study period (1999-2005), rainfall varied between 917 to 1778 millimeters annually and up to 40-45% of the rainfall occurred in the monsoon period. High intensity monsoon rainfalls caused major portion of the total annual runoff and soil loss on all land uses. An average maximum air temperature of $27^{o}C$ was observed in June, while average minimum of $1^{o}C$ was measured in January. The mean maximum and minimum soil temperature of $29^{o}C$ and $2^{o}C$ were measured in July/August and January, respectively. Average daily wind speed measured at 1.8 m (6 ft) height ranged from 33 to 82 km/hr in August and June. At 3 m (10 ft) height maximum daily wind speed ranged from 71 to 130 km/hr in January and March. Daily evaporation ranged from 0 to 12 millimeters and average monthly evaporation was in the range of 33 millimeters in January to 146 millimeters in June. Average relative humidity in the watershed varied from 54% in May to 76% in August. Daily sunshine hours ranged from 0 to 13 hours. Average monthly maximum sunshine was 269 hours recorded in May and minimum was 148 hours recorded in February (PARDYP, 1999-2005). Table 2.1 provides additional details of all meteorological parameters in the Hilkot watershed.

Table 2.1 - Meteorological parameters summary in Hilkot watershed, Paksitan (Jehangir, et al, 1999-2005)

Months	Air Temperature (^oC)		Soil Temperature (^OC)		Wind Speet		Evaporation (mm)/month	Humadity (%)	Sunshine Hour (monthly)
	Max	Min	Max	Min	6 Feet	10 feet			
Jan	9	1	7	2	50	71	33	58	158
Feb	10	2	9	2	71	97	40	63	148
Mar	15	5	13	4	74	130	74	56	211
Apr	20	10	19	11	80	127	109	58	217
May	25	13	27	17	78	121	137	54	269
Jun	27	16	29	20	82	114	146	59	265
Jul	26	17	28	21	56	88	123	70	252
Aug	26	17	27	21	33	78	113	76	255
Sep	25	15	25	18	42	77	106	73	247
Oct	22	12	20	13	48	82	93	64	267
Nov	16	7	14	6	42	76	60	60	225
Dec	11	3	8	3	46	78	53	62	166
Max	27	17	29	21	82	130	146	76	269
Min	9	1	7	2	33	71	33	54	148
Average	19	10	19	11	59	95	91	63	223

2.4 Field Measurement and Data Collection

2.4.1 Measurement Network

PARDYP established an effective and efficient network of meteorological, hydrological stations, and erosion plots in Pakistan. The selection of sites and the establishment of hydrometric stations were carried out in 1998, while the proper data collection was started in 1999. There were six hydrological and six meteorological stations at different sites of the watershed representing different altitudes, catchments with different land uses, and various soil and climatic conditions. In addition, four erosion plots on the degraded, pasture, forest, and agricultural lands were established to calculate and compare runoff and soil loss at different plant covers and soil conditions. Figure 2.4 presents the hydro meteorological and erosion plot network in the watershed.

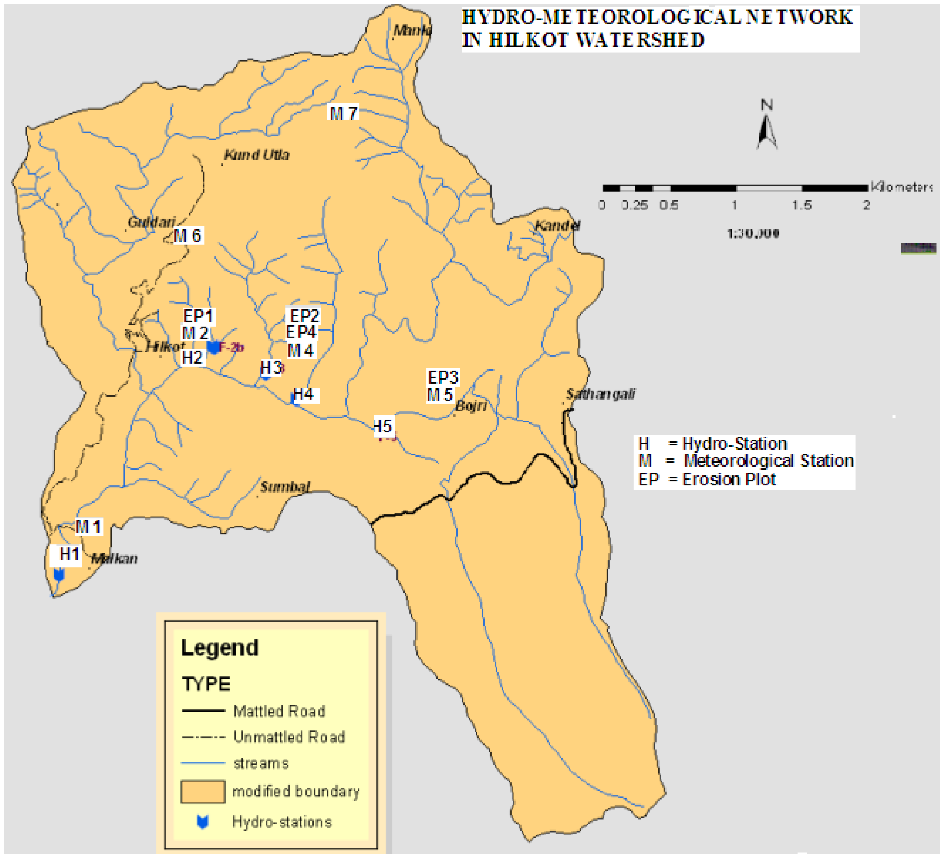


Figure 2.4 - Hydro-meteorological and erosion plot network at Hilkot watershed, Pakistan (PARDYP, 1999)

2.4.2 Data Collection –Nested Approach

In the Hilkot watershed, the project activities were carried out on three scales including the watershed as a whole, the sub-catchments, and the test plots. Each level formed a part of the next higher level (e.g., an erosion plot was part of a sub-catchment and a sub-catchment was a part of the whole watershed). As Figure 2.5 schematically indicates nested approach that allowed investigating the processes from small plot to the whole watershed level. All relevant parameters were monitored at each level. For example, on plot level, rainfall was measured with a tipping bucket, and runoff and soil loss were determined by means of erosion plot method. The meteorological stations were established very close to the erosion plots. Automatic (tipping bucket) and manual rain gauges were used to measure rainfall amount and intensity in all meteorological stations. Data from the tipping bucket were downloaded monthly. Erosion plots at different land uses and surface flow collectors (drums) were used for runoff and soil loss at the plot level estimation. The whole catchment was monitored with hydrological stations (flume) equipped with different stage measuring devices (Hofer, 1998).

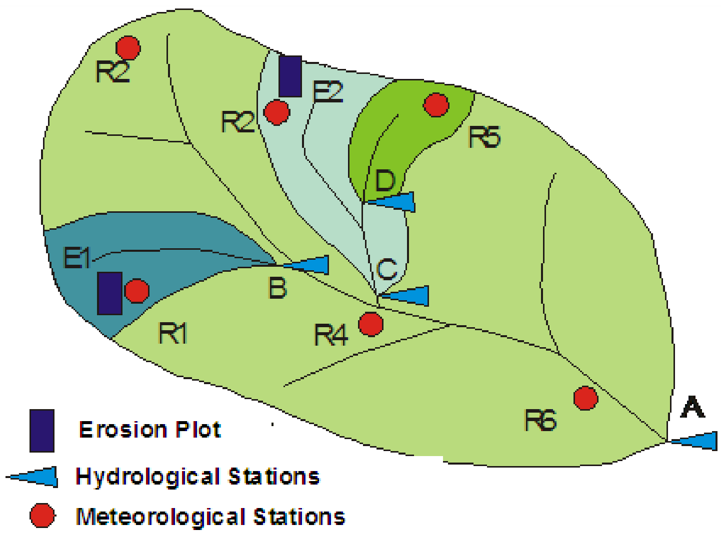


Figure 2.5 - Schematic diagram for the measurement network (Hofer, 1998)

2.4.3 Erosion Plot Network

In Hilkot watershed, four erosion plots were established on various land uses (i.e., degraded, forest, pasture, and agriculture) (Figure 2.6). A 100 m^2 rectangular plot (Figure 2.7) was established measuring 20m by 5m. Table 2.2 lists detailed information about all the plots and their properties. Metal sheets were inserted along the line with 15cm kept inside the ground and remaining 30cm pointing outwards to control additional water entrance. Lower end of the erosion plot was left open for the gutter that diverts runoff and eroded material into the collection system. The collection system composed of 4 drums of 200 liter each interconnected with each other. The metallic gutter was 5m long covering plot width. Rainwater ran off the plot and streamlined into drum through the gutter (Nakarmi, 2000).

After each rainfall event, water depth in each drum was recorded for daily total runoff and samples from each drum were taken to analyze the total sediment loss. The samples were filtered in the laboratory and oven dried to calculate soil loss. Samples were processed in the field laboratory in the following manner:

- filter paper was dried in an electric oven at 60-65°C,
- the filter paper was weighed directly from the oven (before it can recapture moisture),
- a 100 ml sample was filtered through a filter paper,
- the filter paper with sediment was dried in the oven,
- the sample was weighed while still warm, and
- the net weight of the sediment sample was calculated as the difference between the weight of filter paper plus sediment and the dry weight of filter paper.

The sediment derived from the sample was extrapolated to the content of the entire drum. The results from all drums were then summed up to determine the total soil loss from the plot. Runoff and soil loss were calculated per unit hectare.

Table 2.2 - Erosion plots network in Hilkot watershed, Pakistan

Site No	Land use	Elevation (m)	Area (m^2)	Slope (%)	Textural Class	Bulk Density (g/cm^3)
Plot 1	Degraded	1677	100	50	Silt Loam	1.66
Plot 2	Pasture	1707	100	43	Silt Loam	1.68
Plot 3	Forest	1707	100	42	Loam	1.45
Plot 4	Agriculture	1723	100	22	Silt Clay	1.59

2.4.4 Hydro Station Flow Measurements

Hydrological monitoring in the Hilkot watershed in Pakistan was conducted at hydrometric stations at the catchment outlet (Figure 2.8). The water level at hydro station (i.e. stage) was measured with respect to pre-set datum. All continuous discharge derived from a continuous stage record depended on the accuracy of the stage values. Different instruments depending on flow, structure, and capacity of streams were used for the stage height measurement.

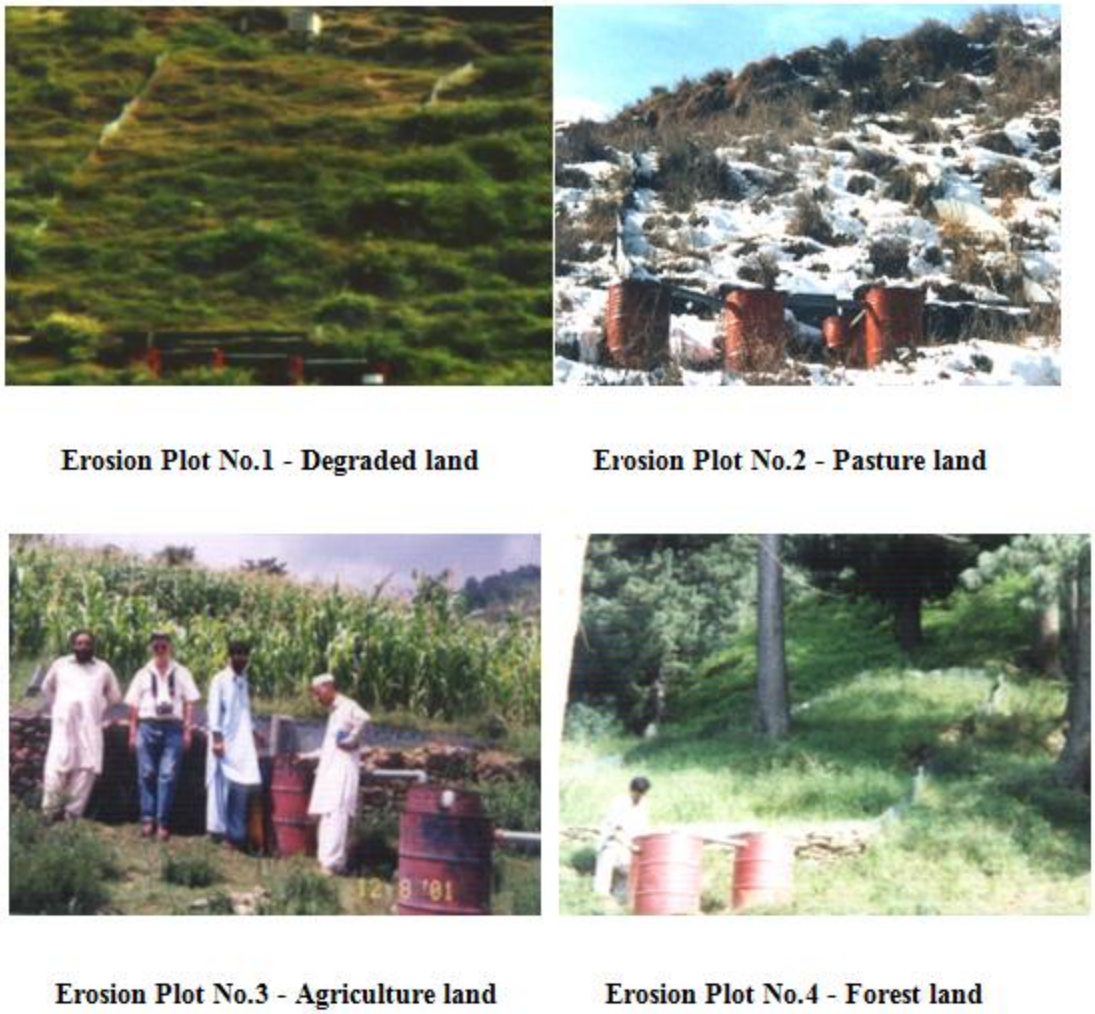


Figure 2.6 - Erosion plots at different land uses in Hilkot watershed

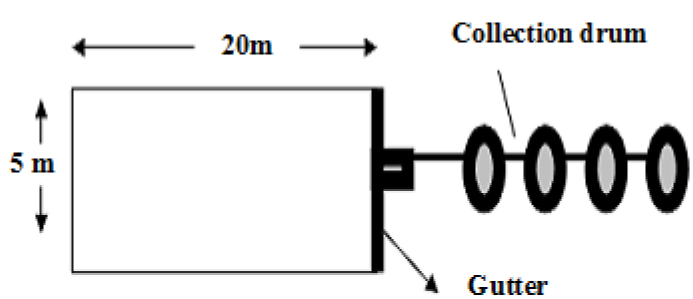


Figure 2.7 - Erosion plot diagram and dimension in Hilkot watershed, Pakistan (Zokaib, 2005)

In Hilkot watershed, manual staff gauge and automatic water level recorders (floater type) measured the continuous water level (Figure 2.9). Manual staff gauge provided a quick and easy visual reading of water level. Staff gauge was fixed vertically with the concrete wall in the stream, unaffected by flow turbulence. The automatic water level recorder provided continuous water level with high accuracy on a chart. The floater changed its position with rise or falls of water level in the water tank and was registered on a chart. A single chart provided 16 to 32 days of data depending on season and chart type. This data was converted to discharge by using stage discharge relationship curves (rating curves). Discharge was measured and sediment samples were taken on different water levels during flood to generate stage vs. discharge and stage vs. sediment concentration relationships. Discharge measurements and sediment sampling were challenging. Due to steep topography of the area the floods were generally very short in duration and most occurred during night time. Thus, a monitoring team was trained for each station. A small bridge was constructed at each station for sediment sampling and discharge measurement during floods.

Figure 2.8 - Main hydro station at Hilkot watershed, Pakistan

A- Staff Gauge B- Automatic Water Level Recorder

Figure 2.9 - Stage measurement's instruments used in Hilkot watershed, Pakistan

Chapter 3: Literature Review

"Between earth and earth's atmosphere, the amount of water remains constant; there is never a drop more, never a drop less. This is a story of circular infinity, of a planet birthing itself".

(LINDA HOGAN, Northern Lights, Autumn 1990)

This chapter reviews the previous studies in the literature and provides an overview of water crises, runoff and soil loss issues in Hindu Kush Himalayas region, seasonal distribution, land use impacts on runoff and soil loss, and runoff and sediment transport modeling.

3.1 Water Quantity/Water Scarcity

The Hindu Kush Himalayas region is one of the largest fresh water resources in the world. These mountains are often considered as "water towers" by storing water in the form of snow. They supply major contributions to river flows and control seasonal discharge variability in the plains. Therefore, water resources degradation in the mountains for quantity and quality poses serious threats to the peoples and ecosystem (Merz, 2004). Rodda (2001) argued that Hindu Kush Himalayas region is facing water scarcity and projected an increasingly water scarce in years to come. Major causes of water resources degradation are increasing population that directly increases water demand for agriculture, industries and household use, and widening the demand and supply gap.

Water is Life – a perception shared by most of the residents in catchments of the Hindu Kush Himalayas. Simultaneously water is destructive in form of floods and reason of great despair in many regions of the world (ICIMOD, 2000). Presently problems related to water are mostly concerned with quantity. In Hindu Kush Himalayas, which falls in monsoon region, the problem is annual extremes, on annual basis "too much" during wet season and "too little" during the dry season, respectively (Merz et al., 2000). A large quantity of water are available during the monsoon season (July to September), but the region is generally dry, and insufficient water is present in the winter season (December to February). During the monsoon period, large amounts of surface runoff leave the watershed, causing erosion and sedimentation in streams. This seasonal precipitation greatly influences water supply in different seasons, and water scarcity is even common in the high precipitation areas during dry periods. Rainfall intensity is usually high in the monsoon season as compared to the rest of the year (Zokaib et al., 2005 and ICIMOD, 2000). Sivall (1977) showed that the monsoon circulation affects the northeastern edge of the Himalayan foreland much stronger than the one on the North West. Further, he demonstrated that the Afghani Hindu Kush is not affected by the monsoon.

The water quality and the quality of life in all its infinite forms are critical everywhere including Pakistan. On one hand, the fresh water resources in Pakistan have been drastically reduced, while on the other hand, the available water resources have been inefficiently used in the agriculture, industrial, commercial, and household sectors. The gap between supply (water availability) and demand (its extensive use) has been widening (PARC, 2006). Pakistan's population is increasing at an alarming rate and water demands for different sectors are increasing day by day forcing people to convert different land uses to agriculture land and for steep cultivation in hilly areas (PCRWR, 2006). Pakistan's fresh water resources have been drastically reduced due to the degradation of water related ecosystems and deterioration of water quality. Increasing water demand in Pakistan puts substantial pressure on the limited water resources (WAPDA, 2005). A study conducted by the Siran project, in Hazara (Pakistan) shows 52% decline in the resource from 1967 to 1992. Similar cases are present in other areas of Pakistan including the Kaghan and Allai valleys. Almost more than 50% of the natural forests have been already utilized for different purposes. About 60% of the natural grazing and pasture lands have production levels lower than one third of their potential. Due to water scarcity and management, more than one-third of the country is under risk of desertification (Shah, 2006).

It is estimated that by 2025, Pakistan requires almost 100% of its utilizable water resources to feed an increasing population. Rural communities, which face poor access to safe drinking water for their domestic demand, are threatened by reducing water (WAPDA, 2005). According to Gleick (2000), the per capital water use in the Hindu Kush Himalayas countries was below 60 l/person/day in the year 2000. The minimum per capital water use was estimated for Bhutan with (10 l), Nepal (12 l), Bangladesh (14 l), Myanmar (15 l), Afghanistan (28 l), India (31 l), Pakistan (55 l), and China (59 l) which is far below from the developed countries like Canada (329 l/day) (Environment Canada, 2007). It is not only the amount of water which in most cases affects water availability, deteriorated water quality has also impacts on water availability.

Most developing and third world countries still have no access to safe and affordable drinking water. Alcamo et al. (2000) stated that about 38% of the world population lives under severe water stress. Sufficient water resources for future generation are a major global issue. Internationally, the water demand has increased six fold from the previous century and about half of fresh water resources have been directly used for human purposes (Cosgrove and Rijsberman, 2000). Shiklamonov (2000) reported that water availability is dramatically decreasing since 1995. Negi and Joshi (2002) concluded drinking water as a major issue in the Himalaya. Natural springs are drying and drinking water scarcity is putting substantial pressure on the local population. Singh and Pandey (1989) also identified water shortage due to the drying up springs in the Himalaya and reported forest degradation as the major cause. A study conducted by Zokaib et al (2004) showed that due to low precipitation almost 30 % of natural spring dried up during 5-10 years. Chalise et al. (1993) reported changes in land use patterns as one of the causes of drying up of groundwater resources. Over the past 20 years, people have been more concerned about the environment and land degradation, which rings attention on major issue of environment and natural resources in hilly areas. The expansion of agriculture to steep areas and increase in cropping intensity has a direct impact on sediment production.

3.2 Runoff and Soil Erosion in Hindu Kush Himalaya

Runoff and soil erosion are often considered as the most important parameters in every watershed hydrology. With different climate and soil conditions, runoff and soil loss rates vary with the change of land use type. The quantification of runoff and soil erosion is a major challenge; not only in water resources management and environmental planning but also in irrigation and water distribution systems design and maintenance (Walling and Horowitz, 2005). Rai and Sharma (1998a) observed that large amount of sediment leaves the Himalaya through its rivers. Verma and Kothyari (2004) reported the Hindu Kush Himalayas region as the most fragile mountain system of the world, which produce millions of tons of eroded fertile soil that is transported to the down streams every year. Surface erosion from the upland area is causing a serious dilemma for farmers due to the loss of fertile top soil. On the other hand, sediment accumulation can also be equally problematic to downstream farmers (Terrence et al., 2001).

The Hindu Kush Himalayas is a densely populated area and human activities are the major cause of environmental and land degradation in the region. Merz (2004) indicated soil degradation and forest depletion as the most serious environmental issues in Hindu Kush Himalayas. The impacts of environmental and land degradation activities are significant and are commonly linked to natural catastrophes such as landslides, droughts and flooding (Guzman, 1991). Banskota (2001) reported that the ecosystem of the great Himalayas Mountains is one of the most important life support systems on the earth. The rivers, which arise from the Himalayas, flow down to the plains and contribute to agriculture, industry, and energy sectors that sustain millions of people. However, watersheds in the Himalaya are poorly managed causing accelerated soil erosion. The major problem is extensive deforestation of mountain slopes for various reasons. Issues such as the increasing demand of agriculture land for food and fiber, forage production, households' needs for timber played a major role in forest reduction and land use change, affecting downstream reservoirs and water distribution systems (Echolom, 1976).

3.3 Land Use and Vegetative Cover

Aru (1985) recognized land and soil degradation as key environmental issues. Process of degradation varies with space and time. Soil, as a land component, is involved in this process while land use or management has been found to control the intensity and frequency (Imeson, 1995). Numerous investigators (Rauzi, 1963; Orr, 1970; Busby and Gifford, 1981; and Wood and Blackburn, 1981) have reported the influence of vegetation cover and land grazing on water infiltration, runoff, and soil erosion. Ground cover is also recognized as an important component for determining adequate reclamation of disturbed land. The land use changes from range and forest lands to agricultural and other land uses have been widespread in the past several decades in the mountain of Himalaya (Rai et al., 1994 and Singh et al., 1983). Such changes in land use type/cover cause environmental degradation through soil degradation and nutrient loss. Due to high demand of food and forage, agricultural land is increasing significantly over the past decades at the costs of other land uses in the Himalaya (Sharma et al., 1992). The forest dominated watersheds in the region are thus changed into agrarian watersheds resulting accelerated runoff, sediment, and nutrient losses (Sharma et al., 2007). The bare soil without proper vegetation on steep land with intensive agricultural practices is more vulnerable to soil erosion and results decrease in soil fertility (Rai and Sharma, 1995).

Many researchers concluded that vegetative cover and land use type in a watershed affect runoff and soil erosion (Reed, 1971; Patton and Schumm, 1975; and Newson, 1985). Runoff and soil erosion decrease exponentially by increasing the percentage of vegetative cover (Lee and Skogerboe, 1985 and Francis and Thomes, 1990). Vegetation and land use have obviously vital roles in increasing infiltration and reducing overland flow by increasing detention time, and thus regulating runoff and soil loss by reducing surface runoff volume and velocity (Bryan and Campbell, 1986 and Pizarro et al., 2005). Newson (1994) reported that surface conditions are closely related to the ability of rainfall to infiltrate. Plant cover can also play a tremendously important role by preventing the movement of sediment particles on pasture, agriculture, and forest lands. Consequently, the absence of vegetative cover under certain conditions can lead to the transport of soil materials (Chonghuan and Lixian, 1992). Improving vegetation directly affects the hydrologic cycle and has significant impact on water yield. Hays et al. (2000) concluded that good plant cover is necessary to maintain a healthy watersheds, control sedimentation, increase infiltration to reduce surface runoff and maintain water table. Dangol et al. (2000) argued that runoff and soil erosion is more affected by land management activates than land use type. A poor quality forest produces higher sediment than a well maintained agriculture field. Most of soil loss occurred within ten days of sowing and weeding from terraced rainfed agriculture fields.

Kinghton (1998) defined sediment yield as the total sediment outflow from a catchment in specified time, with suspended sediment as the major factor. Sediment yield information is necessary to manage reservoirs and other related structures. Suspended sediments may also carry different pollutants affecting water quality. Therefore, for water resources engineering and modeling, suspended yield estimation is vital (Walling and Webb, 1996 and Lane et al., 1997). Sediment yield in each river depends on the types of land use in the catchment area. By changing land use from forest and agro forestry to rainfed agriculture, the sediment rate increased by 11% from 1988 to 1992 (Rai and Sharma, 1998a). Rai and Sharma (1998a) also concluded that the annual rate of sediment and nutrient loss from small watersheds ranged from 4.18 to 8.82 tons per hectare. Lu and Higgitt (1999) and Ludwig and Probst (1998) reported that sediment yields are affected by different natural factors including climate, geology, and land use. The relationships between these factors and soil loss have been studied at regional and global scales through regression and correlation analysis. Glazyrin and Tashmetov (1995) discussed the significance of other important factors such as mean elevation of the catchments, recurring earthquakes, glaciated area, proportion of solid precipitation, and catchment lithology in runoff and sediment generation in mountainous region.

Certain areas of the Hindu Kush Himalayas region are intensively cultivated with up to four crops per year. The increasing demand of irrigation water and intensive use of fertilizers and pesticides is a major concern for surface as well as groundwater quality (Bhawani et al., 2004). Merz et al. (2000) reported that with increasing population and intensifying agriculture, the demand of water resources is also increasing. In the Hindu Kush Himalayas region, groundwater is also depleting and affecting the natural springs. Study conducted in Nepali Himalaya has shown that communities living on hill ridges are facing acute water shortage for agriculture and domestic purposes. Maize is the staple food produced on these agriculture lands. A decline in maize production has been observed due to insufficient availability of water in the cropping season. Loss of fertile soil layers from steep terraces is a major issue, which results in a loss of production (Schreier et al., 1995). The majority of the Himalayan people mainly rely on farming on small terraces and livestock. Water scarcity for irrigation and drinking is a limiting factor for agricultural production and quality of life. Due to rangeland conversion form pasture to agriculture, fodder is becoming scare. In Hindu Kush Himalayas, staple food maize is largely produced on these steep rainfed terraces. A decline in productivity has been observed and maintaining soil fertility has become a major challenge. Loss of top soil of fertile top soil due to surface erosion is a major issue on agricultural lands (Hofer, 1998).

Vegetation plays an important role in regulating surface runoff, as it reduces velocity of runoff water, surface water volume, and high discharge by increasing infiltration rate (Pizarro et al., 2005). Bosch and Hewlett (1982) concluded that increasing pasture areas and forest cover could reduce the total annual flows by up to 40%. Many studies found that vegetative cover and land use management practices have considerable influence on surface runoff and soil erosion (Bryan and Campbel, 1986 and Kosmas et al., 1997). Decrease in forest covers causes important changes in the hydrological cycle of the watersheds, although its effect is highly variable and unpredictable (Anderson, 1990). Valdiya and Bartarya (1991) observed the impacts of land use and geology on sediment and water balance in Himalayan watershed and observed that direct infiltration of rainwater in watershed is the main cause of spring recharge. Sharma et al. (1992)

concluded that land use/cover and hydrology is critical in prediction of sediment and nutrient budget and understanding the variability in relationship between different parameters is critical.

3.4 Sediment Budgeting

In Pakistan, Indus River is the largest and the most important resource for potable water. Most of the country's irrigation water or electric energy depends on the Indus River (Ahmad, 1993). Most of Indus River flow originates from the mountains of the Himalayas and Karakorum, and it carries huge amount of sediment that are ultimately dumped in water reservoirs like Terbala dam (MONENCO, 1984). The upper catchment area of Indus River in northern Pakistan is one of the highest sediment transporters (Meybeck, 1976). These sediments create problems like siltation of reservoirs, damages to infrastructures and turbines, affecting water quality, and transport of chemicals from agriculture fields. Comprehensive studies of suspended sediment yield in the catchment area of Indus River are essential for a successful water resource management in Pakistan (Ali, 2009).

Phillips (1991) argued sediment budget is very important component of a catchment response to environmental changes. As an essential component in sediment management and control strategies, sediment budgeting is an important tool to plan for scientific and management problems involved in the runoff and soil erosion prediction, their response to land use change, slopes, and variations in climatic factors (Walling and Collins, 2008 and Walling and Horowitz, 2005). Moreover, sediment budget is a useful framework to find the relationships between sources and sediment yield and to determine how these relationships are affected by changes in climate factors and land use (Wasson, 2002). Reid and Dunne (1996) defined a sediment budget as "an accounting of the sources and disposition of sediments while traveling from origin to eventual exit from a drainage basin". A detail sediment budget explains the sediment loss rates, sediment transport process, and its effect on water distribution systems and hill slopes (Dietrich et al., 1982). A simple sediment budget model for any watershed is expressed as:

$$I = O + \Delta S \qquad (3.1)$$

Here, ΔS is the rate of sediment accumulation within the watershed and I and O are rates of inflow and outflow sediment into and from the watershed, respectively (Slaymaker, 1993).

According to Sutherland and Bryan (1991), sediment budget studies are not an alternative to monitoring. However, budgeting can complement monitoring programs, whereas monitoring can be used to improve budget estimates. Sediment budgeting studies can be used for other watersheds with similar land use, slope, geology, soil type, and climate. Sediment budgeting is a more comprehensive technique than sediment yield estimation because sediment yield is sometimes not responsive to storage, erosion rate, or land use changes in the drainage basin (Trimble, 1999).

3.5 Runoff and Soil Loss Modeling

Research on water induces soil erosion dates back to the beginning of the 20th century when soil erosion was identified as a major problem in the United States. Chapline (1929) found that due to overgrazing, the soil water holding capacity reduces and results in accelerated runoff and increase in soil erosion, which ultimately decrease in soil fertility. Cook (1936) identified three major variables directly affecting soil erosion including soil susceptibility to erosion, (soil erodibility), erosivity of rainfall and runoff, and protection by vegetative cover. By the late 1960's, the research efforts in USA were focused on estimating soil erosion by water through mathematical methods to improve erosion prediction and control measures (Mayer and Moldenhauer, 1985). Universal soil loss equation (USLE) and revised USLE (Renard et al., 1991) are two of the most well known empirical models used for estimation of soil erosion from different land uses. The USLE was developed as a method to predict soil erosion and it continues to be the most widely applied soil erosion model in the world (Lane et al., 1992). Knisel, (1980) developed the Chemicals, Runoff and Erosion from Agricultural Management Systems (CREAMS) model for soil loss estimation with particularly emphasis on agricultural practices. A major benefit of the CREAMS model is the ability to give correct estimation for an individual storm, which is important because a small number of high intensity events normally dominate the annual total.

An approach of a GIS-based Gama Geomorphologic Instantaneous Unique Hydrograph (GGIUH) model for sediment and surface runoff was developed and tested at Ajay River in India (Sahoo et al., 2005). Rajurkar et al. (2003) developed a model based on Artificial Neural Network for estimating daily river flow and flood events. Gupta and Chakrapani (2005) reported that sediment measurement and variation at a stream/river level is important for planning and designing hydraulic structures and water-resources projects. Lohani et al. (2007) studied the quantification of water balance and sediment yield in two forest watersheds in Kerala State in India. There exist a number of studies arguing that including the rainfall intensity throughout a storm may affect the modeled results. Wainwright and Parsons (2002) concluded that overland flow models under predicts runoff that use mean rainfall intensity.

Hydrologists have a long tradition working with different mathematical models for different purposes (Jayatilaka and Connell, 1995). Ibbitt and McKerchar (1992) stated the role of models as tools to express the hydrologic processes and to predict system responses to possible natural and/or man made changes. The World Meteorological Organization (WMO, 1990) reported prediction, planning, and design as the three basic purposes for hydrologic modeling. Depending on availability of data and objectives, a number of watershed scale hydrology and sediment yield models have been developed in different part of the world. UBC model (Quick and Pipes, 1972), SWAT model (Neitsch, et al., 2002; Arnold et al., 1998), LISEM model (Jetten, 2002 and Roo and Wesseling, 1996), PREVAH model (Gurtz et al., 1997 and Vivirol et al., 2009), AGNPS model (Young et al., 1987), RUSLE model (Renard et al., 1991), and AnnAGNPS model (Bingner et al., 2001) are typical hydrologic models in the literature. Table 3.1 summarizes a list of some widely used available hydrologic models and their applications. These models are often mathematically complex and required large number of input parameters. Some of these parameters may not exactly known and they are often very difficult (if possible at all) to determine in a real engineering practice. Further, many of them some time may not be directly quantifiable. Regardless of which model is in use, no model or group of models will ever be comprehensive enough to be applicable to all problems and geographical situations. Thus, it is reasonable to modify existing models and/or to develop new ones (Lane et al., 1988 and Barfield et al., 1989).

The selection and use of a particular model depends on climatic condition, available data, and modeler's objectives. Since mathematical models of runoff and erosion estimation are often used, these models need thorough understanding of each basin response and physical conditions. Ibbitt and McKerchar (1992) expressed the role of models in hydrology as tools to study hydrologic processes and to watch a system's responses to changes. Historical hydrologic data are important in many applications such as soil conservation practices, flood control, water resource planning, urban development guidance, and ecological management and planning. In the absence of field measured data, model data and relationships are often used (Marsh and Marsh, 1995).

Table 3.1 - Some available hydrologic models and their applications

Model Name	Time Scale	Model Applications	Input Data
University of British Columbia Catchment Model (UBC Model)	Hourly to daily	Stream flow forecast	Temperature, Precipitation, Elevation, Soil moisture content, Soil and groundwater storage, Runoff from sub catchments, Surface and subsurface flow, Continuous meteorological input data, Snow pack, Stream flow
Precipitation-Runoff-EVApotranspiration-Hydrotope (PREVAH Model)	Hourly/ daily	Hydrological cycle, Water balance, Discharge , Precipitation behaviour	Elevation, Precipitation, Snowfall, Evapotranspiration, Discharge, Landuse/cover, Soil depth, Field capacity, Saturated hydraulic conductivity, Net radiation , Vegetative cover
Soil and Water Assesment Tool (SWAT Model)	Daily	Impact of land management practices on water and sediment , Stream flow, and Water quality	GIS soil maps ,Precipitation, Temperature, Wind speed, Solar radiation, Landuse data
Limburg Soil Erosion Model (LISEM Model)	Single event	To find the effects soil conservation measures on the soil loss	Rainfall, Interception, Vertical movement of water in the soil, Overland flow, Channel flow, Soil particles detachment, Transport capacity
Revised Universal Soil Loss Equation (RUSLE Model)	Hourly/ daily	Soil loss and sediment yields	Soil loss, Rainfall-Runoff erosivity factor, Soil erodibility factor, Slope, Slope length ,Unit-plot conditions, Cover management factor, Conservation practice factor
The Water Erosion Prediction Project (WEPP) Model	Daily/ monthly	Daily runoff, subsurface flow, and sediment data, climatic data	Precipitation amount, duration and intensity, Temperature, Solar radiation, Dew point temperature, Wind speed, Slope length , Slope steepness

3.6 Stream Flow

The quantification of runoff and soil loss is a major challenge in water resources and environmental planning, irrigation and water distribution systems design and maintenance. High sediment loads in rivers and streams present major challenges to resource management. Safe (1996) reported that for the discharge estimation of a river, a stage discharge relationship or rating curve is a fundamental technique. The quality of a stage-discharge relationship determines the accuracy of the computed discharge data in streams/rivers. Rating curves become particularly important for large rivers during flood forecasting and warning, water resource assessment and management (Mosley and McKerchar, 1993). Milliman and Syvitski (1992) investigated the relationships between stream suspended sediment and corresponding discharge at different scales through correlation and regression analysis. Goodness of fit was determined by using different analysis on basis of R^2. The RPT et al. (1989) consider the coefficient of determination (R^2) as a criterion of goodness of fit. Gawne and Simonovic (1994) and Maidment (1993) suggested that in addition to R^2, some other parameters like constant radiance, normality of residuals and mean squared error (RMSE) are also goodness of fit requirements of a linear or non linear regression models.

Chapter 4: Impacts of Land Uses on Runoff and Soil Degradation

"A land-use decision is also a water decision."

(Malin Falkenmark)

This Chapter contains the journal paper on "Impacts of Land Uses on Runoff and Soil Degradation in Hilkot Watershed - Pakistan". The main emphasis in this Chapter is on the first two research objectives; to investigate runoff, soil loss measurements from different land uses, and compare their seasonal distribution at plot level. This chapter marks the completion of runoff and soil loss data analysis and detail study of land use impacts on runoff and soil loss generation.

Water availability is rapidly becoming a worldwide concern of the 21st century from both quality and quantity points of view. Locally, water scarcity is a major problem in large areas of Hindu Kush Himalayas region, which is the youngest and most fragile mountain system in the world. The region provides a large quantity of water during the monsoon season (July to September), while insufficient water is present in the winter season (December to February). Overall, the region is considered as dry and thus water authorities have been facing critical problems in supplying drinking as well as agricultural water with acceptable quantity and quality. During the monsoon period, large amounts of surface runoff leave the watershed, causing erosion and sedimentation in the streams (Merz et al., 2000 and ICIMOD, 1999). Shiklamonov (2000) reported that water availability is dramatically decreasing since 1995 and still showing a decreasing trend by 2025.

Surface vegetation is one of the most important factor in regulating surface runoff and soil erosion by increasing infiltration and reducing velocity of runoff water (Karvonen et al., 1999) Hofer (1998a) reported that the impacts of soil conservation methods are directly visible in micro scale catchments, as they reduce soil loss rates. Many researchers highlighted the importance of vegetative cover and land use management practices in runoff and soil loss generation (Bryan and Campbel, 1986 and Kosmas et al., 1997). McGrath et al. (2001) compared the land use impact on soil nutrient losses in Amazonia and found significant difference in nutrient concentration with the change in land use type. Sharma et al. (1992) reported that land use effect is critical in prediction of sediment and nutrient budget. Different studies were conducted to examine the natural resource dynamics in Himalayas and other mountain areas. Malmer (1996) studied the effect of forest plantation on hydrology and nutrient losses in experimental catchment area in Sabah, Malaysia. Sharma et al. (2001), Narayan et al. (1991), and Pathak et al. (1984) determined the surface flow, sediment yield, and nutrient losses from different forested sites in Central Himalayas in the monsoon seasons.

Conducting a direct field-data measurement, the main objectives of the current research were to: 1) to measure and indicate the rainfall, runoff and soil loss variations and their relationships on different land uses; 2) to determine total monthly and annual runoff and sediment losses from four different land uses; and 3) to compare seasonal distributions of rainfall, runoff and soil loss for the four different land uses.

4.1 Results and Discussion

4.1.1 Annual and Seasonal Distribution of Rainfall

Figure 4.1 shows the annual rainfall in the Hilkot watershed area during the study period (1999 – 2005). As the Figure indicates, the total annual maximum rainfall of 1178 mm was recorded in 2003, while the minimum of 917 mm occurred in 2004. Average rainfall observed in the study period was about 1160 mm. The Hilkot watershed falls in the monsoon region, where monsoon rains plays an important role in annual total rainfall. The watershed received most of the rainfall in the monsoon season lasting from July to September and received little rainfall in the autumn (October to December) during the study period with a monthly rainfall ranges from 0 to 319 millimeter. Figure 4.2 shows that about 25% of rainfalls occur in the winter season, which prolongs from October to February, while the monsoon period (July to September) and the pre monsoon period (March to June) receives 40% and 35 % of annual total rainfall, respectively.

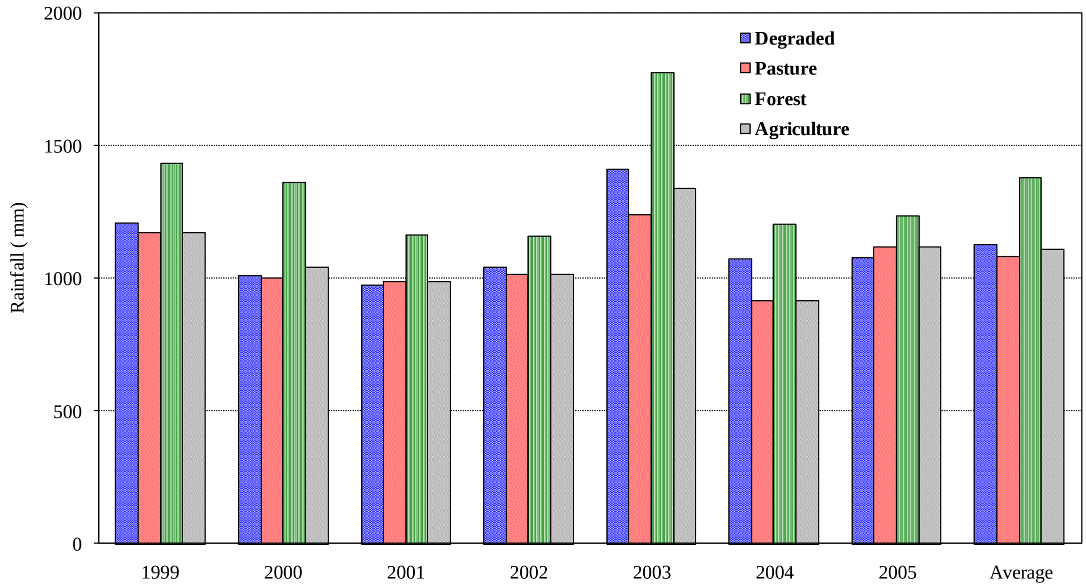


Figure 4.1 - Annual rainfall on all land uses in Hilkot watershed, Pakistan

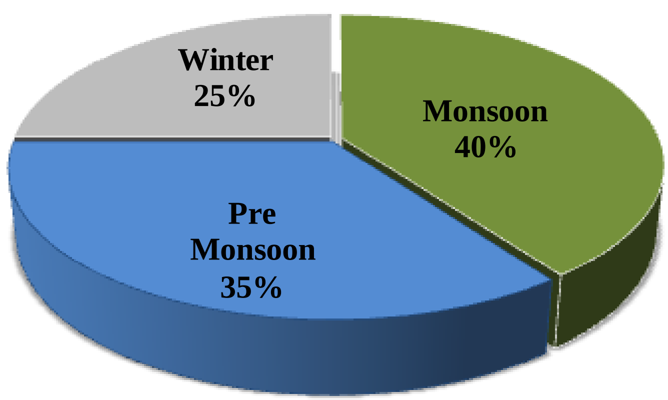
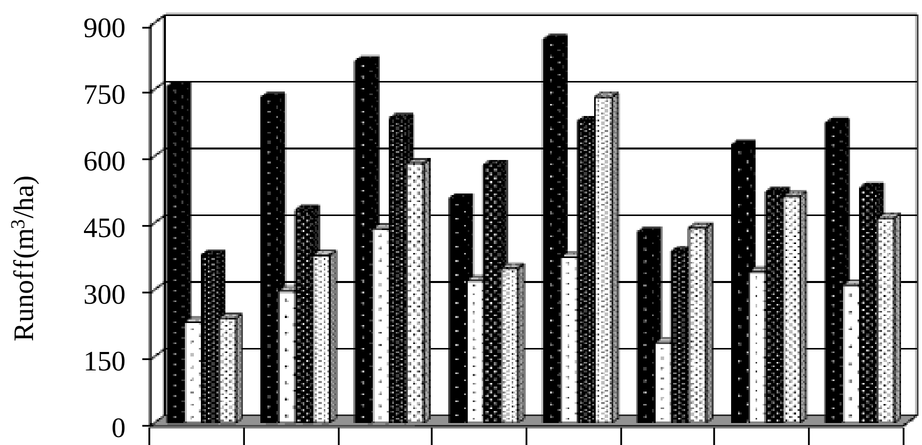


Figure 4.2 - Seasonal distribution of rainfall in Hilkot watershed, Pakistan

4.1.2 Annual and Seasonal Distributions of Runoff

Figure 4.3 indicates annual runoff from different land uses during the study period. The figure clearly shows that the runoff pattern varies very much among different land uses. The annual mean maximum runoff was recorded 674 m^3/ha from the degraded plot due to less plant cover, while mean annual minimum runoff of 310 m^3/ha was observed from the pasture plot due to its good vegetative cover. On the other hand, average annual runoff during seven years of the study from the forest and agriculture plots were 529 m^3/ha and 461 m^3/ha, respectively. Data also reveals that an annual runoff from the degraded land ranged from 429-814 m^3/ha, while the range for the pasture, forest and agriculture plots were 181-372 m^3/ha, 377-685 m^3/ha and 235-732 m^3/ha, respectively.

Figure 4.4 indicates the seasonal runoff distribution from all land uses in the Hilkot watershed. The figure shows that almost 50% of runoff in all the erosion plots occurred during the monsoon period (July to September) while in the pre-monsoon period a total of 42 to 46 percent runoff was recorded. Runoff in the post-monsoon period (October to December) was negligible as compared to the total annual runoff. There were some big runoff events contributing a major portion of the total annual runoff on all plots. The biggest runoff events up to 80 m^3/ha were recorded in a degraded plot on the 10th of June and 23rd of July 2001 when 50 and 80 millimeter of rainfall were recorded, respectively.



	99	2000	2001	2002	2003	2004	2005	Ave
Degraded	756.4	732.3	813.6	505.0	862.2	428.9	625.1	674.8
Pasture	226.3	297.0	436.3	320.0	372.5	180.6	339.8	310.4
Forest	376.9	478.5	685.0	580.0	678.5	385.6	519.7	529.2
Agriculture	235.1	377.0	583.4	348.0	732.7	438.5	510.0	460.7

Figure 4.3 - Annual runoff from different land uses in Hilkot watershed, Pakistan

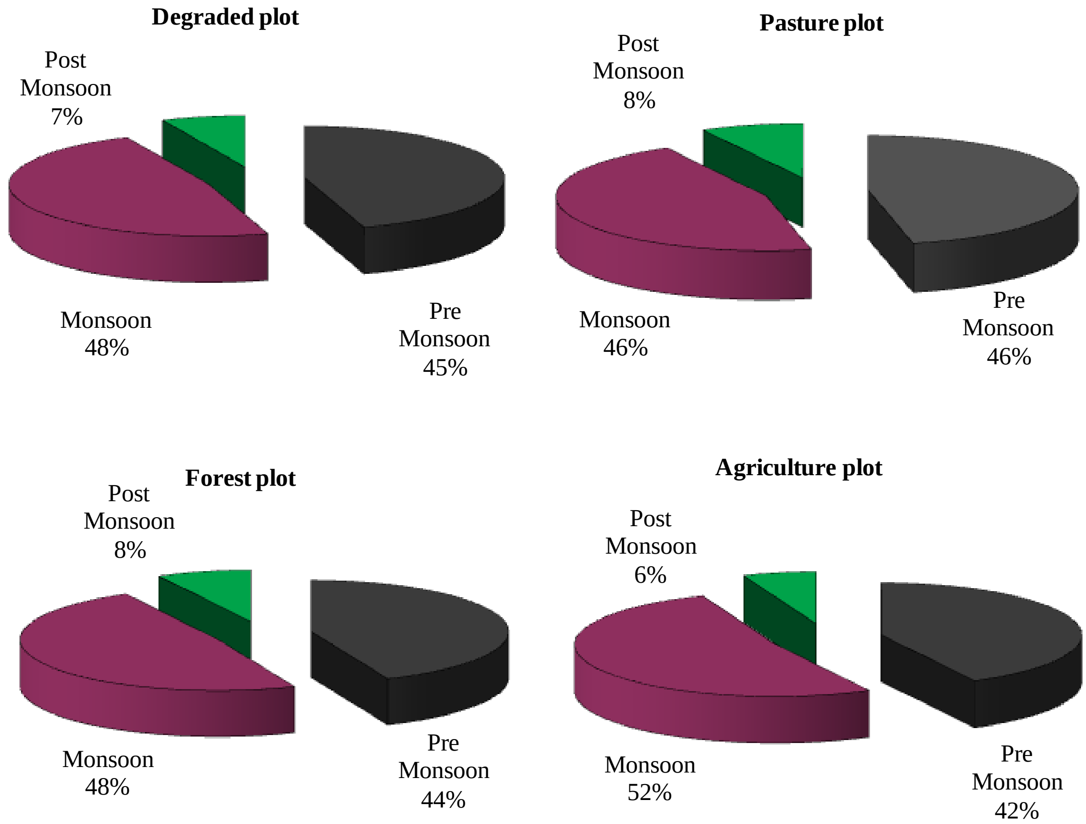


Figure 4.4 - Seasonal runoff distribution from all land uses in Hilkot watershed, Pakistan

Figure 4.5 reveals the percentage of water lost (i.e., runoff) from all land uses. The rainfall intensity is not very high throughout the year except in monsoon period. Most of water infiltrate into the soil leaving very small amount for runoff in almost all land uses. The figure shows that percentage from the degraded land was highest especially in the monsoon when percentage of runoff reaches up to 12% of total rainfall amount. Pasture land allows only 4% of rain water to leave the field mainly due to good vegetation and infiltration rate. In winter, normally rainfall intensity was low and infiltration rate was high, resulting very low percentage of surface runoff from all the land uses, especially from agriculture, forest, and pasture land.

4.1.3 Annual and Seasonal Distributions of Soil Loss

Erosion of topsoil begins when water detaches individual soil particles from clods and other soil aggregates. Raindrops are the major cause of soil particle detachment. Raindrops can

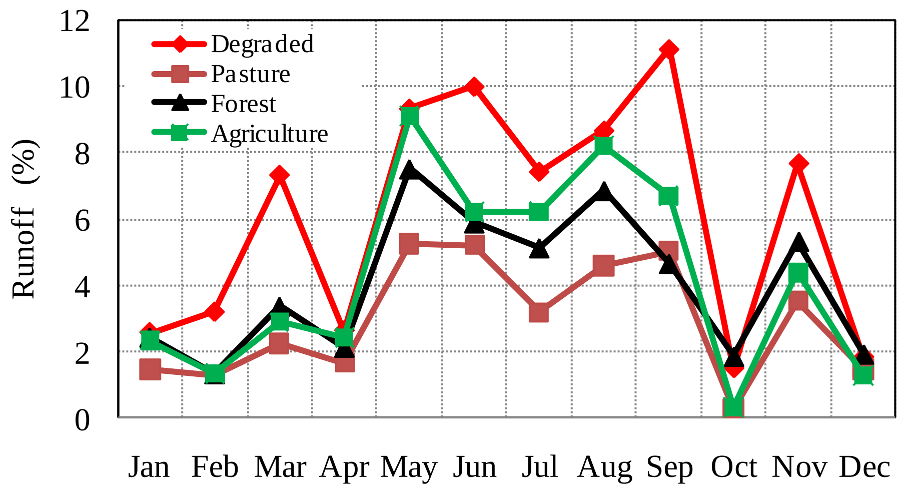
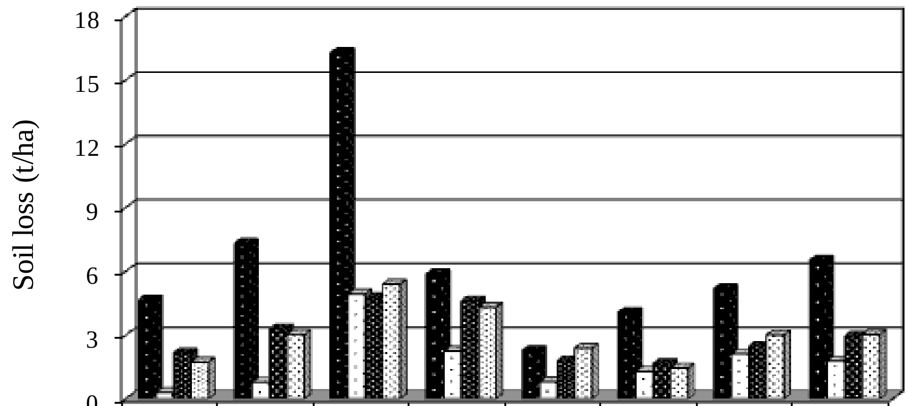


Figure 4.5 - Runoff percentage from all land uses

be especially erosive when residue, mulch, or vegetation is not present to absorb the driving shear forces. Figure 4.6 indicates the annual soil losses measured on different land uses in Hilkot watershed. The figure shows that annual soil loss from different land uses ranged from 0.3 to 16.3 tons per hectare (t/ha) during the study period. Average annual maximum soil loss (6.5 t/ha) was recorded from the degraded plot due to its less vegetative cover. The average minimum soil loss that was recorded from the pasture plot was 1.8 t/ha due to good vegetative covers. Similarly, average soil loss was about 3.0 t/ha measured from the forest and agricultural plots. Rai and Sharma (1998b) observed similar soil loss rates (4.18 to 8.82 t/ha /year) from Mamlay watershed in India from rainfed agriculture land use which also falls in the monsoon region. Runoff and soil losses were found higher from the agricultural land during the study period when it was prepared for sowing.

Seasonality plays an important role in annual runoff directly effecting both runoff and soil erosion. Figure 4.7 shows that about 50 percent of the soil losses in all erosion plots were recorded in the monsoon period, except for the agricultural plot where about 66% of the soil loss was recorded in the pre-monsoon period when plant cover was not well established and high intensity rainfall events make major distraction. It was further shown on different occasions that the pre-monsoon storms were more destructive and leading to main soil loss in agricultural fields due to sowing and weeding practices (Carson, 1985 and Carver and Schreier, 1995). This is mainly due to the soil cover by seasonal vegetation (e.g. crops and grass). Figure 4.7 also reveals that the soil loss was negligible in the post monsoon period (October to December) mainly because of less rainfall and low intensity.



	1999	2000	2001	2002	2003	2004	2005	Ave
Degraded	4.7	7.3	16.3	5.9	2.3	4.1	5.2	6.5
Pasture	0.3	0.8	4.9	2.3	0.8	1.3	2.1	1.8
Forest	2.2	3.3	4.8	4.6	1.8	1.7	2.5	3.0
Agriculture	1.7	3.0	5.4	4.3	2.4	1.5	3.0	3.0

Figure 4.6 - Annual soil loss (t/ha) from different land uses in Hilkot watershed, Pakistan

It should be emphasized that most of the soil loss from the agricultural land occurs during the pre-monsoon period; the month of May followed by the monsoon period in June and early July. Runoff and soil losses were higher in June and July if any intense rainfall events occur. Two possible reasons for this are the intense rainfall events of the pre-monsoon and the early monsoon period and the lack of vegetation cover on the rainfed agricultural land during this time. After harvest of the winter crop (usually wheat) in late May, the rainfed agricultural land remains follow up to the time of planting the monsoon crop (usually maize) in June. Maize crop does not provide good ground-cover in its early stages. Therefore, high intensity rainfall events in the early monsoon period can be as destructive as the pre-monsoon period rains. The onset of the monsoon season reduced this agriculture source markedly due to the improvement of vegetative cover.

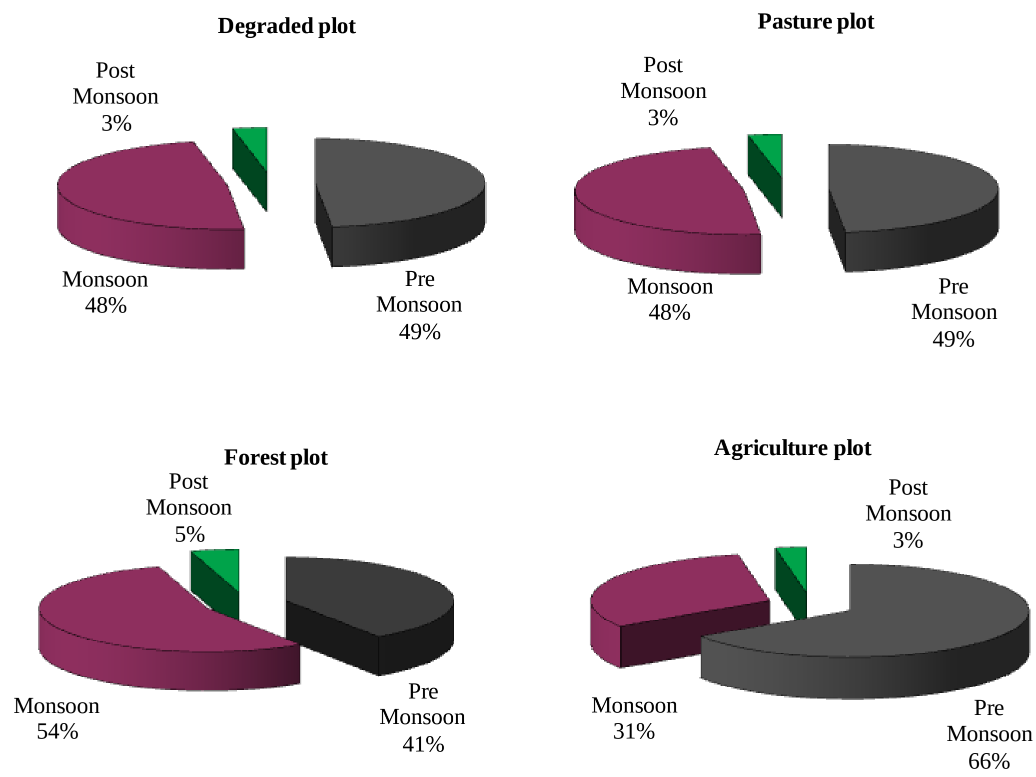


Figure 4.7 - Seasonal soil loss distribution in all land uses in Hilkot watershed, Pakistan

4.1.4 Impact of Land Use on Sediment Yield

Land-uses contribute differently in the sediment yield production. Life-time estimates of sediment yield are therefore essential in water resources systems analyses for their performance and maintenance cost. Different techniques and/or treatment strategies can reduce sediment loads and save the systems from complete failure and increase their functionality. Figure 4.8 shows the results for the time required to fill a hypothetical reservoir of volume of 200 Mm^3 (1000 m*1000 m*20 m) with sediment loads carried with surface water of the Hilkot watershed (with a catchment's area of 1600 ha). As the figure shows, the reservoir will fill in 29 years with degraded land catchment with highest erosion risk level, while pasture land (with good vegetation and plant cover) will take 116 years to fill the same reservoir. Similarly, forest and agriculture land with moderate erosion risk level will take 51 and 55 years, respectively. Thus, lifetime of reservoir can be increased almost 4 times by changing the type of land use of its catchment from degraded to pasture land.

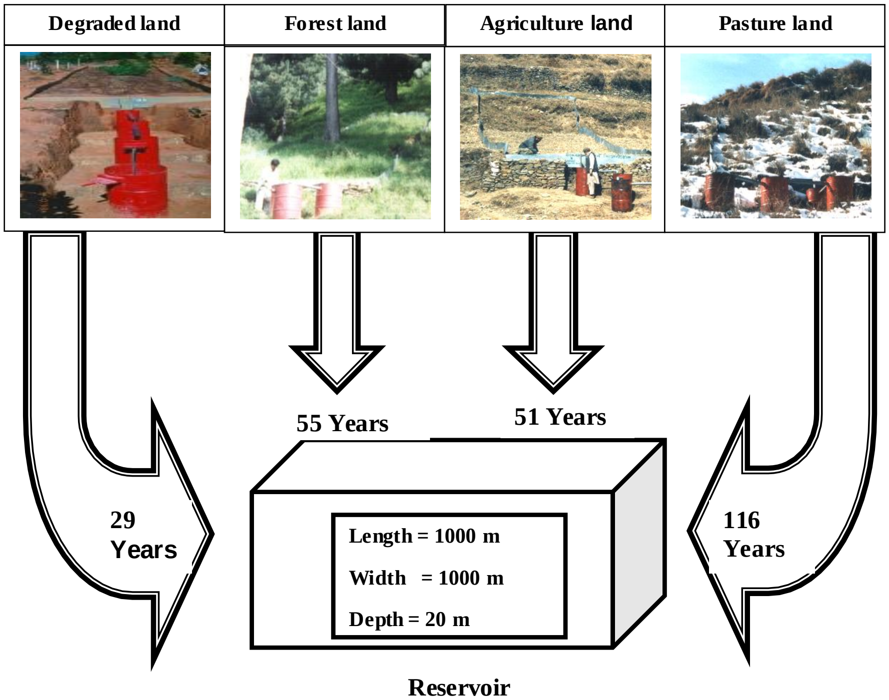


Figure 4.8 - Reservoir filling time with sediment from different land uses

4.2 Summary

Chapter discussed the rainfall, runoff and soil loss from four land uses with different vegetative cover in Hilkot watershed. Results illustrated that Hilkot watershed received the most of the rainfall in the monsoon season. High intensity monsoon rainfall caused a major portion of runoff and soil loss from all land uses. The results also revealed that vegetation played very important role for runoff and soil erosion. Degraded land produced the highest runoff (675 m^3/ha/year) and sediment loss (6.5 ton/ha/year) throughout the study period. Lower soil loss was observed from the pasture and forest areas due to good vegetative cover. The next chapter will present rainfall, runoff, and soil loss relationships on different land uses

Chapter 5: Rainfall, Runoff, and Soil Loss Relationships

"Water is the driver of nature."

(Leonardo da Vinci, 1451-1519)

This Chapter includes a journal paper on "A study on rainfall, runoff, and soil loss relationships at different land uses – A case in Hilkot watershed in Pakistan". The Chapter addresses the 3rd research objectives of investigating rainfall, runoff and soil loss relationships and impacts of land use at plot level. Daily rainfall, runoff and soil loss data were analyzed to find their relationships. Polynomial regression models were developed for relationships and correlations for all land uses.

Even in intensively monitored watersheds, reliable data sets for all of the influential parameters are unavailable. Therefore, alternative methods like relationships and models are always needed for predicting different parameters when using available information. Over the years, several studies in different parts of the world were conducted to predict runoff and soil loss at the plot and the watershed level. Soil erosion models range from simple to very complex, and are generally developed either for research purposes or for developmental projects proposed by resource management agencies (Deo et al., 1999). Data collected from the field or laboratory experiments are used as a base to develop the relationships and models. Even a simple regression model that includes only vegetative cover, rainfall amount, runoff, and soil loss will be very useful for those who cannot get detailed data and who may simply want to know the impacts of land use on rainfall, runoff, and soil loss relationships (Croke and Nethery, 2006 and Labat et al., 2002).

Thus, by intensive seven-year-period (1999-2005) data monitoring for rainfall, runoff, and soil loss, the mathematical relationships among these parameters were discovered for different land uses in the Hilkot region. In this regard, the short term objectives of the present study were: 1) to find and compare monthly runoff and soil losses from four different land uses; 2) to develop rainfall, runoff, and soil loss relationships for different land uses.

5.1 Results and Discussions

5.1.1 Annual Rainfall Amount and Classification

Figure 5.1 indicates the seven-year monthly-averaged rainfall in the region. The Figure clearly reveals that the Hilkot watershed receives the majority of its rainfall in the monsoon season (July to September), while receiving minimum rainfall in autumn (October to December). The average annual rainfall in the watershed was about 1160 mm.

The event size daily rainfall distribution (Figure 5.2) shows that low-magnitude rainfalls (i.e., less than 20 mm) in the region were much more frequent than high-magnitude rainfalls (i.e., greater than 50 mm). Moreover, the high-magnitude rainfall events accounted for only 3% of the total annual, while a majority of the events (60%) were small and in the range of 0–20 mm. The rest of the events (37%) were in the range of 20–50 mm; which represented a major contribution to the annual total.

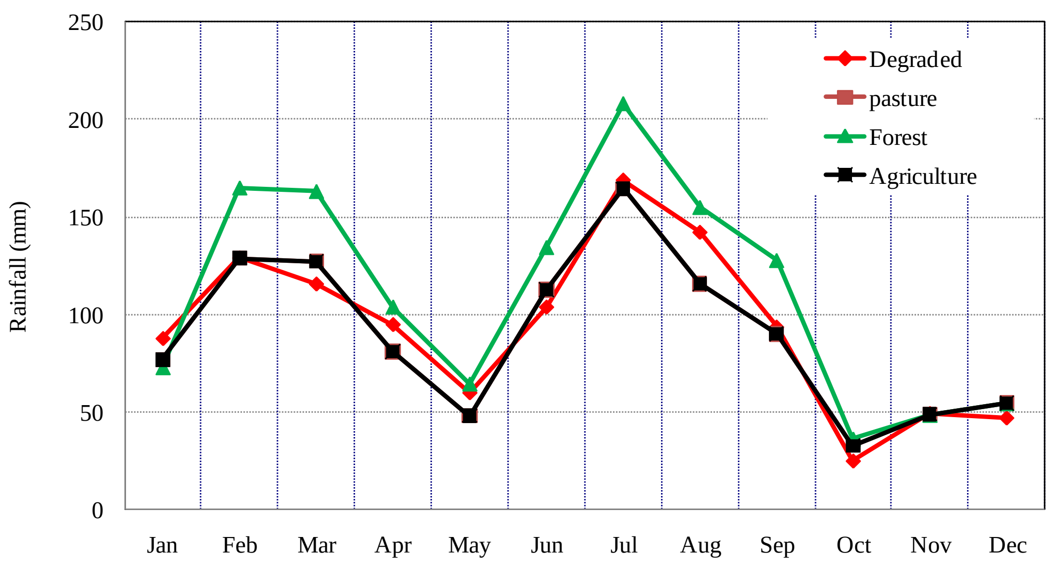


Figure 5.1 - Average monthly rainfall in the Hilkot watershed, Pakistan

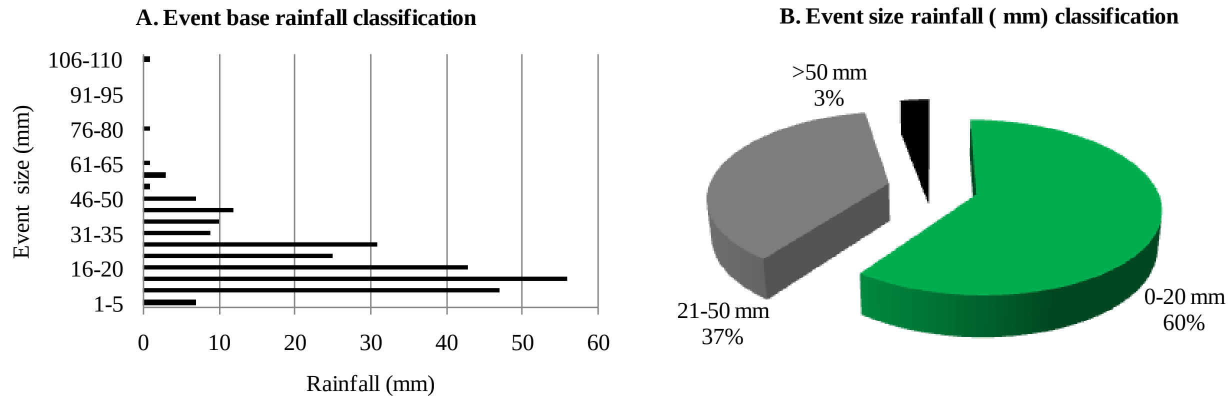


Figure 5.2 - Event base rainfall distribution in Hilkot watershed, Pakistan

5.2 Monthly Runoff and Soil Loss

Figure 5.3 presents average monthly runoff and soil loss data for all four land uses at plot level. The Figure illustrated that the percentage of runoff water from the degraded land was comparatively higher than that of the all other land uses. The proportion of runoff water was high during the monsoon season (July-September) when rainfall intensity was normally high. In winter, low-intensity rainfall followed by high infiltration rates resulting in a very low percentage of surface runoff from all the land uses especially from agricultural, forest, and pasture lands.

Figure 5.3 also shows the soil loss data for each land use. The Figure presents an increase in the soil loss rate by increasing runoff amounts. Overall, the degraded land produced a high amount of soil loss throughout the year but in the months of June and July soil loss increased sharply. A significant amount of soil loss was observed from the agricultural plot in June when plant cover was not well established and early rains eroded a considerable amount of soil from the fields. Overall, runoff and soil losses were higher from July to September (monsoon period) due to the high amount and intensity of rains, while they were lower in winter when rains were low in amount and intensity. The Figure clearly indicates that pasture, forest, and agricultural lands generate very low soil loss during the winter months.

Figure 5.3 also indicates that there is a time-lag between runoff and maximum soil loss in all four land uses. This is mainly because there were some very significant runoff and soil loss events, which contributed to the major portion of monthly/annual total runoff from the different land uses in the watershed even though the amount of rainfall associated with those events was not very high. Generally, these events occurred in the pre-monsoon period, when the land surface was desiccated, or in the early monsoon season when rainfall intensity was high, and vegetative covers were not well established and thus the lands were bare and vulnerable to soil erosion. If high-intensity rains occur in the months of May-July, plant cover at that time of the year was partially developed resulting in significant soil losses in a single event. The largest single measured runoff events in the watershed were recorded on degraded and forest land plots (80 m^3/ha/day), while the highest soil loss events in the watershed was also from the degraded land (1.5 t/ha/day) and from the forest land (0.95 t/ha/day). In the agricultural plots, all major events were measured in the months of May and June, which are sowing and weeding time. Figure also indicates that soil loss curve in plot-level looks symmetric in all land uses except in degraded land. In degraded land vegetative cover throughout the study period was not well established while on all other land-uses vegetative cover was good enough to control runoff and sediment throughout the year (i.e. in form of some grass on pasture, organic matter on forest plot and crop cover on agriculture land).

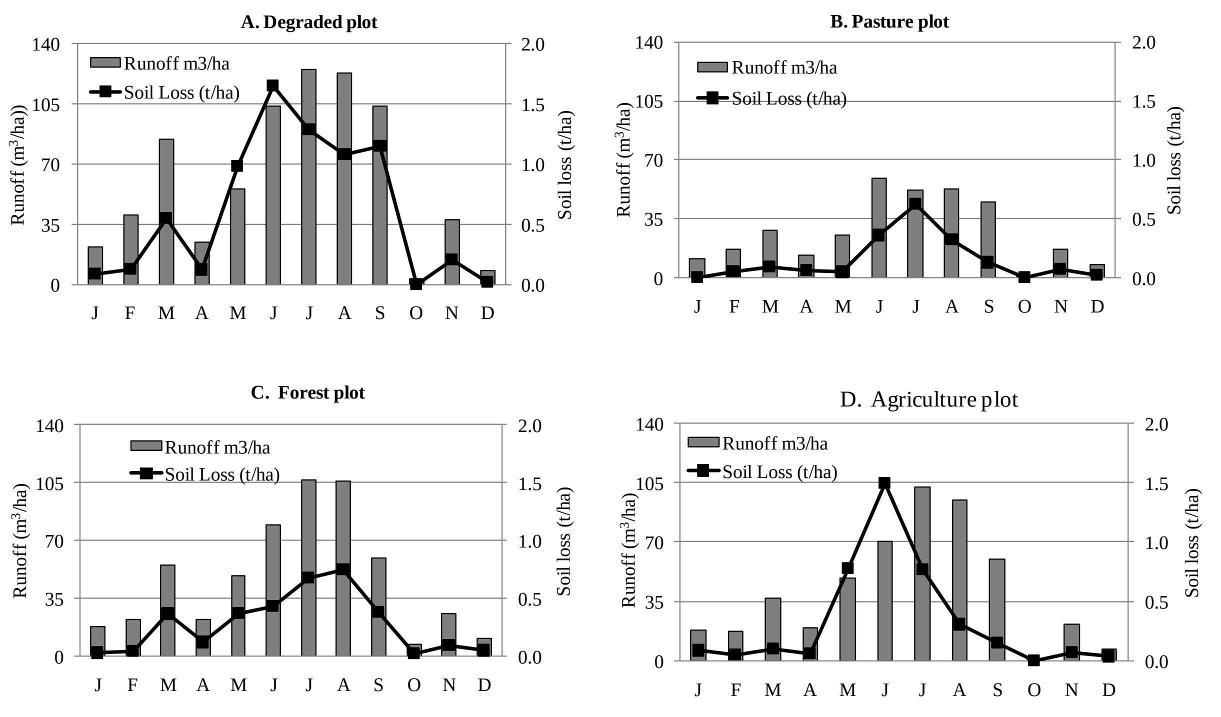


Figure 5.3 - Average monthly runoff and soil loss from all land uses in Hilkot watershed, Pakistan

5.2.1 Risk Characterization for Different Land Uses

Runoff severity characterization was done to provide a conceptual risk level for different land uses on the basis of annual runoff and soil loss throughout the study period. High runoff and erosion risk is mostly associated with high rainfall intensity and lack of vegetative cover. Rainfall amount and intensity on all land uses were almost identical with insignificant differences due to small catchment area. Throughout the study period degraded land with less vegetation, produced highest amount of runoff and soil loss while it was low on pasture. Table 1 indicates that, on degraded land average annual runoff (674 m^3/ha) and annual sediment loss (6.5 ton/ha) was maximum while pastureland produced minimum runoff (310 m^3/ha) and soil loss (1.8 t/ha). Due to high amount of runoff and soil loss production degraded land was rank at high severity level, while pasture showed very low severity level by producing lowest runoff and soil loss. Forest and agricultural land showed moderate severity levels for both runoff and soil loss. Table 5.1 shows severity levels based on total runoff and soil loss generation for all land uses during study periods.

Table 5.1 - Runoff and soil loss severity level of all land uses

Average Annual Runoff			
Risk Ranking	**Land Use**	**Runoff (m^3 /ha)**	**Runoff Sevearity Level**
1	Degraded	674	High
2	Forest	529	Moderate
3	Agriculture	460	Moderate
4	Pasture	310	Low
Average Annual Soil Loss			
Risk Ranking	**Land Use**	**Soil Loss (t/ha)**	**Soil Erosion Level**
1	Degraded	6.5	High
2	Forest	3.0	Moderate
3	Agriculture	3.1	Moderate
4	Pasture	1.8	Low

5.2.2 Rainfall, Runoff and Soil Loss Probability of Occurrence

Statistical analysis was conducted to determine the cumulative distribution functions (CDFs), for rainfall, runoff, and soil loss in each land-use. The analysis was based on the mean rank formula of:

$$P = \frac{i}{N+1} \tag{5.1}$$

Here, P is the cumulative probability of having a particular event to be smaller than or equal to i^t event and N is the number of data values or events.

Estimation of CDF could be particularly important when average regional rainfall, runoff and soil loss is of the interest. Figures 5.4- A, B, and C present the CDFs for rainfall, runoff and soil loss, respectively. CDF for rainfall (Figure 5.4-A) shows that it is 95% likely that rainfall amount will be smaller than 50 mm/day and only a 5% chance that it will be greater than 50 mm/day in the watershed area. Figure 5.4-B illustrates the CDF for runoff on the degraded, pasture, agricultural, and forest lands. The Figure shows very similar trends for higher events especially when the runoff is greater than 20 m^3/ha. In small events, degraded land generated higher runoff compared to the other land uses. For the above three land uses, almost 95% of runoff events were smaller than 40 m^3/ha and only 5% of events were greater than 40 m^3/ha. From the pasture land 95% of the events were smaller than 30 m^3/ha leaving only 5% of the events greater than that.

CDF for soil loss (Figure 5.4-C) illustrates that there is no distinct visible difference in terms of cumulative soil losses from the three land uses of pasture, agricultural, and forest land. However, the degraded land generated a comparatively higher amount as expected. The CDFs of soil loss for pasture, forest, and agriculture are almost identical showing that the amount (not the type) of vegetation is influential. The figure also shows that 95% of events were less than 0.25 t/ha from the agricultural, forest, and pasture lands, while from the degraded land almost 95% of the events were smaller than 0.35 t/ha.

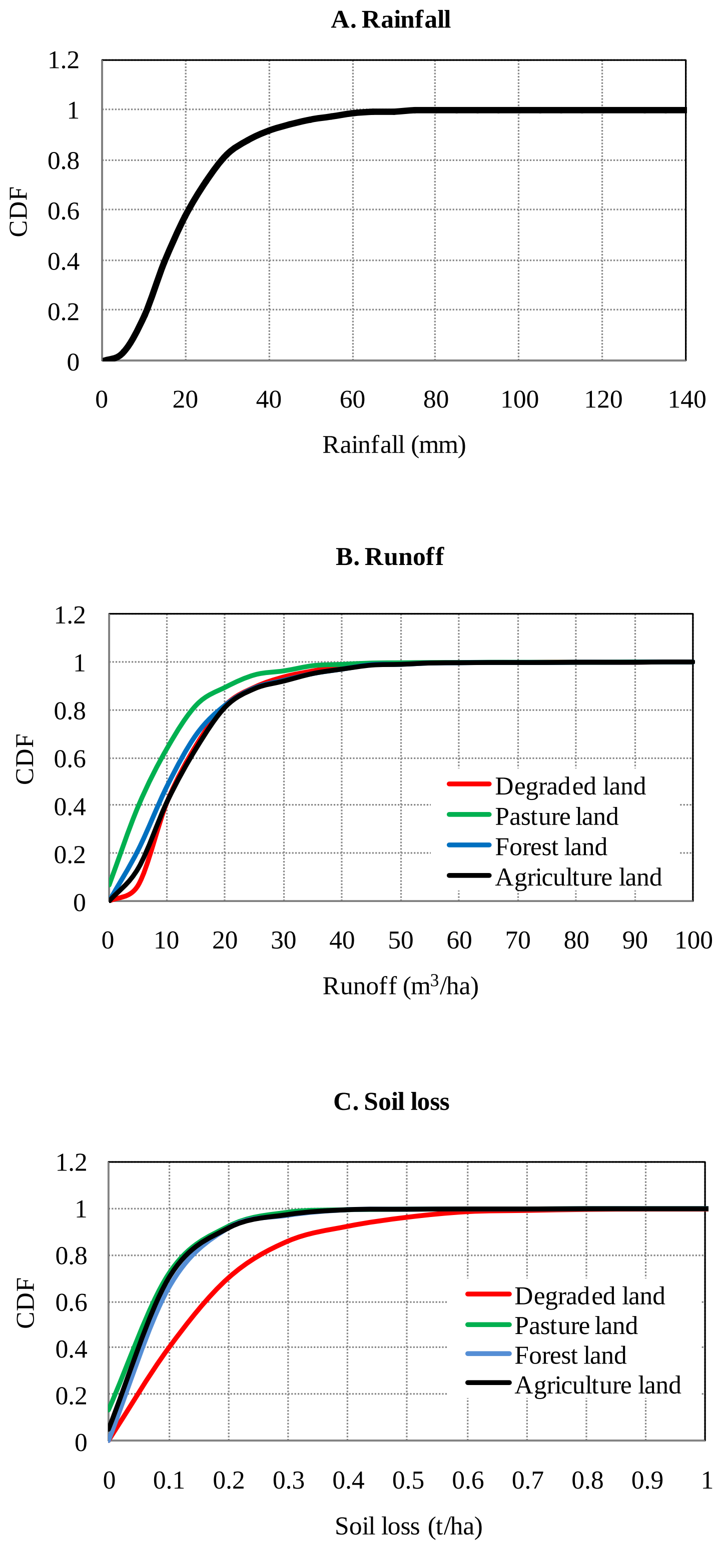


Figure 5.4 - CDFs for rainfall, runoff, and soil loss on all land uses in Hilkot watershed, Pakistan

5.2.3 Rainfall and Runoff Relationship

Runoff starts when the storage capacity of the land is exceeded by rainfall inputs. Different parameters such as land-use, vegetative cover, rainfall intensity, soil type, initial soil moisture condition, and slope of the land have impacts on the runoff rate and thus on the rainfall-runoff relationship. This study considered only the amount of rainfall and runoff to establish the relationships for all land-uses and other factors were assumed constant for simplicity and based on data availability. Figure 5.5 plotted the rainfall-runoff relationship for all the land uses. The best nonlinear polynomial regression models were also fitted to the data and superimposed on the figure. Overall, the figure indicates that using only precipitation amount to explain the runoff is not sufficient and that the inclusion of a vegetation parameter, rainfall intensity, soil moisture condition etc. are crucial to further improve the results. All of the erosion plots established on the different land uses showed relatively good correlation between rainfall and runoff. Runoff correlation coefficients for the degraded plot was highest (R^2= 61%), while it was minimum on the agricultural plot (R^2= 42 %). The relationship was weak for the agriculture plot because of variations in vegetative cover in different seasons and disturbance of the soil for sowing and weeding purposes. Table 5.2 indicates a list of R^2 values and the polynomial regression models for each land use. Note that in the regression equations, '*R*' represents the runoff amount (m^3/ha) and '*RF*' means rainfall amount (mm).

5.2.4 Runoff and Soil Loss Relationship

Runoff and sediment load relationship is complex and many factors such as topography, soil type, soil condition, rainfall intensity, land use etc can influence it. Figure 5.6 presents runoff and soil-loss relationships for on all land uses superimposed by regression models. The figure indicates good correlations between runoff and soil loss on all four land uses. Runoff-soil loss correlation from the degraded land is stronger while as expected the relationship is lowest from the agricultural land due to agricultural activities, change in vegetative cover and soil condition at sowing, weeding, and harvesting time. The impacts of these are significant especially during the early monsoon season when the crop canopy was not well established.

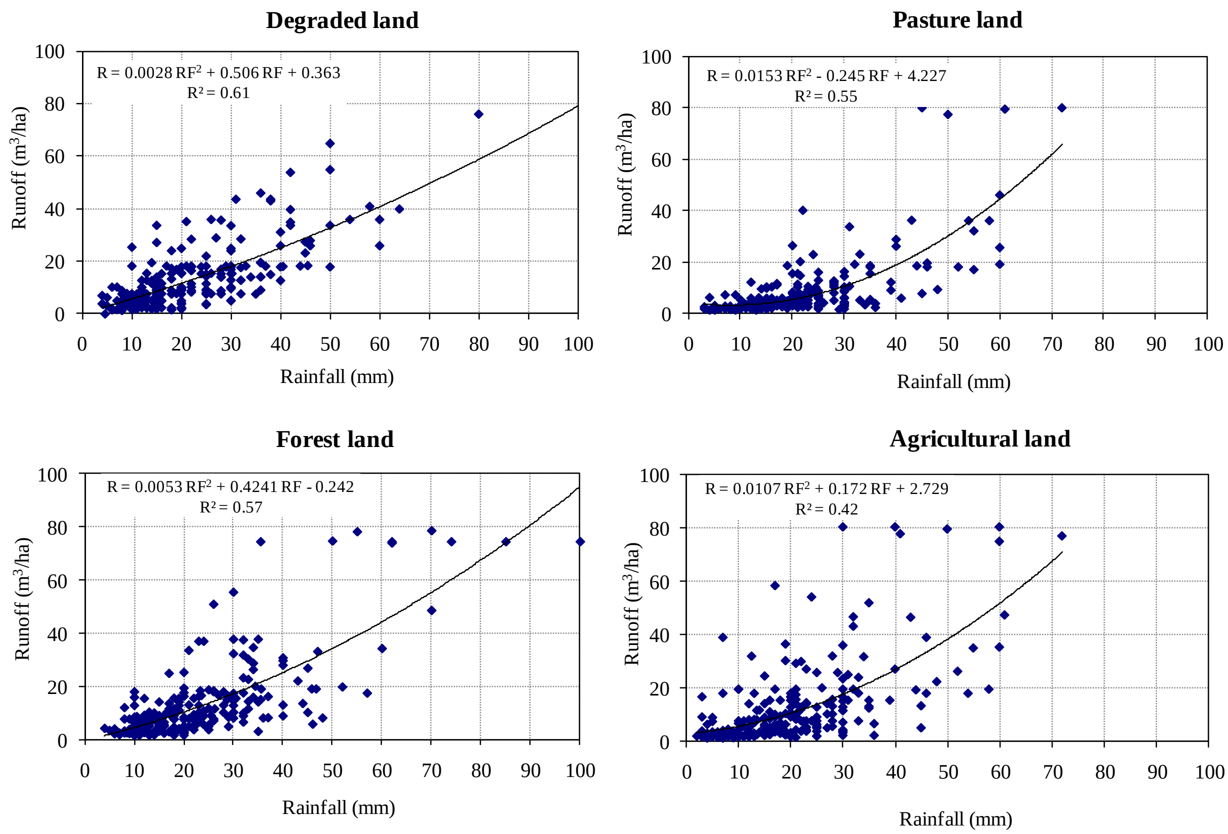


Figure 5.5 - Rainfall and runoff relationship for all land uses

Table 5.2 - Equations and correlation values for rainfall and runoff relationship

Land Use	R^2	Polynomial Regression Equation
Degraded plot	0.61	$R = 0.0028\ RF^2 + 0.506\ RF + 0.363$
Pasture plot	0.55	$R = 0.0153\ RF^2 - 0.2459\ RF + 4.2277$
Forest plot	0.58	$R = 0.0053\ RF^2 + 0.4241\ RF - 0.2422$
Agriculture plot	0.42	$R = 0.0107\ RF^2 + 0.1722\ RF + 2.7293$

During that time of the year maize and rice crops were in the initial growth stages. However, in all cases, events of high runoff amount do not always produce high soil loss. Certain events with very high runoff amounts hardly mobilize any sediment due to low intensity rains and good vegetation on the ground. Other events with small amount but high rainfall intensity generate high runoff with more sediment load. The initial condition of the soil also plays an important role in soil erosion. The R^2 value was found maximum from the degraded plot (69%), while it was lowest from the agriculture plot (48%). In the equation '*SL*' means the soil loss and

‘*R*’ represents runoff amount. Table 5.3 indicates the correlation coefficient value (R^2) and the polynomial regression models for different land uses.

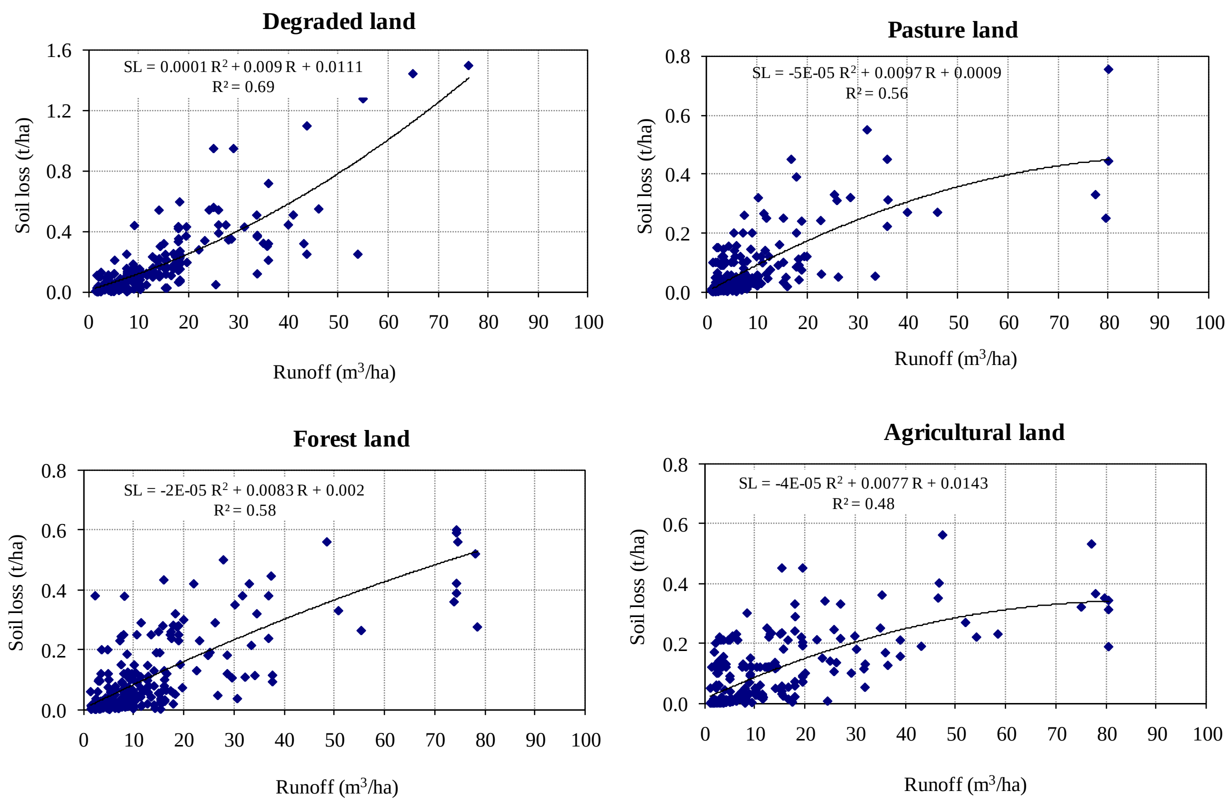


Figure 5.6 - Runoff and soil loss relationship for all land uses

Table 5.3 - Equations and correlation values for runoff and soil loss relationship

Land Use	R^2	**Polynomial Regression Equation**
Degraded Plot	0.69	$SL = 0.0001\,R^2 + 0.0097\,R + 0.0111$
Pasture Plot	0.56	$SL = -5E\text{-}05\,R^2 + 0.0097\,R + 0.0009$
Forest Plot	0.58	$SL = -2E\text{-}05\,R^2 + 0.0083\,R + 0.002$
Agriculture Plot	0.48	$SL = -4E\text{-}05\,R^2 + 0.0077\,R + 0.0143$

5.2.5 Rainfall and Soil Loss Relationship

For soil erosion, both rainfall intensity and plants cover plays more important role rather than rainfall amount and duration. The biggest events, in terms of soil loss, typically occurred during periods of ploughing, weeding or sowing in the agricultural fields. These management practices led to loosened topsoil conditions. If a high intensity rainfall occurs immediately following one of these practices, it results in a high amount of soil loss in a single event. Schreyer et al. (1995) reported that agricultural practices on steeper slopes and on marginal lands are a cause of land degradation in the uplands of Hindu Kush Himalayas. Conversion of forest and pasture land into agricultural fields makes the land more susceptible to erosion. Rainfall and land use type play important roles in runoff generation and soil loss. Figure 5.7 presents the rainfall and soil loss relationships from all land uses superimposed by regression model for each land use. Scatter data-points on the figure show that the rainfall-soil loss relationships were not very strong on the degraded and forest land uses. The correlation value (R^2) and the polynomial regression models established for different land uses are presented in the Table 5.4. The correlation values (R^2) was maximum from the agricultural land (62%), while it was minimum from the degraded land (45%). In the equation '*SL*' represents the soil loss and '*RF*' is the rainfall amount.

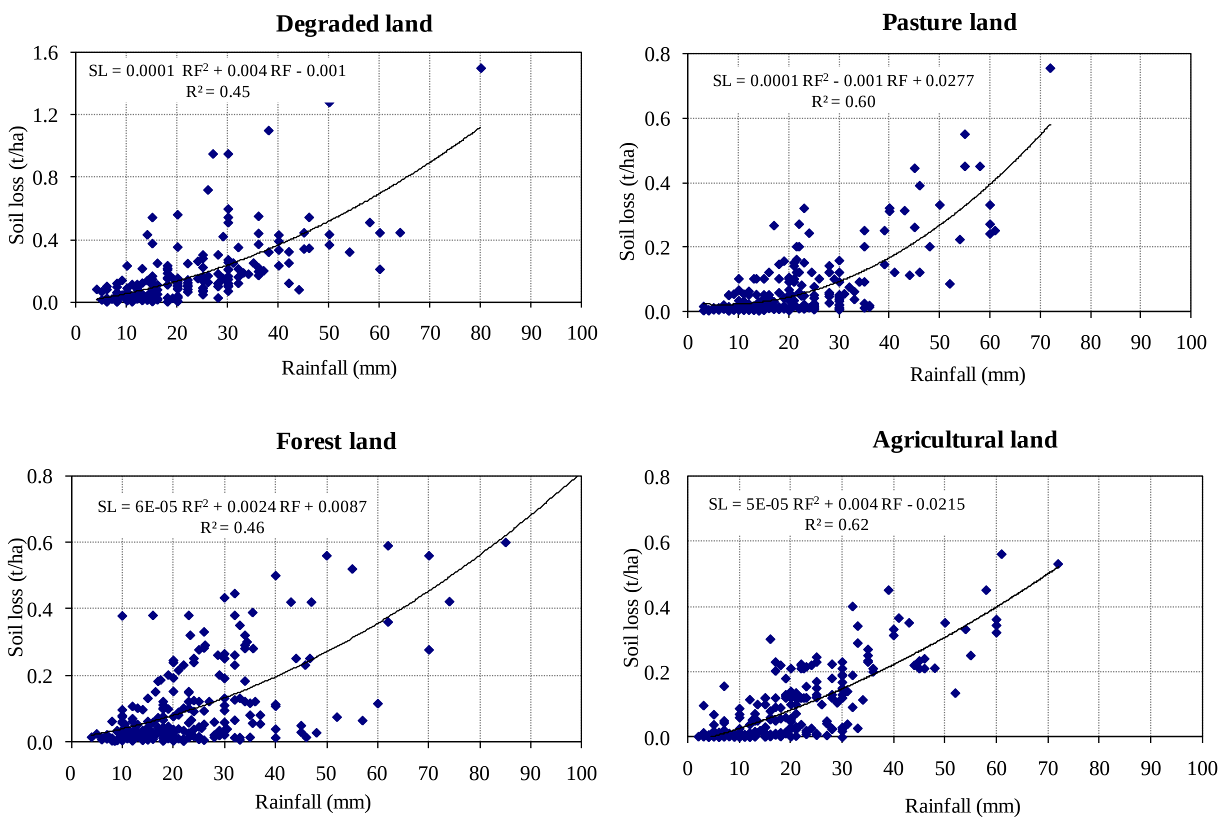


Figure 5.7 - Rainfall and soil loss relationships for all land uses

Table 5.4 - Equations and correlation values for rainfall and soil loss relationship

Land Use	R^2	Polynomial Regression Equation
Degraded Plot	0.45	$SL = 0.0001\ RF^2 + 0.0043\ RF - 0.0012$
Pasture Plot	0.6	$SL = 0.0001\ RF^2 - 0.0018\ RF + 0.0277$
Forest Plot	0.46	$SL = 6E\text{-}05\ RF^2 + 0.0024\ RF + 0.0087$
Agriculture Plot	0.62	$SL = 5E\text{-}05\ RF^2 + 0.0042\ RF - 0.0215$

5.3 Summary

Chapter discussed the rainfall, runoff, and soil loss relationships on different land uses. Regression model was developed and results showed very strong relationship between rainfall, runoff, and soil loss on all land uses with strong R^2 value. Next chapter will discuss mathematical modeling to calculate runoff and sediment loss at plot and watershed level.

Chapter 6: A Mathematical Model for Surface Runoff and Soil Erosion

"Model results are only as reliable as the model assumptions"

(S. Sorooshian and V.K. Gupta)

This Chapter discusses a journal paper "A New Approach on Modeling Soil Erosion and Surface Runoff in a Watershed". The Chapter discusses the mathematical approach to estimate runoff and sediment losses on plot as well as watershed level. Model data was presented with measured data for validation and was optimized by using genetic algorithm approach.

The increasing population in most part of the world demands steep land cultivation in hilly areas and construction of new reservoirs to meet agricultural and energy demands. As water resources and sediment transport issues continue to grow scarcely, the demand intensifies for innovative approaches that provide better understanding and management of the available resources. To fully understand a hydrologic system and the involved runoff and soil erosion processes, continuous monitored data is important. Unfortunately, in most countries (if not all of them), climatic and hydro-meteorological data which are required for planning and designing of any development and research projects are unavailable. Even if it exist such data are not reliable enough to be always used. Therefore, there is a need to take an alternative method to provide and/or predict some estimates of the influential parameters and consequently a system response to the changes. In the absence of reliable field data, demand for alternative methods such as mathematical models and different relationships among the involving parameters are increasing (Bultot et al., 1990). Marsh and Marsh (1995) reported that in the absence of reliable data for specific area, different relationships and hydrological models are the most effective and reliable tools to estimate water flow. Sophisticated hydrologic models and parameters relationships will help the water authorities to make more informed decisions while designing or operating their systems. Several models have been developed over the past couple of decades but research work in the Hindu Kush Himalaya region is rare (if there is any). In addition to the complexity of the models, most of generally require a large number of input parameters that are not often available or exactly known. Some parameters are not even directly quantifiable.

The intent of this research was not to thoroughly describe or model the erosion process and hydrologic behavior of a watershed. The goal was to highlight the key factors and to set conceptual bases for creating a simple but reliable-enough mathematical/numerical model for estimating the soil loss rate in a watershed.

6.1 Mathematical Modeling

A comprehensive model of a hydrologic event must consider all the influential factors through a multi-objective approach. However, due to the overwhelming complexity of this task, this research mainly studied some aspects of effective parameters and investigated some parts of their impacts on water cycle in the Hilkot watershed from both quality and quantity points of views. Although a single-objective decision model may often be sufficient for simple cases, there are many situations calling for decisions based on multiple objectives. In these cases, the aim should be to simultaneously balance a group of possibly conflicting objectives. Multiple objective problems may seem crucial in water resources engineering, not only because of the multi-dimensional nature of almost all hydrologic events, but also because there are always many open questions to answer. In fact, there is no universally accepted definition of "optimum" in hydrologic problems unlike their single-objective counterparts. Hence, this makes it difficult to even compare the results of one model to another. Normally, the decisions about what the "best" solutions are correspond to the preferences and values of the decision makers. Even the modeling process itself is a multi-objective problem.

Thus, the goal of a modeling process strongly depends upon 1) how easy the solutions can be mathematically obtained; 2) how computationally-efficient the modeling technique is, 3) how comparable and important the various objectives are; and finally 4) how well the solutions represent reality. Clearly, these are all judgment calls depending on many external constraints and the purpose of the modeling exercise. Although there are almost unlimited alternatives/possibilities to the conventional hydrologic models, they can be broadly grouped according to where they fall in the "simplicity" vs. "accuracy" spectrum. Typically, the more accurate a modeling is, the more complicated it is. It has been shown how modeling techniques have gradually developed to reflect observations in real systems. Interestingly, however, the main preoccupations of mathematically modeling of a hydrologic event are the simplicity and accuracy of the model (their ultimate goals) rather than the modeling technique itself. Thus, the main effort of this study is to develop an “accurate” but “simple-enough” model to be usable in engineering practice (at least in the preliminary stages when not enough data is available).

The thermodynamic laws as well as Newton's laws are often stated for a specific quantity of matter in a system. In hydrology (e.g., a rainfall/runoff event), however, the engineers and or designers are often keen to know what happens in a fixed volume through which mass flows at a certain rate. They may also be interested in the rates of mass into and out of a system. Thus, the control volume form of the system laws is of great importance. Rather than focusing on a particle of mass moving through the volume, it is more convenient to focus on the volume occupied by the mass.

6.1.1 Surface Runoff Model

Using a control volume approach, the surface runoff flow can be mathematically modeled by the conservation law of mass. For a control volume, the rate of change of mass inside the volume is given by the difference between the inflow and outflow mass flow rates. For a single flow coming in and a single flow going out this is:

$$\frac{dm_w}{dt} = \dot{m}_{w_{in}} - \dot{m}_{w_{out}} \tag{6.1}$$

Here, m_w is mass of the flowing water (M); the first and second terms on the right side are the rates of inflow and outflow mass of water (MT^{-1}) into and from the control volume; and t is the time. Replacing for the mass and mass flow rates into the equation (6.1) will result in:

$$\frac{d}{dt}(\rho_w V) = \rho_w Q_{in} - \rho_w Q_{out} \tag{6.2}$$

in which, ρ_w and V are density (ML^{-3}) and volume (L^3) of water, Q_{in} and Q_{out} are inflow and outflow discharges (L^3T^{-1}) into and from the control volume, respectively. Substituting for the volume in terms of the plan area (L^2) of the watershed (A_p) times the depth (L) of flow (h), the equation (2) becomes:

$$\frac{dh}{dt} = \frac{Q_{in} - Q_{out}}{A_p} \tag{6.3}$$

In general, the hydrologic routing expressed by the equation (6.3) employs the use of the continuity equation and either an analytical or empirical relationship between the rainfall and discharge at the outlet of a watershed. If the inflow and outflow hydrographs for a watershed are known (e.g., from the field measurements), the runoff depth and/or water storage over the watershed can be determined by integrating (either numerically or analytically) the equation (6.3).

6.1.2 Water Quality Model

Similar to the surface runoff, the soil loss and its transport can also be modeled by using a mass conservation law for the suspended sediment loads. Using a control volume approach, this can be mathematically represented as:

$$\frac{dm_s}{dt} = \dot{m}_{s_{in}} - \dot{m}_{s_{out}} + S_t \tag{6.4}$$

Here, m_s is the mass (M) of the suspended loads in the system; $\dot{m}_{s_{in}}$ and $\dot{m}_{s_{out}}$ are the inflow and outflow rates of mass (MT^{-1}) into and from the control volume; and S_t is the rate (MT^{-1}) of the released eroded material from the ground surface into the bulk flow. Since precipitation is the only inflow to the system and that is fresh water with no turbidity (i.e., $\dot{m}_{s_{in}} = 0$), the equation (6.4) can be expressed as:

$$\frac{d}{dt}(VC) = 0 - CQ_{out} + S_t \tag{6.5}$$

Here, C is the concentration (ML^{-3}) of suspended loads carried with the flow and V is the volume (L^3) of water ($V = A_p h$). Thus:

$$\frac{d}{dt}(A_p hC) = -CQ_{out} + S_t \tag{6.6}$$

Rearranging the equation (6):

$$A_p \frac{d}{dt}(hC) = A_p\left(C\frac{dh}{dt} + h\frac{dC}{dt}\right) = -CQ_{out} + S_t \tag{6.7}$$

This can be simplified as:

$$h\frac{dC}{dt} + C\frac{dh}{dt} = \frac{-CQ_{out} + S_t}{A_p} \tag{6.8}$$

Combining the equations (6.3) and (6.8):

$$\frac{dC}{dt} = \frac{-CQ_{in} + S_t}{A_p h} \tag{6.9}$$

The system of governing equations (6.3) and (6.9) must be solved simultaneously for the unknown concentration and flow depth (*C* and *h*) along with an appropriate set of boundary conditions. This research assumed the boundary conditions of no initial surface runoff and thus suspended load and/or water turbidity in the watershed. This is:

$$h = 0 \quad \text{and} \quad C = 0 \quad \text{at time}\ t = 0 \tag{6.10}$$

Note also that this study enjoys the Euler method to numerically integrate the governing equations of (6.3) and (6.9) with initial conditions of (6.10).

6.1.3 Soil Erosion Model

This research studied the erosion process through a model originally proposed by Boxall et al. (2001) based on a cohesive transport theory for analyzing the discoloration events in water distribution systems. Defining a self cleaning threshold limit for the acting shear stresses at ground surface, this study enjoyed a three-step erosion model. Considering erosion, suspension, and regeneration as the main causes for the release of materials from the ground surface to the bulk flow, even a small surface runoff seems to be sufficient to carry the fine materials as a persistent suspension wash load. Hence, ignoring the regeneration of the materials (due to settling) and defining R_s as the rate of soil supply from the ground surface ($ML^{-2}T^{-1}$), the mobilization of a soil particle can be described as:

$$R_s = \frac{P(\tau_a - \tau_s)^n}{Q} \tag{6.11}$$

where τ_a is the available or acting shear stress ($ML^{-1}T^{-2}$) at the ground surface; τ_s is the erosion yield strength at the surface ($ML^{-1}T^{-2}$); and Q is the flow discharge (L^3T^{-1}). The coefficient P and the dimensionless exponent n are used to describe the eroding forces at the ground surface. The materials removed by the excess shear force from the ground surface are then washed away with the bulk flow and carried along the watershed. Thus, the change in water turbidity due to the passage of flow can be obtained by multiplying the supply rate of soil by the surface area swept by the runoff as:

$$S_t = R_s \times A_p \tag{6.12}$$

Note that the parameters P and n are highly problem dependent and they must be determined through a careful calibration procedure.

The theory of sediment transport in fluid flows is relatively well established through a large volume of published research. However, the majority of this work is associated with cohesion less sediments (as large as sands and gravels) with specific gravities around 2.0. On the other hand, the soil types often carried with surface runoffs in a watershed may also include fine cohesive soils in the range of silt to clay. The difficulties with cohesive particles arise from the fact that they flocculate within the flow. This causes the transport to be rather complicated due to the interactions between the flow properties and flow conditions. In the cohesive range, the grains are held by cohesive forces, which bind them to their neighbors at discrete points of contact. The bond can be broken by shear or normal forces. In soil mechanics, the threshold or critical bed shear stress follows the well-known Columb's equation (Lambe and Whitman, 1979) as:

$$\tau_s = c_s + \sigma \tan\varphi \tag{6.13}$$

in which τ_s is the shear strength ($ML^{-1}T^{-2}$), σ is the effective normal stress ($ML^{-1}T^{-2}$), c_s is a measure of cohesive strength ($ML^{-1}T^{-2}$), and φ is the angle of repose. For the surface runoff in a watershed, the normal stress is effectively negligible (no pore pressure). Thus, this research approximates the erosion yield strength at the ground surface in the equation (6.11) by the cohesive strength of the soil particles.

In uniform, turbulent, incompressible flows in open channels of a prismatic cross section, the acting shear stress at the boundaries varies about proportional to the hydraulic radius of the channel and the slope of energy grade line as:

$$\tau_a = \gamma_w R_h S_f \tag{6.14}$$

in which R_h is the hydraulic radius (L) defined by $R_h = A/W_p$; A is the cross-sectional area (L^2); W_p is the wetted perimeter (L); S_f is the slope of energy grade line; γ_w is specific weight ($ML^{-1}T^{-2}$) of water ($\gamma_w = \rho_w\, g$); and g is the gravitational acceleration. In the case of the surface runoff, the flow depth is relatively negligible when compared with the width (perpendicular to the flow direction) of the watershed at the plan view. Thus, approximating the watershed area as a very wide-channel, the hydraulic radius can be determined by:

$$R_h = \frac{A}{W_p} = \frac{bh}{b+2h} \Rightarrow R_h \approx h \tag{6.15}$$

Here, b is the width (L) of the wide channel section. Note that the slope of the energy grade line in the equation (6.14) can be determined from Manning equation or approximated by the slope of the ground surface (S_o).

6.1.4 Calibration Technique

This research enjoys the genetic algorithm (GA), a stochastic search technique, to calibrate the parameters (P and n) in the proposed soil erosion model. The GA is an optimization/calibration technique that has been successfully applied in various areas of water resources providing the best possible fit to a model’s results. The technique was originally presented by Holland (1975) and later developed by Goldberg (1989) and Gen and Cheng (2000). GA uses the mechanism of natural selection to search a wide portion of a solution space. In application of GA, several sets of decision alternatives are formed. The alternatives are evaluated and ranked according to their fitness with respect to an objective function. The alternatives then compete in a selection process where those with high fitness values are selected, while eliminating the alternatives with poor fitness values. The selection process is repeated until all the alternatives of the population are identical. Efficiency of the algorithm depends on the operating parameters and the convergence criterion. The higher the number of individual evaluations for converging to the optimum, the less efficient is the procedure. More details on GA can be found in the literature (Holland, 1975 and Goldberg, 1989).

6.1.5 Stage-Discharge and Suspended Sediment Relationships

Continuous monitoring of river flow is essential for estimation of water availability, water resource management, and planning. The continuous recording of velocities in river is practically impossible, while it is relatively simple and more applicable in practice to continuously measure water levels and then convert them to correspondence discharge. At gauging stations, where the flow is contained within the known cross section and is controlled by bed structure, the discharge '*Q*' is the function of head '*H*' (water level). Continuously recorded water levels were converted to corresponding discharge by using the rating curve. The Stage discharge relationship (rating curve) was established by measuring the discharges at different water levels. Once the number of flows at different water level for a specific hydrological station have been measured, it is possible to set up the relationship between correspondence water levels and flows. At the hydro station, discharges were measured by using the current meter (Dongal et al., 1998) the salt dilution method (Merz, 1998) and the volumetric method depending on the flow amount and conditions of streams at different water levels.

The most accurate curves are obtained when the measurements are spread evenly over the complete range of water levels. However, field experience shows that most of the time this is difficult to attain. High water levels are much rarer than low water levels. Therefore, most of the time rating curves are usually quite accurate in their lower parts due to a number of measured values, but get more uncertain in higher parts because of the low number of available observations. During high floods, discharge measurements are much more difficult, as high water levels do not occur very often and usually stay for a very short duration. The attempt has to be made to measure as many high flows as possible.

Sediment sampling was carried out at the watershed outlet during flood events at different water levels for the establishment of the stage vs. sediment concentration relationship.

The concentration of suspended sediment in a river is a function of the discharge. In reality, suspended sediment and discharge relationship is much more difficult to establish than the stage discharge relationship, since the relationship is less stable due to involvement of various factors. The suspended sediment concentration was measured at the hydro station during the flood events. For each sample taken, the measured sediment concentration was coupled with the corresponding water level.

6.2 Results and Discussion

The following sections present and discuss the available field data and model results from January 1999 to December 2005 for plot level (84 month) and January 2000 to December 2005 (72 months) for the watershed and monthly average of all years. Please note that the time scale for all the figures in the following sections starts from January to December.

6.2.1 Stage Discharge Relationship

Figure 6.1 shows a very strong relationship between stage and discharge for hydro stations at the watershed outlet. Using polynomial transformation, a regression analysis was applied to develop the functional relationship. The figure indicates the best regression fit to the measured data. High accuracy can be achieved by covering wide range of data points. In the figure, the value of R^2 = 99% showed a very strong correlation. The regression equation provides the following stage- relationship:

$$Q = 4.053H^2 - 86.762H + 581.22 \qquad (6.16)$$

where Q is discharge (lps) and H is water level (cm).

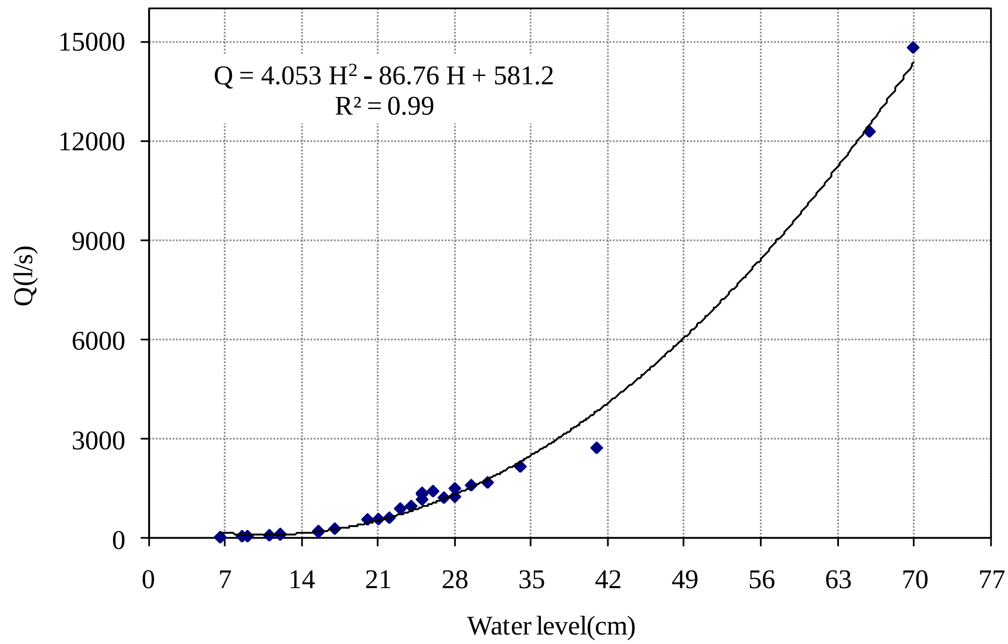


Figure 6.1 - Stage discharge relationship curve for hydro stations in Hilkot watershed, Pakistan

6.2.2 Discharge vs. Suspended Sediment

The total monthly-suspended sediment load was estimated based on daily measurements using discharge and sediment load relationships at the gauged station at the watershed outlet. Developing a rating curve for water level vs. sediment is challenging and complex because of the involvement of various parameters. Normally, no strong correlation was seen between discharge and sediment. Figure 6.2 shows a rating curve for the water level (cm) vs. sediment concentration (g/l), at the outlet of the Hilkot watershed. The figure also indicates the best linear regression fitted to the data. In the figure, the scatter points indicate that there are other factors in addition to the flow discharge, which may influence the sediment concentrations in the river. These factors include periodic mass movements, bank collapses, construction activities, and so on. Irregular sampling of suspended sediment concentration may also be a cause for weak relationships. The linear regression model provides the following relationship established for the water level vs. sediment at hydro stations:

$$S = 0.0861H - 0.3024 \tag{6.17}$$

Where *S* is sediment concentration (g/l) and *H* is water level (cm).

Please note that it is very weak to draw conclusions from the measured suspended concentration and the calculated sediment load because only part of the eroded soil material reaches to the receiving streams and gets recorded as suspended sediment concentration. High amounts of rain may sometimes produce negligible sediment if the rainfall intensity is low and the watershed is covered with vegetation. While on the other hand, a small amount of high intensity rain may generate significant amount of sediments in the streams.

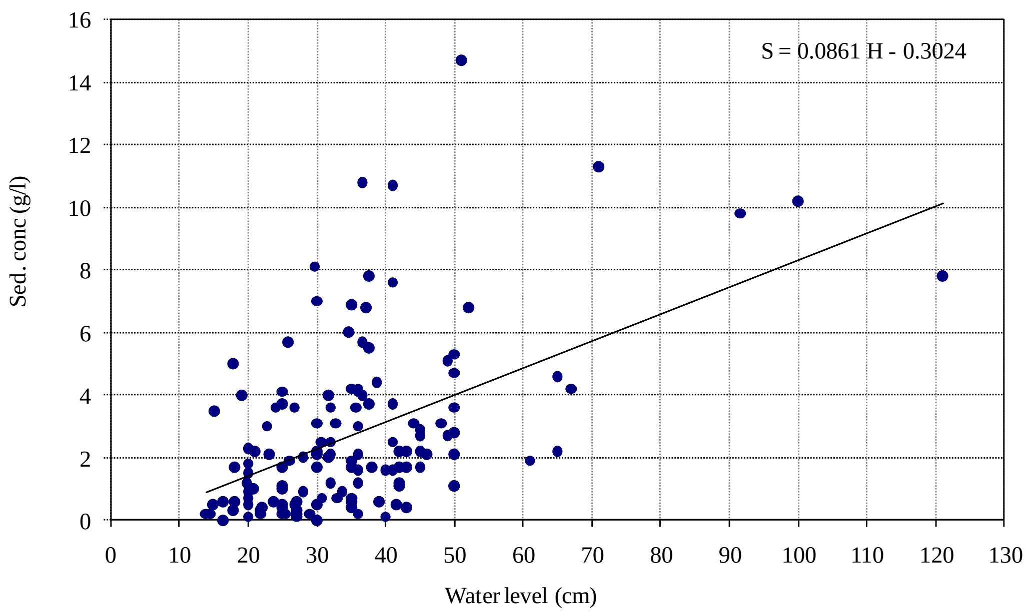


Figure 6.2 - Suspended sediment rating curve at watershed outlet

6.2.3 Stream Flow Measurements

Figure 6.3 shows average monthly water level throughout the study period. Data shows that base flow from the watershed was very low in winter season (October- February). The water level rises during March when the area receives some pre monsoon rains followed by low water levels during the dry months of May-June. A good amount of water was available during monsoon seasons (July to September) when almost 40% of the rain occurs in the area.

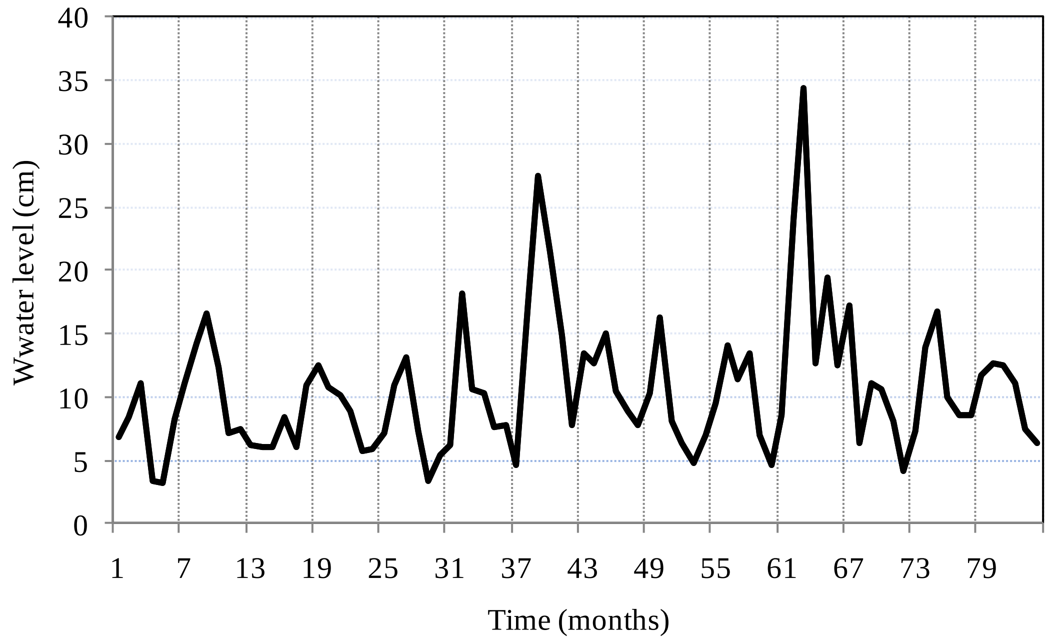


Figure 6.3 - Average monthly water level (cm) at watershed outlet

6.2.4 Flood Hydrograph at Main Hydro Station

A flood hydrograph shows how a stream/river responds to one particular storm. Many factors may influence the shape of the hydrographs. These include precipitation amount and intensity, catchment shape and gradient, land use and vegetation, surface slope, soil type, etc. Catchment area of Hilkot watershed was small and steep, causing flow and stream levels to rise very quickly after rainfall, having a flashy response. Once flood reaches the peak, it falls rapidly and most of time with 10-12 hours achieving base flow again.

Figure 6.4 shows the two single storm hydrographs at the main outlet. In the hydrograph, the zero time (or starting time) shows the beginning of runoff and the peak describes the maximum flow rate. The rising limb shows increase in discharge while the recession limb shows the decline in discharge volume. Hydrographs show the positive skew, with recessing time greater than the rising time. In both events flood reaches from initial flow to peak flow within 3-4 hours, falls very quickly, and reaches the base flow again within 10-12 hours due to steepness of area. Normally, base flow of the area was very low, runoff water leaves watershed in a very short time period.

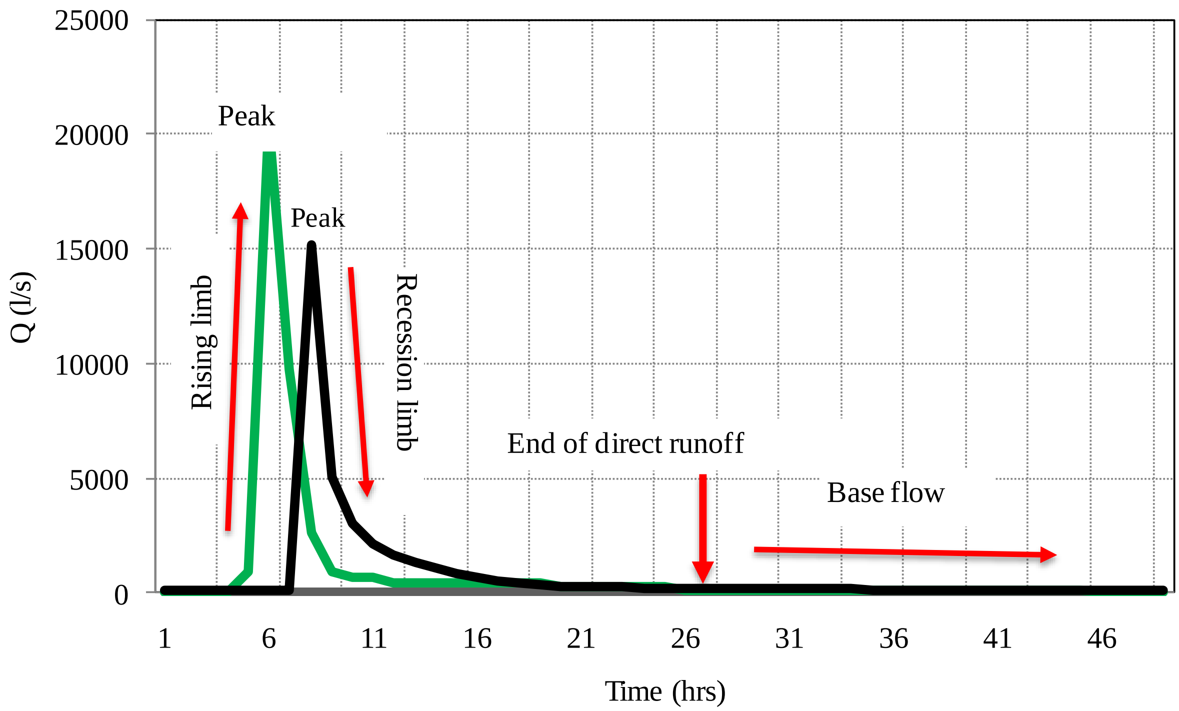


Figure 6.4 - Flood hydrograph at main hydro station in Hilkot watershed, Pakistan

6.2.5 Surface Runoff at Plot Level

The proposed model was run for runoff estimation at the plot level and for different land uses in the Hilkot watershed. Figure 6.5 presents the measured data and the model results. Overall, the figure shows similar trends for the field and model runoff-data for all land uses. The figure highlights some fluctuations in runoff during the study period. As the figure indicates, the model provides a comparatively higher runoff than measured data for pasture, forest, and agriculture lands. One possible explanation is that the plant cover varies during different seasons on pasture, forest, and agriculture lands and that has impacts on the surface runoff. In general, vegetation tends to increase the infiltration rates. Plants are among the natural factors controlling the proportion of precipitation that is converted to runoff in a given landscape and the time it takes for runoff to enter a receiving water body (e.g., river, lake, etc.). Vegetation helps reduce runoff and thus soil erosion by slowing water velocities in the vegetated areas. Vegetation may also reduce erosion by trapping excess sediment, nutrients, and farm chemicals. In fact, a number of factors (including seasonal effects, event characteristics, rainfall intensity, infiltration rate, and variations in vegetative cover during different parts of the year and rainfall intensity) influence the runoff generation. These factors were ignored in the model for the sake of simplicity and the lack of available data. During the monsoon seasons (July to September), when rainfall starts, it increases the availability of water which helps in improving the vegetative cover quickly. A quick variation in plant cover also resulted in variation of measured and model data.

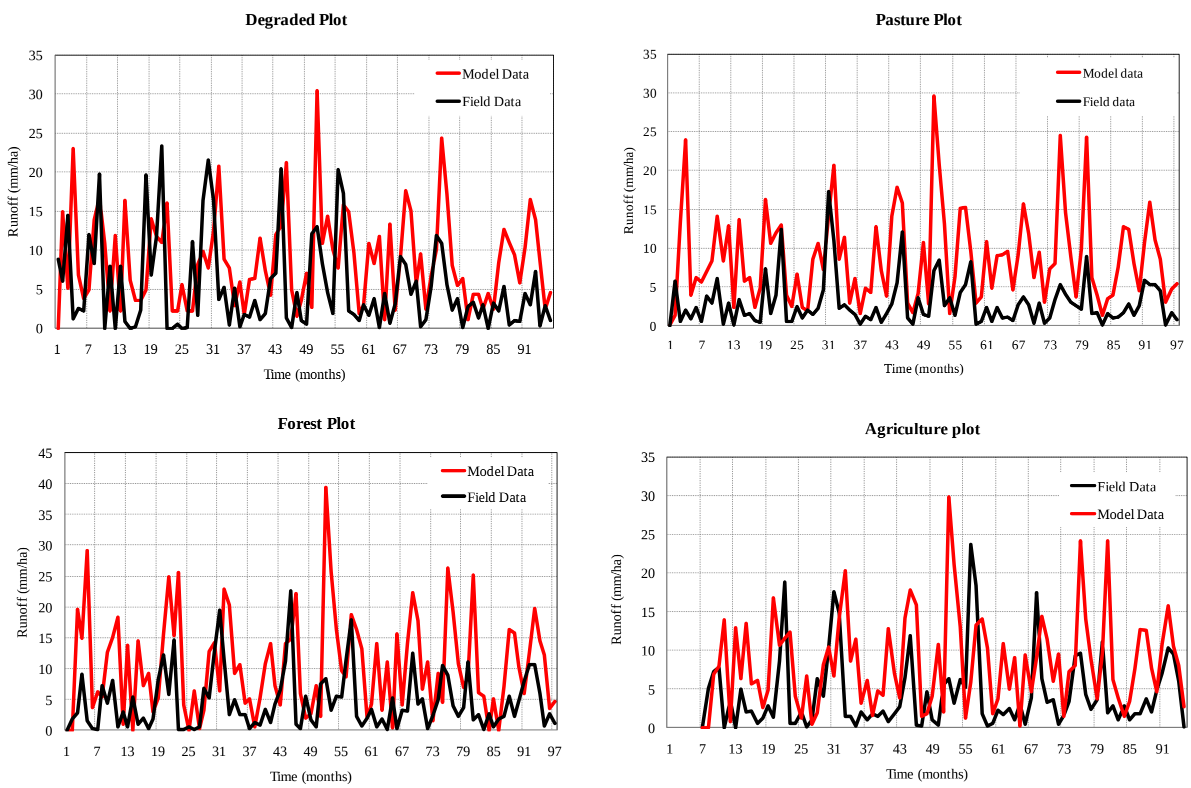


Figure 6.5 - Model vs. field data for surface runoff at different land uses at plot level

6.2.6 Surface Runoff at Watershed Level

At the watershed level, the proposed model was developed at gauged station at watershed outlet. Figures 6.6 and 6.7 demonstrate the measured inflow and outflow from watershed, and the measured vs. predicted runoff at the watershed outlet. Overall, the model data closely followed the trend seen with the observed data and successfully reproduced field data. The study considered influential parameters such as slope, inflow to the system (rainfall only), and the outflow from system. As the figures indicates the model responded very well in predicting discharge from the watershed and showed a very good trend with the field data. The model showed sensitivity and predicted different responses to different events due to the nature of the storm. Simulated data gave higher values throughout the year because, for model data, only rainfall was considered as inflow, while the other parameters like natural springs that contribute major portions of inflow, were ignored due to unavailability of data. In fact, developing a model at the watershed level is challenging and complex in nature because it is controlled by the various factors that may vary in space and time and hardly known exactly. Although the natural springs in the study area contribute considerable portions of inflow, the continuous monitoring of all springs and thus differentiating the base flow from the runoff water can be very complex and costly. Flow variations in the field data at the main outlet occurred due to the low monthly outflows during the cropping season. At that time people diverted most of the water to their rice fields, leaving a very small quantity in the stream as a base flow and resulting substantial variation; the fact that is observed during the monsoon period (July to September) when rainfall intensity was high and measured runoff proportion was also high due to low infiltration.

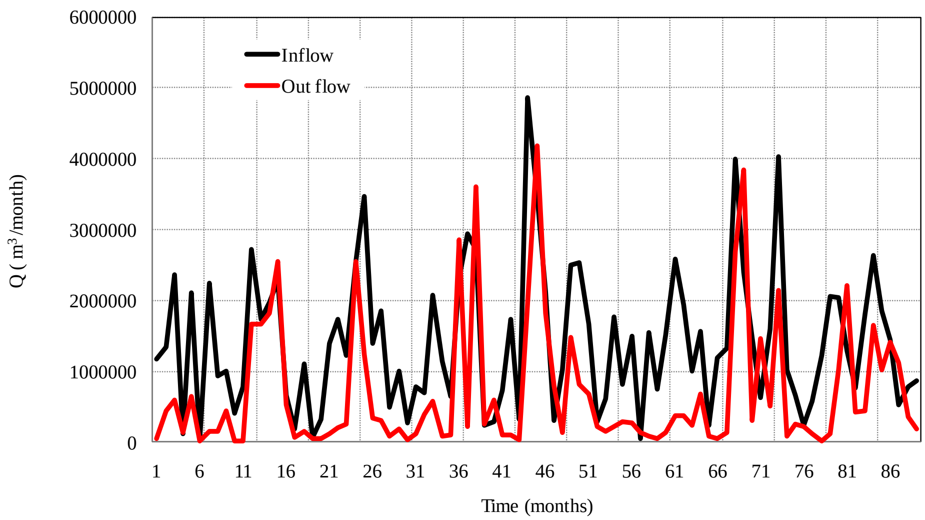


Figure 6.6 - Measured inflow vs. outflow at watershed outlet

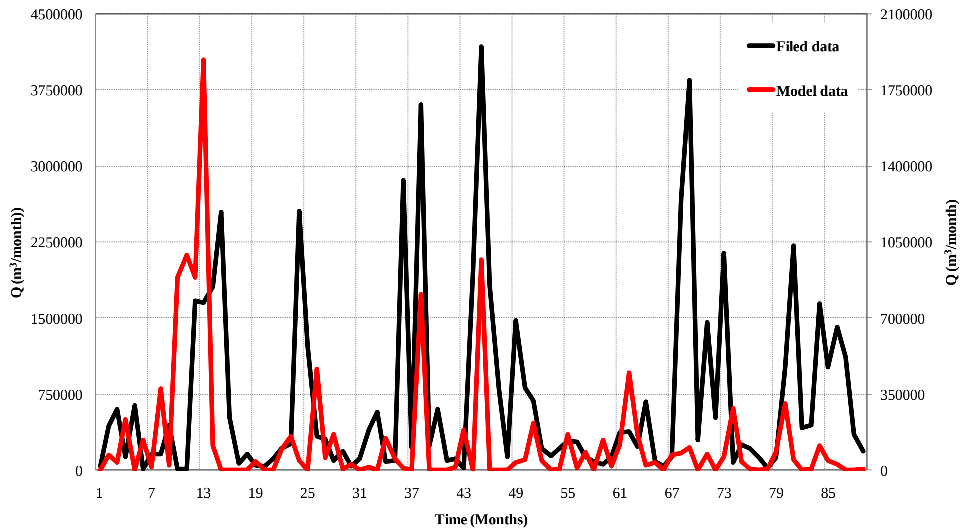


Figure 6.7 - Measured vs. model runoff at watershed outlet

6.2.7 Soil Loss at Plot Level

Figure 6.8 presents model and field soil loss data from all land uses. For almost all land uses, the model data presented a very similar trend to the field data throughout the study period and reasonably reproduced data with some variations. Variations increased in monsoon periods (July to September) and for other specific events when rainfall intensity was very high or plant cover was low, resulting in high soil loss. Similar to the field data, the model results clearly indicate the highest soil-loss for the degraded land where there is virtually no barrier for the soil erosion. On contrary, the figure clearly shows the lowest soil loss for the pastureland. Forest and agriculture lands presented similar trends. In fact, soil erosion potential is increased if the soil has no or very little vegetative cover of plants and/or crop residues. Plant and residue cover protects the soil from raindrop impacts and splashes, tends to slow down the movement of the surface runoff and allows excess surface water to infiltrate. Ground cover limits runoff by providing a physical barrier, which also increases the chance for the runoff to infiltrate. Vegetative cover also serves as a filter to increase the removal of particles from the runoff. The effectiveness of any crop, management system, or protective cover also depends on how much protection is available at various periods during the year, relative to the amount of erosive rainfall that falls during these periods.

As discussed earlier the proposed model ignored some important parameters like event characteristics, variations in vegetative cover, and seasonal rainfall effects in terms of intensity since limited data were (and still are) available for the Hilkot watershed area. Superimposed on these interactive processes, the sediment load, or amount of sediment in the flow, may also influence the soil detachment rates. Moreover, as the sediment load increases, the ability of the flowing water to detach more sediment decreases. Thus, this study considered only two parameters including rainfall amount and ground surface slope. The erosion-model parameters (*n* and *P*) were calibrated by using genetic algorithm to obtain the best possible fit. Table 6.1 shows the results of the calibration process for the model parameters *n* and *P* in all land uses. Interestingly, the calibration process reveals a small variation (between 0.3 to 0.5) for the parameter *n* for all land uses, while the parameter *P* varies quite widely (between 0.1 to 0.8) over the land uses.

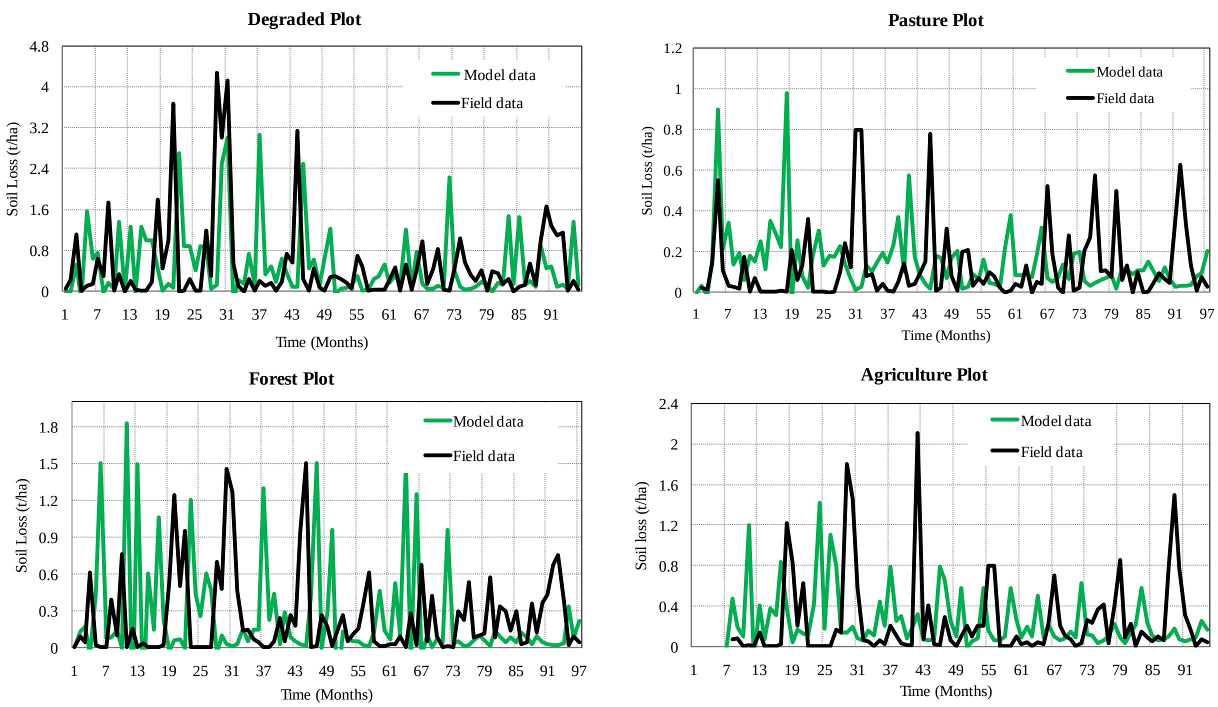


Figure 6.8 - Model and field data for soil loss at different land uses at plot level

Table 6.1 - Calibrated model parameters for all land uses

Land use	*P*	*n*
Degraded	0.31	0.41
Pasture	0.19	0.4
Forest	0.8	0.3
Agriculture	0.76	0.54

6.2.8 Soil Loss at Watershed Level

Figure 6.9 shows the measured and model sediment rate throughout the study period at watershed outlet, while Figure 6.10 presents the monthly average data for the seven year. Overall, the figures indicate identical trends for both model results and field data at the outlet of the Hilkot watershed. The model indicates some variations in some parts of the year specifically in March and monsoon period (July to September) when rainfall intensity was very high and infiltration was low resulting in high soil erosion. The model also indicates some variations because of the available spring's water addition and water diversion to agriculture fields for irrigation purposes. Springs water is normally very clean, moves slowly in the streams, and hardly mobilizes any sediment and thus causing small impacts on the sediment load level at the main outlet. Where variations were observed, they could be easily overcome by improving inflow and out flow data by adding spring and irrigation water. Similar to the plot level results, the GA technique calibrated the erosion-model parameters and provided 0.04 and 2.97 for the parameters n and P of the soil-erosion model, respectively. Interestingly, the calibrated values for the parameters n and P at watershed level are very different from the corresponding values at the plot level in Table 6.1.

One way ANOVA on ranks was performed comparing field and model data (22 degrees of freedom) and there was no significant difference ($P < 0.05$). Figure 6.10 shows the performance measures of the model at the watershed level. The model is able to represent the observed data well.

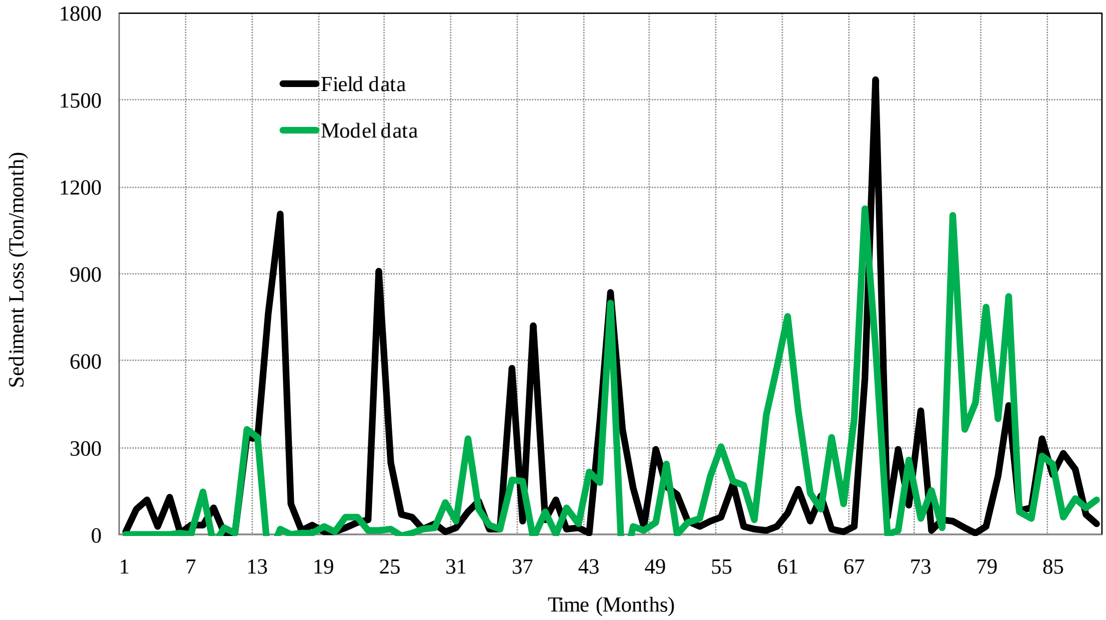


Figure 6.9 - Measured vs. model's soil loss data at watershed outlet

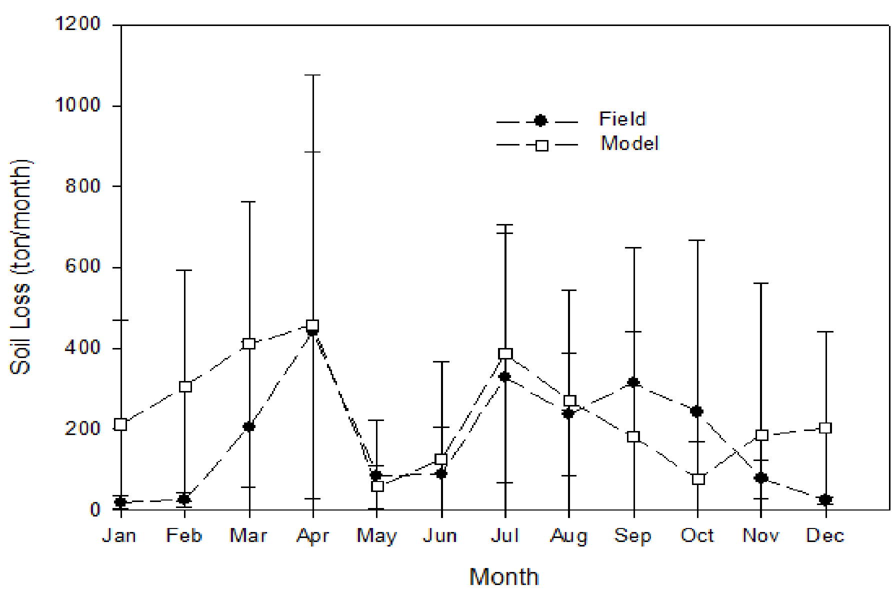


Figure 6.10 - Model performance measure chart at watershed level

6.2.9 Impacts of Ground Surface Slope on Soil Loss

Slope of ground surface may play an important role in generation of runoff and sediment loss from all land uses since a higher level of erosive energy is generated by flowing water over steep slopes than by the water moving over shallow slopes. Naturally, the steeper the slope of a land field is, the greater the amount of soil loss from erosion by water is expected. Figures 6.11 and 12 indicate the impacts of ground surface slope on soil loss at plot and watershed levels, respectively. Overall, the model results show that soil loss increases with increase in slope. As the Figure 6.12 highlights the soil-loss changes on plot level are not very significant except for agriculture plot where the soil loss increases considerably with an increase in slope. For the watershed level, however, the impacts of slope are much more noticeable and the amount of soil loss increase significantly by increasing slope. Figure 6.12 indicates that at watershed level, soil loss almost doubles when ground surface slope increases from 20 to 25 percent, while it reduces to half at 15% slope. It should also be mentioned that the greater accumulation of the surface runoff might also increase the slope length and consequently, increase the soil erosion rate by water. Studies have demonstrated that the surface runoff increases as a product of slope length and grade. Consolidation of small fields into larger ones often results in longer slope lengths with increased erosion potential, due to increased velocity of water, which permits a greater degree of scouring and thus carrying capacity for sediment.

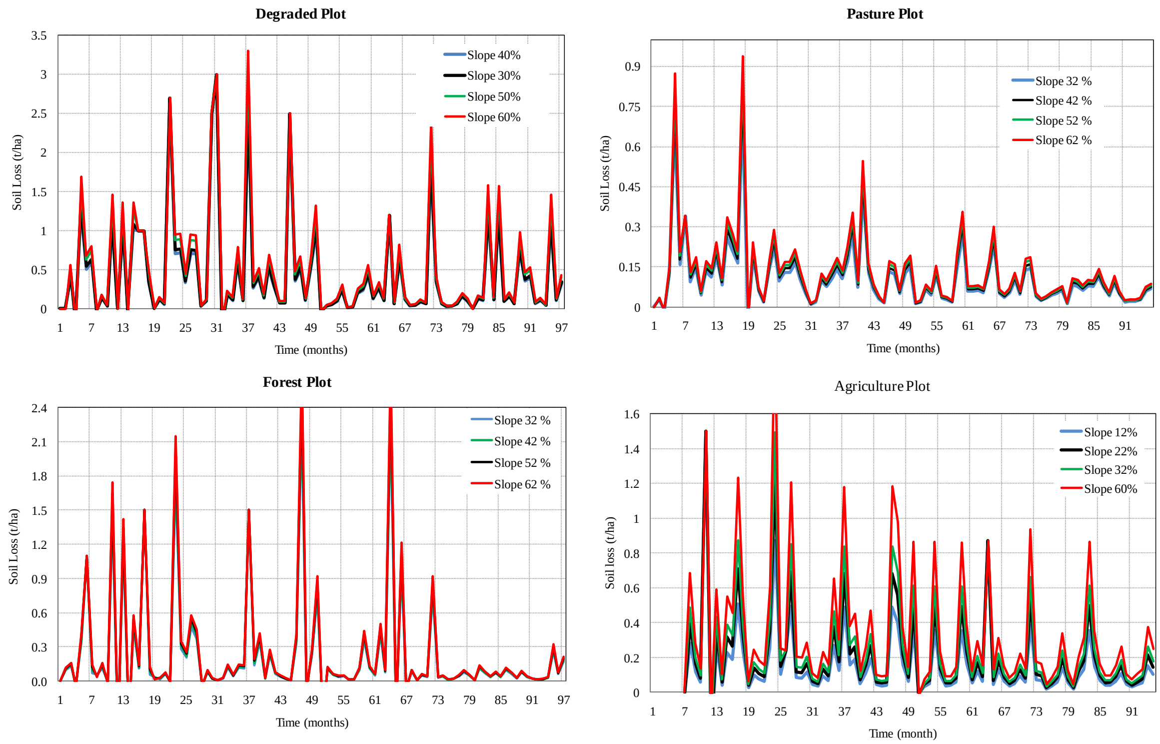


Figure 6.11 - Impacts of ground surface slope on soil loss at plot level

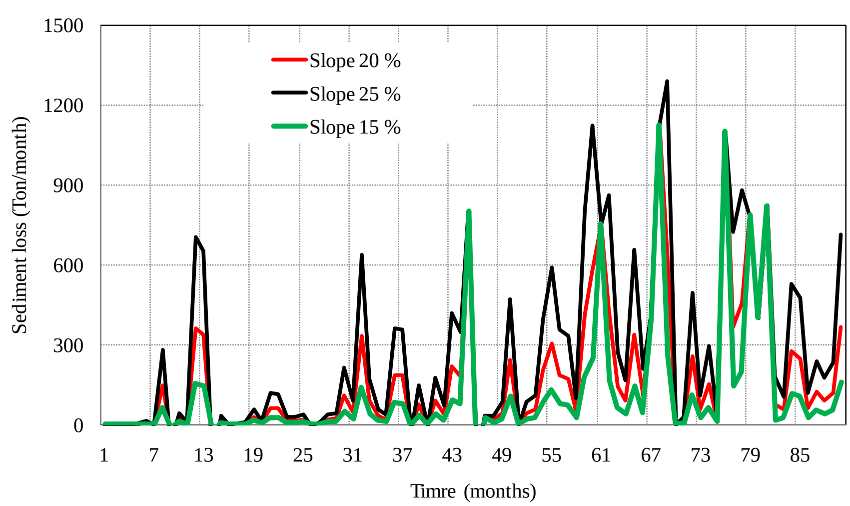


Figure 6.12 - Impacts of ground surface slope on soil loss at watershed level

Chapter 7: Summary, Conclusions and Recommendations

"There is a water crisis today. But the crisis is not about having too little water to satisfy our needs. It is a crisis of managing water so badly that billions of people and the environment suffer badly."

(World Water Vision)

7.1 Summary

The 2010 extreme monsoon flooding in Pakistan, which affected millions of people and took away thousands of lives, highlighted the need for countries in the region to be better prepared for extreme weather events in order to minimize damages. The population growth has increased load on natural resources especially land and water locally and globally. New sources are becoming scare, so the emphasis must be given to better utilize and protect all available resources. A high rate of runoff and sediment loads in rivers demands an efficient monitoring and quantification methodologies so that effective and efficient resource management strategies can be designed. Surface soil erosion from most of the areas is a serious threat to sustainable agriculture and sediment accumulation in downstream reservoirs and water distribution systems. The major issues associated with water in the Hindu Kush Himalayas region include water quantity and quality, flooding, and land degradation caused by water. Many countries in the region are already facing acute water shortage during dry seasons as well as flooding in rainy seasons with severe soil degradation.

The dissertation analyzed seven-year data collected in Hilkot watershed by PARDYP (1999- 2005) to get a better understanding of the behavior of different land uses in the watershed. The study was conducted by using a nested approach in catchment size of 1600 ha. A network of meteorological and hydrological stations and erosion plots were established. The study was performed at two scales: the watershed as a whole and the test plots. To investigate runoff and soil erosion, hydro station (flume) at watershed outlet and four erosion plots in various land uses (i.e., degraded, forest, pasture, and agriculture land) were established. The 100 m^2 rectangular erosion plots were established measuring 20 m by 5 m with a collection system of four drums interconnected with pipe. After each rainfall events, the runoff volume was calculated from the depth of water in each drum, while samples from each drum were taken and then analyzed in the laboratory for total sediment loss. Data was analyzed for monthly, annual, and seasonal basis. Cumulative distribution functions (CDF) and relationships were established for rainfall-runoff, and soil losses at plot level and mathematical models for runoff and soil loss was developed for different land uses and at the watershed scale.

7.2 Conclusions

- Runoff and sediment yield was highly dependent on season, land use type and rainfall intensity. Vegetative covers were the strongest observed management control for runoff and sediment generation. Data showed that the whole watershed area was highly seasonal and variable. Acute water shortage during winter and dry spells with considerable surplus water during monsoon period was observed. High intensity rainfall events may occur in any season, but for the Hilkot watershed, they were most frequent during the monsoon season. The majority of annual rainfall occurred during monsoon period (July to September) with a distant dry season from November to January. About 38% of the rainfall occurred in the monsoon period (July to September), while the watershed received 35 and 27 percent of the total rainfall in the pre-monsoon (March to June) and the winter period (October to February), respectively. Annual mean rainfall was over 1100 mm. During the study period, a majority of the events (60%) were small and in the range of 0-20 mm, while 37% of the events were in the range of 20-50 mm.

- Runoff and soil loss were observed from four land uses with different vegetative cover in Hilkot watershed, Pakistan. The results revealed that vegetation played very important role for runoff and soil erosion. Degraded land produced highest runoff and soil losses throughout the study period. Soil losses and runoff were found higher from the agricultural land when it was prepared for sowing and soil was loose, therefore susceptible to erosion. Lower soil loss was observed from the pasture and forest areas due to good vegetative cover. Variation in vegetative cover on all land uses also explained the large inter annual variation in runoff and soil loss generation. High Intensity rains during vegetative cover developing stage (May-June) caused significant losses in a single event. In all the erosion plots, almost 50% of the runoff and soil loss occurred during the monsoon period while winters were dry with small amount of runoff and soil loss.

- Polynomial regression models were developed for predicting rainfall, runoff, and soil loss relationships for different land uses. The models for all land uses showed acceptable correlations among the parameters on all land uses.

- This dissertation also presented a mass-balance control-volume approach for estimating surface runoff and sediment loads carried with flow at the plot as well as watershed levels in the Hilkot. The method required detailed measurements of rainfall, runoff, and suspended sediment concentration. The model was then calibrated with field measured data by using the genetic algorithm approach. For the reason of simplicity and limited availability of data, the research focused only on the amount of rainfall, the slope of the ground surface, while other parameters like rainfall event characteristics, variation in vegetative cover, and rainfall intensity were ignored. Overall, there was no significant difference between the model predictions and the field data indicating applicability of the model for small scale basins. Model results also highlighted some variations in some events that were possibly impacted by the events characteristics. In the future, adding missing parameters like event characteristics, rainfall intensity, and variation in vegetative cover, inflow from springs, infiltration, irrigation water outflow, and evaporation can increase the reliability of the model's results. A major advantage of the proposed model was the low input parameter requirements; the simple data input format, as well as the fast and simple calibration process through the application of the genetic algorithm. At the plot level, the variations between model and field data were direct results of ignoring rainfall intensity and behavior of runoff and soil loss under different vegetation covers. At the watershed level, accuracy could have been improved by quantification of diverted irrigation water and differentiating the base flow from the runoff water.

7.3 Recommendations and Future Work

- An awareness campaign is necessary to realize the water users about the present scenario of the available local water resources. Results of this research showed that seasonality played an important role in water scarcity in cropping season, which could be managed with better water management policies. More water is lost as runoff during monsoon; therefore, water-harvesting technology is also suggested for utilization of excess water in dry periods and protection of water reservoir downstream from sedimentation. Modern water management techniques should be studied and applied to obtain the maximum advantages of the available water resources in the watersheds.

- It was obvious from results that low runoff and soil loss were observed from the pasture and forest areas, which were covered with good vegetation. New approaches should also be studied and applied to improve the vegetative covers on degraded land and bare agricultural fields in pre-monsoon seasons (e.g. physical barriers, mulching, inter cropping, and relay cropping). To control runoff and erosion and to better utilize runoff water, vegetation and organic matter content of the fields should be improved to increase infiltration rate. A comparative study on treated and untreated plots on all land uses can also be very useful in future to investigate the impacts of the field interventions on different areas.

- The proposed mathematical model can be improved/expanded by adding other influential parameters like rainfall intensity, seasonal variation in vegetative cover, spring inflow, irrigation water, evaporation, and soil properties etc. This is relatively challenging; however, it is expected that the inclusion of the additional factors and processes of erosion would further improve the accuracy of predictions from the modeling framework.

- Model should be validated with another case study for more precise results.

References

Ali, K.F., and de Boer, D.H. 2007. Spatial patterns and variation of suspended sediment yield in the upper Indus River basin, northern Pakistan. Journal of Hydrology 334: 368–387.

Ali, K. F. 2009. Construction of sediment budgets in large scale drainage basins: The case of the upper Indus River. PhD thesis. Department of Geography and Planning, University of Saskatchewan, Canada.

Anderson, A., Pyatt, D., and Stannard, J. 1990. The effects of clear felling a Sitka spruce stand on the water balance of a peaty grey soil at Kershope Forest. Cumbria Forestry 63, 51-71.

Anderson, A., Pyatt, D., and Stannard, J. 1990. The effects of clearfelling a Sitka spruce stand on the water balance of a peaty grey soil at Kershope Forest. Cumbria Forestry 63, 51-71.

Banskota, M., and Sharma, P. 1994. Development of Poor Mountain Areas, ICIMOD; Estimated based on data and information from Population Reference Bureau, 2007 World Population Data Sheet and Banskota, m. 2004. The Hindu Kush-Himalayas: Searching for Viable Socioeconomic and Environmental Options, pp. 57-105, In: Banskota et al. (eds.) "Growth, Poverty Alleviation and Sustainable Resource Management in the Mountain Areas of South Asia, ICIMOD, and Nepal.

Bingner, R.L., and Theurer, F.D. 2001. AnnAGNPS Technical Processes: Documentation Version 2.

Bosch, J., and Hewlett, J.1982. A review of catchment experiments to determine the effect of vegetation changes on water yield and evapo-transpiration. Journal of Hydrology 55, 3-23.

Boxall, J. B., Skipworth, P. J., and Saul, A. J. 2001. A Novel Approach to Modeling Sediment Movement in Distribution Mains Based on Particle Characteristics, Water Software Systems, 1, 263-273.

Bryan, R.B., and Campbell, I.A. 1986. Runoff and sediment discharge in a semi-arid drainage basin. Zeitschrift fur Geo-morphologic 58, 121-143.

Bultot, F., Dupriez, G.L., and Gellens, G. 1990. Simulation of land use changes and impacts on the water balance – a case study for Belgium. Journal of Hydrology 114, 327-348.

Busby, R.E., and Gifford, G.E. 1981. Effect of live stock grazing on infiltration and erosion rates measured on chained and unchained Pinon-Juniper sites in south eastern Utah. J. Range Mange. 34:400-405

Carson, B. 1985. Erosion and Sedimentation Processes in the Nepalese Himalaya. Occasional Paper No 1, International Center for integrated Mountain Development (ICIMOD), Kathmandu.

Carver, M. 1997. Diagnosis of Headwater Sediment Dynamics in Nepal's Middle Mountains: Implications for Land Management. Unpublished PhD Thesis at University of British Columbia, Vancouver, Canada.

Carver, M., and Schreier, H. 1995. Sediment and Nutrient Budgets over Four Spatial Scales in the Jhikhu Khola Catchments; Implications for Land Use Management'. In, Schreier, H.; Shah, P.B.; Brown, S. (eds.) Challenges in Mountain Resource Management in Nepal. Processes, Trends, and Dynamics in Middle Mountain Catchments. Proceedings of a Workshop Held in Kathmandu, 10-12 April 1995, pp 163-170. Kathmandu: ICIMOD

Chalise, S.R., Bhatta, B.R., Shengji, P., Shah, P.B., and Gurung, J.D. 1993. Natural Resources Management in a Mountain Environment. ICIMOD 10th Anniversary Symposium on Mountain Environment and Development – Constraints and Opportunities. Kathmandu: ICIMOD

Chalise, S.R., and Sial, S.A. 2000. Water for Mountain Households in the Hindu Kush-Himalayas. In, Mehrotra, R.; Soni, B.; Bhatia. K.K.S. (eds.) Integrated Water Resources Management for Sustainable Development. Volume I. Proceedings of the International Conference on Integrated Water Resources Management for Sustainable Development, New Delhi, December 19-21, 2000, pp 602-610. Roorkee: National Institute of Hydrology

Chang, F. J., and Chen, Y. C. 2001. A counter propagation fuzzy-neural network modeling approach to real time stream flow prediction. J. Hydrol., 245, 153–164.

Chapline , W.R. 1929. Erosion on range land: J. Am. Soc. Agron., 21, 423 -429.

Chonghuan. N., and Lixian, W.A. 1992. Preliminary study of soil erosion and land degeneration. Erosion, debris flows and environment in mountain regions, (Proceedings of the Chengdu Symposium). IAHS Publ. No. 209 (1992).

Cook, H.L. 1936. The nature of the controlling variables of water erosion processes: Soil Sci. Soc. Am, Proc, 1: 60-64.

Cosgrove, W.J., and Rijsberman, F.R. 2000. World Water Vision – Making Water every bodies' Business. London: Earth scans Publications. In Water International, 25, 11-32.

Croke, J., and Nethery, M. 2006. Modeling runoff and soil erosion in logged forests: Scope and application of some existing models. Catena 67, 35-49.

Dedkov, A. P., and Moszherin, V. T. 1992. Erosion and sediment yield in mountain areas of the world. In: Erosion, Debris Flows and Environment in Mountain Regions. 29-36, IAHS Publ. No. 209.

Deo, W.E., Jones, D.S., and Warren, S.D. 1999. The Soil erosion model guide for military land managers: Analysis of erosion models for natural and cultural resources applications: US Army engineer waterways experiment station tech report. ITL 99-XX: 129p.

Dietrich, W. E., Dunne, T., Humphrey, N. F., and Reid, L. M. 1982. Construction of sediment budgets for drainage basins: in Sediment Budgets and Routing in Forested Drainage Basins, edited by F. J. Swanson et al., pp. 5–23, U.S.D.A. Forest Service General Technical Report PNW–141.

Dongal, B. S., Pradeep M. D., Madhav P. D., Pravakar B. S., Smita K. S., Dilli R. B., and Merz, J. 2004. Assessing the status of ground water availability and its quality in Shree Ram Pati area, Jhikhu Khola watershed, Nepal. International Center for Integrated Mountain Development, Kathmandu, Nepal

Dongol, B.S., Dhakal, M.P., and Merz, J. 1998. Discharge Measurement with Current Meter Method. Internal Working Paper. Kathmandu: PARDYP

Eckholm, E. 1976. Losing Ground. Environmental Stress and World Food Prospects. New York: W.W. Norton & Company

Environment Canada. 2007. Municipal Water Use Report: Municipal Water Use 2004 Statistics (Ottawa: Author, 2007), p. 3.

Francis, C. F., and Thornes, J.B. 1990. Runoff hydrographs from three Mediterranean vegetation cover types. In: J.B. Thornes (editor), Vegetation and Erosion, Processes and Environments. J. Wiley & Sons, Chichester, pp. 363-384.

GA optimization for excel: http://www.alexschreyer.net/projects/xloptim/

Gawne, K.D., and Sirnonovic, S.P. 1994. A Computer-based System for Modeling the Stage-discharge Relationships in Steady State Conditions, Hydrol. Sci. Journal, 39(5), 487-506.

Gen, M., and Cheng, R. 2000. Genetic algorithms and engineering optimization. A Wiley inter Science Publication. ISBN 0471315311 .

Glazyrin, G.E., and Tashmetov, H.K. 1995. Sediment yield alteration of Mountain Rivers and climate change in central Asia, IAHS Publication ; 226 , 187–190

Gleick, P.H. 2000. The World's Water 2000-2001. Washington: Island Press

Goldberg, D. E. 1989. Genetic Algorithms in Search, Optimization, and Machine Learning. Addison-Wesley, Reading, MA

Gupta, A., Hock, L., Xiaojing, H., and Ping, C. 2002. Evaluation of part of the Mekong River using satellite imagery, Geomorphology, 44, 221–239.

Gurtz, J., Baltensweiler, A., Lang, H., Menzel, L., and Schulla, J. 1997. Auswirkungen von klimatischen Variationen auf Wasserhaushalt und Abfluss im Flussgebiet des Rheins. Schlussbericht (Final Report), NFP 31: Klimaanderungen und Naturkatastrophen, vdf-Hochschulverlug, Zurich

Hays, K. B., Rector, B. S., and White, L. D. 2000. Increasing bare ground indicates poor watershed health. Texas Agriculture Experiment Station. E-108.

Hofer, T. 1998. Hydro-meteorological measurements and analysis in interdisciplinary watershed projects—A strategy paper prepared for PARDYP Project, ICIMOD, Kathmandu.

Hofer,T. 1998b. Hydro-meteorological measurements and analysis in interdisciplinary catchment projects. Discussion paper MNR 98/3. International Center for integrated Mountain Development (ICIMOD) Kathmandu, 25 (1), 11-132.

Holland, J. H. 1975. Adaptation in Natural and Artificial Systems. The University of Michigan Press, Ann Arbor, MI

Ibbitt, R. P., and McKerchar, A.I. 1992. Stream flow and the use of models. In, Mosley, M.P. (ed.) Waters of New Zealand. Wellington: New Zealand Hydrological Society

ICIMOD, 1999. PARDYP- The Project Document, International Centre for Integrated Mountain Development, Katmandu, Nepal

Imeson, A.C. 1995. The physical, chemical and biological degradation of the soil. In:

Jayatilaka, C.J., and Connell, L.D. 1995. A review of catchment scale hydrologic modeling approaches. Report 95/5, Cooperative Research Centre for Catchment Hydrology, Monash University, Clayton, Vic., Australia

Jetten, V. 2002. LISEM user manual, version 2.x. Draft version January 2002. Utrecht Centre for Environment and Landscape Dynamics, Utrecht University, The Netherlands. pp 48.

Joshi, B.K., and Kothyari, B.P. 2003. Chemistry of perennial springs of Bhetagad watershed: a case study from central Himalaya, India. Environmental Geology 44, 572–578.

Karvonen, T., Koivusalo, H., and Jauhiainen, M. 1999. A hydrological model for predicting runoff from different land use areas. Journal of Hydrology 217, 253-265.

Knisel, W.G. 1980. CREAMS: A field scale model for chemicals, runoff and erosion from agricultural management system: USDA Conserv. Res. Rept.26.

Kosmas, C., and Danalatos, N. 1997. The effect of land use on runoff and soil erosion rates under Mediterranean conditions. Catena 29, 45-59.

Labat, D., Mangin, A., and Ababou, R. 2002. Rainfall-runoff relations for karstic springs: multifractal analyses. Journal of Hydrology 256, 176-195

Lambe, W. T., and Whitman, R. V. 1979. Soil Mechanics, New York, Wiley.

Lane L. J., Shirley E. D., and Singh V. P. 1988. Modeling erosion on Hill slope. Chapter 10 Modeling Geo-morphological Systems. Edited by M. G. Anderson. 1988 John Wiley & Sons Ltd.

Lane, L.J., Hernandez, M., and Nicholos, M. 1997. Processes controlling sediment yield from watersheds as function of spatial scale: J, Env. Model, Software, 12: 335-369.

Lane, L.J., Renard, K.G., Foster, G.R, and Laflen, J.M. 1992. Development and application of modren erosion prediction technology – the USDA experience: Aust. J. Soil Res, 30: 893-912.

Lane, L.J., Shirley E. D., and Singh V.P. 1988. Modeling erosion on Hill slope. Chapter 10 Modeling Geomorphologic Systems. Edited by M. G. Anderson. 1988. John Wiley & Sons Ltd.

Lee, C.R., and Skogerboe, J.G. 1985. Quantification of erosion control by vegetation on problem soils. In.

Lohani, A.K., Goel, N.K., and Bhatia, K.K.S. 2007. Deriving stage distribution sediment concentration relationship using fuzzy logic. Hydrol. Sci. J., 52(4), 793-807

Lu, X. X., and Higgitt, D. L. 1999. Sediment yield variability in the Upper Yangtze, China, and Earth Surf. Processes and Landforms, 24, 1077–1093.

Ludwig, W., and Probst, J.L. 1998. River sediment discharge to the oceans: present-day controls and global budget, American Journal of Science, 298, 265-295.

Maidment, D. 1993. Developing a spatially distributed unit hydrograph by using GIS. In: Applications of GIS in hydrology and water resources Proceedings of Vienna conf., April 1993. IAHS publ. no. 211. 181-192.

Malmer, A. 1996. Hydrological effects and nutrient losses of forest plantation establishment on tropical rainforest land in Sabah, Malaysia. Journal of Hydrology 174(1-2), 129–148.

Marsh, W.M., and Marsh, N.L. 1995. Hydro-geomorphic considerations in development planning and storm water management, central Texas Hill Country. Environ. Mgmt. 19, 693–702.

McGrath, D.A., Smith, C.K., Ghotz, H.L., and Oliveria, F. 2001. Francisco de Assis effects of land-use change on soil nutrient dynamics in Amazonia. Ecosystem 4(7), 625–645.

Merz, J. 1998. Discharge Measurement by Means of Salt Dilution. Internal Working Paper.

Merz, J. 2000. Water and erosion studies in an integrated watershed management project in the Hindu Kush-Himalaya. International Centre for Integrated Mountain Development, Nepal.

Merz, J. 2004. Water Balances, Floods and Sediment Transport in the Hindu Kush-Himalayas: Data Analyses, Modeling and Comparison of Selected Meso-scale Catchments. PhD thesis. Institute of Geography, University of Berne, Switzerland

Merz, J., Dongol, B.S., and Weingartner, R. 2000a. Impact of Land Use on Generation of High Flows in the Yarsha Khola Catchment, Nepal . In, Allen, R.; Schreier, H.; Brown, S.; Shah, P.B. (eds.) The People and Resource Dynamics Project. The First Three Years (1996-1999). Proceedings of a Workshop held in Baoshan, Kathmandu: ICIMOD.2-5 March 1999, 185-198.

Merz, J., Allen, R., Shah, P.B., and Weingartner, R. 2000. Degradation of land and water resources – an assessment programme of the current situation in selected areas in the Hindu Kush-Himalayas. Paper presented at the International Conference on Sustainable Management of Natural and Human Resources for a Better Quality of Life in South Asia, Dhulikhel October 14-17, 2000.

Meybeck, M. 1976. Total mineral dissolved transport by world major rivers. Hydrol. Sci. Bull. 21, 265-284.

Meyer, L.D., and Moldenhauer, W.C.1985. Soil erosion by water: the research experience. Agricultural History. 59(2): 192-204.

Milliman, J.D., and Syvitski, J.P.M. 1992. Geomorphic/Tectonic Control of Sediment Discharge to the Ocean: the Importance of Small Mountainous Rivers. In, Journal of Geology, 100: 525-544

MONENCO (Montreal Engineering Company).1984. Hydroelectric Inventory Ranking and Feasibility Studies for Pakistan. CIDA Project 714/00603. WAPDA, Lahore.

Mosley, M.P., and McKerchar, A.I. 1993. Stream flow. In: Handbook of Hydrology (D.R. Maidment editor), McGraw-Hill Inc., New York, USA.

Nakarmi, G. 2000b. A Manual for Erosion Test Plot Monitoring. Internal Working Paper. Kathmandu: PARDYP.

Narayan, D.V., Sastry, G., and Patnaik, U.S. 1991. Watershed Management, Pusa, Indian Council of Agriculture Research, New Delhi.

Negi, G.C.S., and Joshi, V. 2002. Drinking Water Issues and Development of Spring Sanctuaries in a Mountain Catchment in the Indian Himalaya. In, Mountain Research and Development; 22 (1), 29-31

Neitsch, S.L., Arnoild, J.G., Kinery, J.R., Williums, J.R., and King, K.W. 2002.Soil Water Assessment Tool Theoretical Documentation.

Newson, M. 1994. Hydrology and the River Environment. Clarendon Press, Oxford, UK.

Newson, M.D. 1985. Forestry and water on the uplands of Britain-the background of hydrological research and options for harmonious land use. J. Forestry; 79,113-120.

NWFPSTAT - North-West-Frontier-Province bureau of statistics. Status August .2005. http://www.nwfpbos.sdnpk.org/ Statistical data for the district of Manshera. Status August 2005. http://www.nwfpbos.sdnpk.org/Mansehra.htm

Orr, H.K. 1970. Runoff and erosion controls by seeded and native vegetation on a forest burn; Black Hills, South Dakota, UDSA Forest Service Research Paper Rm-60. Rocky mountain forest and range experiment station, Fort Collins, Colo. p., ISBN 0 340 66313 8.

Pakistan Council of Research in Water Resources (PCRWR). 2006. Water Resources Pakistan, 2006.

Pakistan; Strategic Country Environmental Assessment Report: Rising to the Challenges, May, 2006

PARC. 2006. Agriculture, food, water and land vision 2030. A report published by Pakistan Agriculture Research Council.

PARDYP .2004. Soil Survey Report of Hilkot Watershed. Soil Survey of Pakistan. Pakistan Forest Institute Peshawar.

PARDYP. 1999. Participatory Rural Appraisal and Socio-economic Survey of Hilkot Watershed. Pakistan Forest Institute, Peshawar.

Jehangir, M., Zokaib, S., and Shah, H .1999. Hydro- meteorological Year book. PARDYP Project/ PFI/ICIMOD.

Jehangir, M., Zokaib, S., and Shah, H .2000. Hydro- meteorological Year book. PARDYP Project/ PFI/ICIMOD.

Jehangir, M., Zokaib, S., and Shah, H .2001. Hydro- meteorological Year book. PARDYP Project/ PFI/ICIMOD.

Jehangir, M., Zokaib, S., and Shah, H .2002. Hydro- meteorological Year book. PARDYP Project/ PFI/ICIMOD.

Jehangir, M., Zokaib, S., and Shah, H .2003. Hydro- meteorological Year book. PARDYP Project/ PFI/ICIMOD.

Jehangir, M., Zokaib, S., and Shah, H. 2004. Hydro- meteorological Year book. PARDYP Project/ PFI/ICIMOD.

Jehangir, M., Zokaib, S., and Shah, H .2005. Hydro- meteorological Year book. PARDYP Project/ PFI/ICIMOD.

Pathak, P.C., Pandy, A.K., and Singh, J.S. 1983. Partitioning of rainfall by certain forest stands in Kumaun Himalaya. Tropical Plant Science Research 1: 123-126.

Patton, P.C., and Schumm, S.A. 1975. Gully erosion, north western Colorado: A threshold phenomenon: Geology, 3, 88–90.

Phillips, J. D. 1991. Fluvial sediment budgets in North Carolina Piedmont, Geomorphology, 4(3/4), 231–242.

Pizarro, R., Araya, S., and Jordan, C. 2005. The effects of changes in vegetative cover on river flows in the Purapel river basin of central Chile. Journal of Hydrology 327, 249-257.

Quick, M.C., and Pipes, A. 1972. Daily and seasonal forecasting with a water budget model. In Role of Snow and Ice in Hydrology (Proceedings of the UNESCO/WMO/IAHS Symposium, Banff, September

Raghuwanshi, N. S., Singh, R., and Reddy, L.S. 2006. Runoff and Sediment Yield Modeling Using Artificial Neural Networks: Upper Siwane River, India. Journal of Hydrologic Engineering, 11(1).

Rai, S.C., and Sharma, E. 1998. Comparative assessment of runoff patterns within a Himalayan watershed. Hydrological Processes Journal 12, 2235–2248.

Rai, S.C., and Sharma, E. 1995. Land-use change and resource degradation in Sikkim Himalaya: A case study from Mamlay watershed. In. pp. 265-278.

Rai, S.C., and Sharma, E. 1998b. Comparative assessment of runoff characteristics under different land use patterns within a Himalayan watershed. Hydrological Process 12: 2235-2248.

Rai, S.C., Sharma, E., and Sundriyal, R.C.1994. Conservation in the Sikkim Himalaya: traditional knowledge and land-use of the Mamlay watershed. Environmental Conservation 21: 30-34.

Rajurkar, M.P., Kothyari, U.C., and Chand, U.C. 2004. Modeling of the daily rainfall-runoff relationship with the artificial neural network (ANN), J. Hydrol., v. 285, p. 96-113

Rauzi, F. 1963. Water intake and plant composition as effected by different grazing on range land. J. Water Conserv. 18: 114-116.

Reed, L.A. 1971. Hydrological and sedimentation of Corey Creek and Elk Run Basins, North-Central Pennsylvania. US Geol. Surv. Water Supply Paper.

Reid, L. M., and T. Dunne , T. 1996. Rapid Evaluation of Sediment Budgets, Catena Verlag GMBH, Reiskirchen, Germany.

Renard, K.G., Foster, G.R., and Foster, J.P.1991. RUSLE- Revised Universal Soil Loss Equation: J. Soil Water Cons, 46:30-33.

Rendel, Palmer and Tritton (RPT), NEDECO and Bangladesh Consultants Ltd. 1989. Jamuna Bridge Project. Phase I1 Study: Feasibility Report-Volume 11, Dhaka.

Rodda, J.C. 2001. 'Water Under Pressure'. In, Hydrological Sciences Journal, 46 (6), 841-853.

Roo, A.P.J., and Wessling, C.G. 1996. LISEM: A physically-based hydrological and soil erosion model incorporated in a GIS. Hydro GIS 96: Application of Geographic Information Systems in Hydrology and Water Resources Management (Proceedings of the Vienna Conference, April 1996). IAHS Publ. No. 235, 1996.

Safe, F.T.K. 1996. A Study of the Stage-discharge Relationship of the Okavango River at Mohembo, Botswana, Hydrol. Sci. Journal, Vol. 41(1), pp.97-116.

Sahoo, B., Chatterjee, C., and Raghuwanshi, N.S. 2005. Runoff prediction in un-gauged basins at different basin map: Hydrology Jour., Vol. 28, pp. 45-58.

Schreier, H., Shah, P.B., and Brown, S. 1995. Challenges in mountain resource management in Nepal. Processes, trends, and dynamics in middle mountain catchments. Proceedings of a workshop held in ICIMOD, Nepal, 10-12 April 1995, 163-170.

Shah, H., Jehangir, M., Zokaib, S., Salam. A., and Ullah, I. 2002. Annual progress report – PARDYP Pakistan submitted to Pakistan Forest Institute / International Center for Integrated Mountain Development Center, (ICIMOD), Nepal.

Shah, Z. H., and Arshad, M. 2006. Land Degradation in Pakistan: A Serious Threat to Environments and Economic Sustainability. A research report, Institute of Soil and Environmental Sciences.

Sharma E., Sundriyal, R.C., Rai, S.C., Bhatt, Y.K., Rai, L.K., Sharma, R., and Rai, Y.K. 1992. Integrated Watershed Management. Gyanondays Prakashan, Nainital, India.

Sharma, E., Bhuchar, S., Xing, M.A., and Kothari, B.P. 2007. Land use change and its impact on hydro-ecological linkages in Himalayan watersheds. Tropical Ecology 48(2): 151-161.

Sharma, E., Rai, S.C., and Sharma, R. 2001. Soil, water and nutrient conservation in mountain farming systems: Case-study from Sikkim Himalaya. Journal of Environmental Management 61: 123-135.

Shiklamonov, I.A. 2000. Appraisal and Assessment of World Water Resources. In, Water International, 25, No.1: 11-32.

Singh, J.S., Pandey, A.N., and Pathak, P.C. 1983. A hypothesis to account for the major pathways of soil loss from Himalaya. Environmental Conservation 10: 343-345.

Sivall, T. R. 1977. Synoptic - Climatological study of the Asian summer monsoon in Afghanistan. In: Geografiska annual, series A, Physical Geography. 59, 67- 87.

Slaymaker, O. 1993. The sediment budget of the Lillooet River basin, British Columbia, Physical Geography, 14(3), 304–320.

Stoddart, R.1969. In: Chorley, R.J., (Ed.), World erosion and sedimentation in water, Water, Earth and Man, Methuen, London.

Sutherland, R. A., and Bryan, R.B. 1991. Sediment budgeting: a case study in Katiorin drainage basin, Kenya, Earth Surf. Processes and Landforms, 16(5), 383–398. 20.

Tahir, M.A., Chandio, B.A., Abdullah, M., and Rashid, A. 1998. Drinking Water Quality Monitoring in the Rural Areas of Rawalpindi. National Workshop on Quality of Drinking Water. March 7, 1998. Pakistan Council of Research in Water Resources. Islamabad, Pakistan

Terrence, J.T., George, R.F., and Kenneth, G.R. 2001. Soil Erosion–Processes, prediction, measurement and control. John Wiley and Sons, Inc.

Trimble, S. W. 2009. Fluvial processes, morphology and sediment budgets in the Coon Creek Basin, WI, USA, 1975–1993, Geomorphology, 108, 8–23.

Trimble, S.W. 1999. Decreased rates of alluvial sediment storage in the Coon Creek basin, Wisconsin, 1975–93, Science, 285, 1244–1246.

United States Department of Agriculture Soil Conservation Service. 1942. The agriculture, soils, geology, and topography of the Black lands Experimental Watershed, Waco, TX, Hydrologic Bulletin No. 5, USDA-SCS, Washington, DC, 38pp.

Valdiya, K.S., and Bartarya, S.K. 1991.Hydrogeological studies of springs in the catchment of the Gaula River, Kumaun lesser Himalaya, India. Mountain Research and Development 11(3), 239–258.

Verma, P.K. and Kothyari, B.P. 2005. Assessment of rainfall, runoff and sediment losses of the Bheta Gad watershed, India. pp. 155-166. In: R. White & S.K. Bhuchar (eds.) Resource Constraints and Management Options in Mountain Watersheds of the Himalayas. ICIMOD, Kathmandu, Nepal.

Vivirol, D., Zappa, J., Gurtz, J., and Weingartner, R. 2009. An introduction to the hydrological modeling system PREVAH and its pre- and post-processing-tools. Environmental Modeling & Software 24 (2009) 1209–1222.

Wainwright, J., and Parsons, A.J. 2002 .The effect of temporal variations in rainfall on scale dependency in runoff coefficients', Water Resources Research 38(12), 1271. DOI: 10.1029/2000WR000188.

Walling, D. E., and Collins, A.L. 2008. The catchment sediment budget as a management tool, Environmental Science and Policy, 11, 136–143, doi:10.1016/j.envsci.2007.10.004.

Walling, D. E., and Horowitz, A.J. 2005. Sediment Budgets 1, Proceedings of Foz do Iguaçu Symposium April 2005, Brazil, IAHS Publ., 291.

Walling, D.E., and Webb, B.W. 1996. Erosion and Sediment Yield: Global and Regional Perspectives. Proc. Exeter Symp., July 1996, IAHS Publ. 236.

Wasson, R. J. 2002. Sediment budgets, dynamics, and variability: new approaches and techniques, in The Structure, Function and Management Implications of Fluvial Sedimentary Systems, edited by F.J. Dyer et al., IAHS Publ., 276, 471–478.

Water and Power Development Authority (WAPDA). 2002. Water Resources and Hydropower Development vision-2025. Planning and Design Division, WAPDA, Pakistan.

Water Quality Status' Third Report 2003-2004, Pakistan Council of Research in Water Resources (PCRWR), 2005.

Wood, M.K., and Blackburn, W.H. 1981. Grazing system: Their influence on infiltration rates in the rolling plains of Texas. J .Range Manage.34: 334-335

World Meteorological Organization (WMO). 1990. Hydrological Models for Water-resources System Design and Operation. Operational Hydrology Report No. 34. Geneva: WMO WWW URL: http://soils.ecn.purdue.edu:20002/~wepp/nserl.html

Young R. A., Onstad, A., Bosch D., and Anderson, P. 1987. AGNPS, Agricultural nonpoint-source pollution model: A watershed analytical tool. USDA, Conservation Research Report Nº 35.

Zokaib. S., Jehangir, M., Shah, H., and White, R. 2004. Monsoon Failure - Depletion of water resources in Hilkot watershed Pakistan. Proceeding of International conference on sustainable water resource management in the changing environment of monsoon region, held in Colombo, Sir Lanka. Vol.1, pp 123-130.

Zokaib, S. 2000. Study of Runoff ,Erosion Losses and Local Water Harvesting Practices at Hilkot Watershed(Mansehara). MSc. Thesis. Agricultural University Peshawar, Pakistan.

Zokaib, S., Jehangir, M., Shah, H., Merz, J., and White, R. 2005. Measurement and distribution of runoff and soil losses from selected watersheds in the Hindu-Kush Himalayan region. Aquatic Ecosystem Health & Management. 8, 235 – 241.

Appendices

Appendix A

Table A1 - Monthly rainfall (mm) on all land uses in Hilkot watershed

A. Degraded Land									
	1999	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**Ave**	**STDEV**
Jan	158	172	0	64	28	85	106	87	63
Feb	58	62	23	65	317	122	255	129	113
Mar	245	36	93	120	122	11	182	116	81
Apr	70	36	106	75	152	138	86	95	40
May	41	52	94	44	105	25	57	60	29
Jun	51	160	146	127	80	94	68	104	41
Jul	151	124	224	138	179	185	181	169	34
Aug	175	121	93	233	167	159	47	142	61
Sep	129	184	82	51	99	62	47	93	49
Oct	5	0	30	16	20	101	0	25	36
Nov	127	7	65	40	31	25	48	49	39
Dec	0	58	18	71	112	68	0	47	42

B. Pasture Land									
	1999	**2000**	**2001**	**2002**	**2003**	**2004**	**2005**	**Ave**	**STDEV**
Jan	190	140	4	49	20	51	83	77	67
Feb	133	58	20	43	303	93	250	129	108
Mar	241	63	87	130	217	3	150	127	84
Apr	40	26	108	71	133	97	92	81	38
May	64	49	77	40	19	47	40	48	19
Jun	57	170	159	144	64	94	100	113	45
Jul	73	108	217	184	156	161	252	164	61
Aug	86	124	88	170	158	121	64	116	39
Sep	147	142	116	15	104	63	41	90	51
Oct	7	41	31	18	18	98	15	33	31
Nov	132	12	63	45	38	15	36	49	41
Dec	1	69	17	108	111	74	0	54	48

C. Forest Land									
	1999	2000	2001	2002	2003	2004	2005	Ave	STDEV
Jan	198	150	3	53	22	33	50	73	73
Feb	152	74	32	109	401	112	274	165	129
Mar	301	94	134	143	265	4	200	163	102
Apr	38	29	147	74	166	161	112	104	58
May	62	54	76	44	101	41	72	64	21
Jun	54	165	248	146	92	143	92	134	63
Jul	134	260	214	160	199	226	263	208	48
Aug	154	159	95	244	180	190	62	155	61
Sep	191	271	111	60	133	71	57	128	79
Oct	10	41	47	20	20	116	0	36	39
Nov	140	0	53	32	44	16	54	48	45
Dec	0	64	5	73	144	94	0	54	55

D. Agriculture land									
	1999	2000	2001	2002	2003	2004	2005	Ave	STDEV
Jan	190	140	4	49	20	51	83	77	67
Feb	133	58	20	43	303	93	250	129	108
Mar	241	63	87	130	217	3	150	127	84
Apr	40	26	108	71	133	97	92	81	38
May	64	89	77	40	19	47	40	54	24
Jun	57	170	159	144	64	94	100	113	45
Jul	73	108	217	184	156	161	252	164	61
Aug	86	124	88	170	158	121	64	116	39
Sep	147	142	116	15	104	63	41	90	51
Oct	7	41	31	18	18	98	15	33	31
Nov	132	12	63	45	38	15	36	49	41
Dec	1	69	18	108	111	74	0	54	48

Table A2 - Monthly soil loss (t/ha) from all land uses in Hilkot watershed

A.Degraded Land									
	1999	2000	2001	2002	2003	2004	2005	Ave	STDEV
Jan	0.04	0.20	0.00	0.20	0.00	0.23	0.43	0.09	0.15
Feb	0.23	0.03	0.00	0.11	0.27	0.47	1.03	0.13	0.36
Mar	1.12	0.00	1.18	0.16	0.29	0.00	0.56	0.55	0.50
Apr	0.02	0.02	0.29	0.06	0.24	0.51	0.30	0.12	0.18
May	0.11	0.18	4.28	0.18	0.16	0.03	0.20	0.98	1.56
Jun	0.15	1.80	5.54	0.73	0.05	0.41	0.41	1.65	1.96
Jul	0.63	0.44	4.12	0.56	0.69	0.97	1.15	1.29	1.30
Aug	0.30	0.99	0.53	3.13	0.48	0.15	0.39	1.09	1.04
Sep	1.74	3.66	0.11	0.23	0.01	0.43	0.36	1.15	1.34
Oct	0.00	0.00	0.00	0.00	0.03	0.82	0.15	0.01	0.30
Nov	0.33	0.00	0.23	0.45	0.02	0.03	0.23	0.21	0.17
Dec	0.00	0.00	0.01	0.07	0.03	0.02	0.00	0.02	0.03

B. Pasture Land									
	1999	2000	2001	2002	2003	2004	2005	Ave	STDEV
Jan	0.01	0.00	0	0	0.01	0.03	0.20	0.00	0.07
Feb	0.01	0.00	0	0.05	0.2	0.13	0.27	0.05	0.11
Mar	0.02	0.00	0.10	0.14	0.21	0.00	0.58	0.09	0.20
Apr	0.01	0.01	0.24	0.03	0.03	0.05	0.10	0.06	0.08
May	0.01	0.00	0.12	0.04	0.07	0.04	0.11	0.05	0.05
Jun	0.00	0.21	1.46	0.09	0.04	0.52	0.07	0.36	0.52
Jul	0.03	0.06	2.79	0.15	0.1	0.19	0.50	0.63	1.00
Aug	0.02	0.13	0.08	1.32	0.08	0.02	0.06	0.33	0.48
Sep	0.18	0.36	0.09	0.01	0.02	0.00	0.13	0.13	0.13
Oct	0.00	0.00	0.01	0.02	0	0.28	0.00	0.01	0.10
Nov	0.01	0.00	0.04	0.31	0.01	0.01	0.10	0.07	0.11
Dec	0.00	0.00	0.01	0.08	0.04	0.02	0.00	0.03	0.03

C. Forest Land									
	1999	2000	2001	2002	2003	2004	2005	Ave	STDEV
Jan	0.09	0.03	0.00	0.00	0.01	0.03	0.30	0.03	0.11
Feb	0.04	0.00	0.00	0.05	0.13	0.09	0.23	0.04	0.08
Mar	0.61	0.00	0.70	0.24	0.26	0.00	0.53	0.36	0.28
Apr	0.02	0.00	0.47	0.05	0.05	0.28	0.08	0.12	0.18
May	0.00	0.02	1.45	0.26	0.11	0.02	0.10	0.37	0.52
Jun	0.00	0.54	1.27	0.18	0.15	0.67	0.11	0.43	0.45
Jul	0.39	1.24	0.46	0.94	0.35	0.05	0.57	0.68	0.40
Aug	0.10	0.50	0.14	2.40	0.61	0.42	0.08	0.75	0.82
Sep	0.76	0.95	0.14	0.00	0.05	0.09	0.33	0.38	0.38
Oct	0.00	0.00	0.07	0.01	0.01	0.00	0.00	0.02	0.03
Nov	0.15	0.00	0.04	0.26	0.01	0.01	0.14	0.09	0.10
Dec	0.00	0.00	0.02	0.17	0.03	0.00	0.00	0.04	0.06

D. Agriculture Land									
	1999	2000	2001	2002	2003	2004	2005	Ave	STDEV
Jan	n/a	0.14	0.00	0.20	0.00	0.02	0.26	0.08	0.11
Feb	n/a	0.00	0.00	0.11	0.10	0.04	0.23	0.05	0.09
Mar	n/a	0.00	0.17	0.03	0.20	0.00	0.36	0.10	0.14
Apr	n/a	0.00	0.14	0.01	0.10	0.04	0.41	0.06	0.15
May	n/a	0.02	2.87	0.01	0.20	0.02	0.03	0.77	1.15
Jun	n/a	1.22	1.46	3.09	0.20	0.22	0.40	1.49	1.11
Jul	1.57	0.83	0.58	0.07	0.80	0.70	0.86	0.77	0.44
Aug	0.07	0.20	0.06	0.40	0.80	0.20	0.09	0.31	0.27
Sep	0.08	0.62	0.05	0.02	0.00	0.11	0.22	0.15	0.22
Oct	0.00	0.00	0.00	0.01	0.00	0.07	0.00	0.00	0.03
Nov	0.01	0.00	0.06	0.29	0.00	0.00	0.15	0.07	0.11
Dec	0.00	0.00	0.02	0.06	0.10	0.03	0.00	0.04	0.04

Table A3 - Monthly runoff (m^3/ha) from all land uses in Hilkot watershed

A. Degraded Land									
	1999	2000	2001	2002	2003	2004	2005	Ave	STDEV
Jan	9	80	0	18	5	16	54	22	30
Feb	60	9	0	14	122	38	118	41	51
Mar	145	0	112	36	131	0	108	85	62
Apr	13	2	17	10	82	45	57	25	30
May	26	24	164	19	46	7	24	56	54
Jun	23	197	215	64	19	32	38	104	85
Jul	121	69	164	70	204	92	123	125	50
Aug	83	118	37	204	173	82	28	123	66
Sep	198	234	52	13	22	43	33	104	91
Oct	0	0	0	0	18	61	13	4	22
Nov	80	0	52	46	10	2	30	38	30
Dec	0	0	2	9	31	11	0	8	11

B. Pasture Land									
	1999	2000	2001	2002	2003	2004	2005	Ave	STDEV
Jan	6	34	0	12	4	6	33	11	14
Feb	6	0	0	8	71	23	53	17	28
Mar	20	0	15	24	84	0	41	29	29
Apr	9	6	22	5	25	11	30	13	10
May	24	4	47	15	36	6	25	25	15
Jun	5	74	173	28	14	27	21	59	59
Jul	38	16	110	55	43	37	89	52	33
Aug	29	40	23	120	53	26	15	53	36
Sep	61	124	27	1	13	3	16	45	44
Oct	0	0	3	2	0	29	0	1	11
Nov	29	0	15	36	6	3	16	17	14
Dec	0	0	2	14	23	9	0	8	9

C. Forest Land									
	1999	2000	2001	2002	2003	2004	2005	Ave	STDEV
Jan	18	54	0	12	5	5	50	18	21
Feb	28	0	0	8	75	18	104	22	38
Mar	91	0	68	33	83	0	90	55	38
Apr	15	0	52	12	32	52	40	22	19
May	0	18	127	42	55	2	22	48	41
Jun	0	82	195	64	54	33	37	79	58
Jul	72	121	115	112	114	30	110	107	31
Aug	44	57	25	226	179	124	16	106	76
Sep	81	145	49	0	22	43	25	60	45
Oct	0	0	26	2	7	50	0	7	18
Nov	29	0	26	55	19	3	27	26	17
Dec	0	0	3	16	34	24	0	11	13

D. Agriculture Land									
	1999	2000	2001	2002	2003	2004	2005	Ave	STDEV
Jan	n/a	50	0	18	3	17	34	18	19
Feb	n/a	0	0	14	55	24	93	17	36
Mar	n/a	0	63	21	63	0	96	37	39
Apr	n/a	0	40	7	31	31	43	20	18
May	n/a	13	103	18	62	4	23	49	38
Jun	n/a	27	175	26	51	38	36	70	58
Jul	50	13	149	64	236	175	111	102	78
Aug	73	86	15	119	183	63	19	95	59
Sep	77	188	15	3	18	33	28	60	64
Oct	0	0	2	2	2	36	0	1	13
Nov	35	0	20	47	6	4	28	21	18
Dec	0	0	3	9	22	15	0	7	9

Appendix B

Table B1 - Event base rainfall, runoff and soil loss on degraded land

A. Degraded Land							
Event date	Rainfall (mm)	Runoff [m^3/ha]	Soil Loss[t/ha]	Event date	Rainfall (mm)	Runoff [m^3/ha]	Soil Loss[t/ha]
12/01/2000	30.2	15.42	0.36	17/06/2001	26	36.02	0.72
13/01/2000	40.5	18.12	0.32	18/06/2001	6	10.21	0.08
14/01/2000	45.5	18.43	0.43	24/06/2001	20	17.99	0.35
26/01/2000	30	12.95	0.24	01/07/2001	11	3.88	0.11
27/01/2000	25	15.16	0.10	03/07/2001	15	9.06	0.17
01/02/2000	22	8.91	0.03	13/07/2001	29	17.93	0.42
28/04/2000	11	4.00	0.02	16/07/2001	18	8.86	0.18
12/05/2000	7	5.05	0.03	17/07/2001	30	18.19	0.60
24/05/2000	16	10.00	0.05	23/07/2001	80	76.17	1.50
30/05/2000	12	7.00	0.01	29/07/2001	16	11.66	0.11
31/05/2000	14	11.63	0.10	30/07/2001	8	3.72	0.04
04/06/2000	17	18.27	0.15	24/07/2001	15	14.04	0.54
08/06/2000	7	10.26	0.30	04/08/2001	24	18.00	0.26
09/06/2000	4	7.00	0.10	15/08/2001	8.5	6.00	0.03
11/06/2000	22	28.50	0.80	22/08/2001	29	18.27	0.15
21/06/2000	32	7.66	0.33	23/08/2001	10	6.26	0.09
24/06/2000	10	4.11	0.13	03/09/2001	15	9.06	0.06
26/06/2000	20	15.44	0.26	07/09/2001	11	7.61	0.00
27/06/2000	4	7.00	0.46	08/09/2001	10	25.45	0.05
29/06/2000	42	39.80	0.80	12/09/2001	15	9.00	0.08
30/06/2000	21	18.27	0.29	13/09/2001	6	1.93	0.10
02/08/2000	13	12.80	0.14	14/09/2001	16	5.00	0.05
03/08/2000	15	10.31	0.09	20/09/2001	13	6.00	0.01
10/8/200	4.6	3,6	0.25	02/11/2001	19	7.77	0.02
11/08/2000	4.2	3.60	0.39	04/11/2001	38	43.74	1.10
12/08/2000	15.2	12.80	0.03	14/01/2002	36	9.12	0.44
15/08/2000	15.5	10.21	0.09	15/01/2002	15	9.06	0.07
08/09/2000	10	7.61	0.07	22/02/2002	20	5.02	0.04
14/9/00	11	5.18	0.08	23/02/2002	25	9.30	0.07
20/9/00	105	76.09	1.18	01/03/2002	10	1.86	0.01
21/9/00	21	35.22	0.81	10/03/2002	38	15.03	0.32
24/9/00	18	24.11	0.71	11/03/2002	11	6.34	0.02
26/9/00	15	27.23	0.31	21/03/2002	20	10.00	0.03
13/03/2001	25	7.72	0.14	23/03/2002	10	4.00	0.01
01/04/2001	30	24.11	0.54	24/03/2002	10	2.37	0.01
28/03/2001	20	15.44	0.12	25/03/2002	15	3.67	0.02
29/03/2001	19	16.95	0.15	07/04/2002	15	2.89	0.02
30/03/2001	18	17.39	0.23	23/04/2002	10	2.50	0.02
31/03/2001	8	5.18	0.06	25/04/2002	16	5.10	0.02
17/04/2001	13	5.07	0.12	15/05/2002	20	3.80	0.03
18/04/2001	22	16.50	0.11	30/05/2002	24	15.34	0.15
01/05/2001	9	7.79	0.14	01/06/2002	15	33.77	0.37
17/05/2001	30	25.00	0.95	10/06/2002	16	2.37	0.01
20/05/2001	27	29.00	0.95	19/06/2002	13	2.89	0.05
21/05/2001	25	3.88	0.07	21/06/2002	10	3.67	0.05
05/06/2001	14	19.56	0.43	24/06/2002	28	14.00	0.12
06/06/2001	20	25.00	0.56	26/06/2002	15	9.56	0.12
10/06/2001	50	55.00	1.28	29/06/2002	12	3.83	0.05
16/06/2001	4	3.90	0.08	08/07/2002	22	18.27	0.25

A. Degraded Land

Event date	Rainfall (mm)	Runoff [m^3/ha]	Soil Loss [t/ha]	Event date	Rainfall (mm)	Runoff [m^3/ha]	Soil Loss [t/ha]
10/07/2002	15	7.72	0.07	12/07/03	38	43.12	0.32
11/07/2002	12	12.80	0.10	16/7/3	42	53.96	0.25
18/07/2002	15	8.00	0.01	22/7/3	22	17.96	0.06
20/07/2002	10	4.97	0.02	27/7/3	15	10.31	0.05
21/07/2002	8	2.45	0.01	04/08/03	54	36.00	0.32
22/07/2002	10	4.19	0.02	13/8/3	10	2.19	0.01
23/07/2002	15	7.04	0.05	19/8/3	46	28.00	0.34
30/07/2002	12	10.15	0.04	30/8/3	64	40.00	0.45
05/08/2002	12	9.00	0.02	06/09/03	20	2.27	0.10
07/08/2002	22	10.26	0.08	08/09/03	25	3.54	0.09
12/08/2002	58	41.00	0.51	24/09/03	25	8.08	0.09
13/08/2002	36	19.49	0.37	25/9/3	22	8.34	0.10
14/08/2002	50	65.00	1.45	09/10/03	20	15.65	0.03
15/08/2002	15	3.67	0.05	12/10/03	18	2.37	0.00
24/08/2002	5	6.26	0.07	17/11/3	30	10.21	0.10
25/08/2002	25	9.06	0.16	13/12/3	30	10.21	0.10
01/09/2002	15	1.86	0.03	14/12/3	40	12.75	0.23
02/09/2002	9	3.67	0.04	15/12/3	28	7.61	0.10
04/09/2002	18	7.56	0.16	17/1/04	15	2.53	0.04
08/11/2002	36	46.10	0.55	18/1/04	20	9.38	0.15
20/12/2002	14	1.91	0.01	22/1/04	10	1.86	0.04
21/12/2002	30	5.15	0.21	23/1/04	20	2.37	0.00
25/12/2002	20	2.43	0.13	09/02/2004	20	10.15	0.15
31/1/03	15	4.97	0.00	10/02/2004	36	14.20	0.17
17/2/03	32	28.58	0.35	18/2/04	30	10.15	0.11
18/2/03	40	31.20	0.43	27/2/04	18	1.60	0.03
19/2/03	45	23.24	0.34	29/2/04	8	2.37	0.01
20/2/03	40	26.01	0.39	20/4/04	8	1.34	0.01
21/2/03	35	7.56	0.25	21/4/04	6	1.86	0.01
01/03/03	15	10.34	0.03	22/4/04	10	2.63	0.01
02/03/03	45	27.47	0.44	23/4/04	10	3.67	0.03
10/03/03	15	10.31	0.02	27/4/04	32	12.83	0.16
11/03/03	13	7.61	0.02	29/4/04	34	14.07	0.18
15/3/03	15	5.02	0.01	30/4/04	28	8.88	0.12
29/3/03	60	26.01	0.44	01/05/2004	5	3.15	0.01
30/3/03	31	43.71	0.25	28/5/04	6	1.60	0.01
04/04/03	28	7.72	0.12	07/06/2004	12	2.37	0.02
14/4/03	30	5.02	0.12	12/06/2004	10	1.65	0.02
16/4/03	50	17.93	0.43	15/6/04	10	1.75	0.02
19/4/3	50	33.77	0.37	18/6/04	11	2.27	0.03
20/4/03	40	17.93	0.33	21/6/04	13	2.27	0.03
01/05/03	37	18.19	0.20	24/6/04	6	2.01	0.02
02/05/03	46	25.99	0.54	26/6/04	13	15.50	0.21
29/5/3	18	1.60	0.11	27/6/04	12	3.77	0.05
09/06/03	20	4.19	0.10	02/07/2004	14	5.10	0.04
20/6/3	20	1.86	0.00	04/07/2004	15	7.56	0.08
27/6/3	32	12.90	0.12	06/07/2004	7	1.65	0.02
05/07/03	42	35.00	0.32	08/07/2004	36	19.66	0.20
08/07/03	8	1.75	0.00	12/07/2004	6	1.67	0.02

A. Degraded Land

Event date	Rainfall (mm)	Runoff [m^3/ha]	Soil Loss [t/ha]	Event date	Rainfall (mm)	Runoff [m^3/ha]	Soil Loss [t/ha]
14/7/04	16	7.72	0.08	05/03/05	10	4.97	0.03
16/7/04	22	17.93	0.14	17/3/2005	8	4.97	0.02
23/7/04	8	1.73	0.02	18/3/2005	30	18.27	0.07
28/7/04	26	15.50	0.17	19/3/2005	60	36.00	0.21
29/7/04	18	13.34	0.22	21/3/2005	10	7.46	0.07
11/08/2004	8	4.45	0.00	22/3/2005	12	6.94	0.09
16/8/04	42	33.77	0.12	28/3/2005	8	7.61	0.10
18/8/04	28	14.15	0.10	06/04/05	18	15.42	0.21
19/8/04	6	1.60	0.00	14/4/2005	11	4.97	0.02
20/8/04	8	1.86	0.00	26/4/2005	20	7.61	0.03
25/8/04	44	18.27	0.08	27/4/2005	25	11.53	0.05
28/8/04	10	7.66	0.02	23/5/2005	20	9.71	0.09
02/09/2004	28	35.76	0.30	26/5/2005	12	9.01	0.11
16/9/04	26	7.72	0.13	12/06/05	10	18.27	0.23
10/10/2004	20	9.01	0.14	14/06/05	8	8.91	0.12
10/11/2004	30	18.27	0.27	29/06/05	25	7.56	0.09
19/10/04	22	11.53	0.12	30/06/05	15	8.86	0.11
27/10/04	25	22.05	0.28	01/07/05	20	10.18	0.14
19/12/04	20	2.12	0.03	02/07/05	30	15.34	0.21
30/11/05	11	1.86	0.04	03/07/05	20	10.21	0.08
23/12/04	18	8.96	0.15	11/07/05	20	10.15	0.10
01/01/05	30	9.69	0.15	12/07/05	15	12.75	0.15
2/1//2005	36	14.10	0.22	13/7/2005	30	33.66	0.51
09/02/05	25	14.30	0.30	14/7/2005	25	18.19	0.22
10/02/05	28	15.34	0.03	15/7/2005	33	18.27	0.19
11/02/05	30	16.95	0.25	23/7/2005	12	10.21	0.08
12/02/05	32	17.67	0.21	27/7/2005	30	17.93	0.16
13/2/2005	28	17.05	0.18	08/02/2005	14	12.75	0.14
04/03/05	8	3.67	0.06	08/06/2005	16	15.34	0.25

Table B2 - Event base rainfall, runoff and soil loss on pasture land

A. Pasture Land

Event date	Rainfall (mm)	Runoff [m^3/ha]	Soil Loss[t/ha]	Event date	Rainfall (mm)	Runoff [m^3/ha]	Soil Loss[t/ha]
12/01/2000	55	16.9	0.45	01/07/2001	15	2.4	0.02
13/01/2000	30	8.3	0.05	13/03/2001	26	3.9	0.10
27/01/2000	55	32.0	0.55	29/03/2001	28	10.9	0.12
28/04/2000	11	2.0	0.00	01/04/2001	28	11.7	0.14
31/05/2000	20.5	4.4	0.05	14/04/2001	15.5	3.2	0.03
10/06/2000	5	2.9	0.00	18/04/2001	22.5	5.9	0.05
23/06/2000	4	6.0	0.00	20/04/2001	12	1.6	0.02
24/06/2000	8	1.8	0.05	13/07/2001	28	12.5	0.12
26/06/2000	7	7.0	0.01	16/07/2001	18	5.0	0.06
27/06/2000	21	11.2	0.10	17/07/2001	30	6.0	0.16
29/06/2000	19	18.5	0.04	23/07/2001	72	80.0	0.76
30/06/2000	21	7.3	0.10	24/07/2001	14	2.4	0.01
01/07/2000	19	1.9	0.01	29/07/2001	15	1.9	0.10
04/07/2000	8	2.6	0.05	30/07/2001	12	2.1	0.01
11/07/2000	11	2.1	0.05	04/08/2001	21.5	7.3	0.20
15/07/2000	14	1.9	0.00	07/08/2001	13.5	2.2	0.10
29/07/2000	24.5	10.0	0.12	15/08/2001	9	1.9	0.01
30/07/2000	8	1.3	0.00	22/08/2001	22	5.5	0.20
01/08/2000	21	3.4	0.09	23/08/2001	13.5	5.9	0.05
07/08/2000	12	2.4	0.01	03/09/2001	14	9.4	0.03
10/08/2000	23	9.1	0.05	12/09/2001	17	2.8	0.01
11/08/2000	5	1.9	0.01	13/09/2001	12	2.1	0.00
12/08/2000	16	3.4	0.12	14/09/2001	19	4.4	0.16
15/8/00	22.5	7.4	0.08	07/09/2001	16	4.2	0.01
29/8/00	15	5.0	0.10	08/09/2001	18	3.9	0.10
31/8/00	9	7.0	0.05	11/10/2001	16	2.9	0.01
07/09/2000	17	3.7	0.01	02/11/2001	19	4.7	0.02
08/09/2000	10	3.2	0.10	03/11/2001	22	6.8	0.12
14/9/00	3	2.4	0.00	04/11/2001	18	3.4	0.15
20/9/00	61	79.5	0.25	14/01/2002	20	5.2	0.00
21/9/00	21	5.6	0.14	15/01/2002	25	7.0	0.04
24/9/00	13	4.3	0.01	22/02/2002	20	5.5	0.10
26/9/00	24	22.8	0.24	02/03/2002	13	1.1	0.00
17/05/2001	21.5	20.0	0.12	10/03/2002	39	8.9	0.14
20/05/2001	39	12.0	0.25	11/03/2002	15	3.4	0.00
21/05/2001	21.5	14.6	0.16	21/03/2002	22	4.2	0.06
06/06/2001	17	11.5	0.27	23/03/2002	9	1.1	0.00
10/06/2001	45	80.0	0.44	24/03/2002	10	1.9	0.01
15/06/2001	20	15.3	0.10	25/03/2002	16	3.2	0.04
16/06/2001	22	40.0	0.27	07/04/2002	13	1.3	0.10
26/06/2001	20	26.3	0.05	25/04/2002	21	3.4	0.02

A. Pasture Land

Event date	Rainfall (mm)	Runoff [m^3/ha]	Soil Loss[t/ha]	Event date	Rainfall (mm)	Runoff [m^3/ha]	Soil Loss[t/ha]
30/05/2002	15	10.2	0.02	10/03/2003	15	9.7	0.03
02/06/2002	17	3.7	0.01	15/3/03	18	5.7	0.01
10/06/2002	25	2.9	0.01	29/3/03	60	46.0	0.27
17/06/2002	30	3.2	0.12	30/3/03	31	33.6	0.05
21/06/2002	10	5.1	0.02	03/04/2003	11	1.9	0.00
24/06/2002	25	6.3	0.02	04/04/2003	15	2.4	0.05
26/06/2002	15	2.6	0.01	14/4/03	20	2.9	0.09
27/06/2002	8	2.4	0.01	16/4/03	24	8.1	0.01
29/06/2002	13	2.1	0.00	19/4/03	20	4.2	0.00
08/07/2002	33	22.9	0.06	20/4/03	30	5.7	0.00
10/07/2002	25	8.6	0.02	01/05/2003	21	15.3	0.03
11/07/2002	15	9.6	0.04	02/05/2003	46	17.9	0.39
18/07/2002	12	2.4	0.00	29/5/3	18	2.4	0.00
20/07/2002	13	3.9	0.00	09/06/2003	17	3.9	0.01
22/07/2002	20	2.8	0.01	20/6/03	8	1.5	0.00
28/07/2002	15	2.4	0.01	28/6/03	25	5.7	0.01
30/07/2002	22	2.4	0.01	29/6/03	10	2.6	0.01
05/08/2002	12	4.4	0.05	05/07/2003	35	17.9	0.20
06/08/2002	15	2.2	0.01	12/07/2003	30	4.2	0.01
07/08/2002	28	4.9	0.05	16/7/03	40	26.0	0.31
12/08/2002	58	36.0	0.45	22/7/03	28	7.8	0.03
13/08/2002	36	3.7	0.02	27/7/03	15	2.4	0.03
14/08/2002	50	77.4	0.33	04/08/2003	54	36.0	0.22
15/08/2002	15	4.4	0.01	19/8/03	23	3.7	0.01
25/08/2002	16	4.2	0.02	20/8/3	30	16.1	0.02
30/08/2002	14	1.6	0.01	30/8/3	60	25.5	0.33
31/08/2002	5	1.1	0.01	06/09/2003	6	1.6	0.00
19/09/2002	15	1.4	0.01	08/09/2003	15	2.9	0.00
21/10/2002	12	1.6	0.02	24/9/3	17	5.0	0.01
08/11/2002	43	36.2	0.31	25/9/3	18	3.7	0.01
19/12/2002	11	2.4	0.01	17/11/3	25	3.7	0.00
20/12/2002	33	5.0	0.04	18/11/3	15	1.9	0.00
21/12/2002	35	5.0	0.02	13/12/3	23	6.3	0.01
26/12/2002	19	1.9	0.01	14/12/3	21	10.2	0.02
31/1/03	19	4.2	0.01	15/12/3	25	6.8	0.01
17/2/03	35	15.3	0.25	18/1/04	16	1.9	0.01
18/2/03	40	28.7	0.32	22/1/04	10	1.9	0.01
19/2/03	48	9.1	0.20	23/1/04	10	1.9	0.01
20/2/03	45	7.6	0.26	09/02/2004	31	10.4	0.05
21/2/03	35	5.2	0.01	10/02/2004	10	1.6	0.01
28/2/03	20	5.0	0.01	18/2/04	30	3.9	0.02
01/03/2003	17	10.9	0.03	22/2/04	16	5.7	0.04
02/03/2003	52	17.9	0.08	27/2/04	6	1.6	0.01

A. Pasture Land

Event date	Rainfall (mm)	Runoff [m^3/ha]	Soil Loss[t/ha]	Event date	Rainfall (mm)	Runoff [m^3/ha]	Soil Loss[t/ha]
20/4/04	10	2.1	0.01	23/12/04	19	1.9	0.02
23/4/04	30	2.6	0.01	31/12/04	15	5.2	0.01
29/4/04	15	3.2	0.02	01/01/05	30	1.6	0.00
30/4/03	12	3.2	0.02	02/01/05	36	2.1	0.01
01/05/2004	15	3.2	0.02	09/02/05	25	1.6	0.01
28/5/04	11	3.2	0.02	11/02/05	30	4.2	0.03
07/06/2004	13	2.3	0.02	13/2/2005	28	12.2	0.05
12/06/2004	7	1.6	0.01	04/03/05	8	1.8	0.01
18/6/04	7	2.3	0.01	08/03/05	3	1.6	0.01
21/6/04	10	2.2	0.06	18/3/2005	30	3.7	0.04
26/6/04	23	10.3	0.32	19/3/2005	60	19.0	0.24
27/6/04	20	8.1	0.10	20/3/2005	7	2.6	0.02
09/07/2004	41	5.7	0.12	21/04/05	10	1.9	0.00
02/07/2004	11	3.3	0.02	22/04/05	12	12.0	0.06
14/7/04	13	2.6	0.01	25/5/2005	28	10.2	0.06
16/7/04	32	19.0	0.07	26/5/2005	25	2.1	0.01
28/7/04	11	2.4	0.03	29/6/2005	25	15.9	0.05
30/7/04	10	1.9	0.03	30/6/2005	15	5.0	0.02
04/07/2004	16	2.0	0.05	01/07/05	20	7.6	0.07
11/08/2004	4	1.1	0.00	02/07/05	30	8.9	0.04
16/8/04	34	3.2	0.09	03/07/05	20	6.3	0.03
18/8/04	12	1.9	0.02	11/07/05	20	5.0	0.03
25/8/04	44	18.4	0.11	12/07/05	15	5.7	0.04
02/09/2004	29	1.3	0.10	13/7/2005	30	14.3	0.09
16/9/04	21	2.1	0.15	14/7/2005	25	12.7	0.08
10/10/2004	19	3.9	0.04	15/7/2005	35	18.5	0.09
11/10/2004	46	19.5	0.12	23/7/2005	12	5.7	0.02
19/10/04	16	3.2	0.02	27/7/2005	30	10.2	0.05
27/10/04	12	2.1	0.01	02/08/05	14	5.0	0.02
27/11/04	15	2.9	0.01	06/08/05	16	10.2	0.04
20/12/04	23	2.4	0.15				

Table B3 - Event base rainfall, runoff and soil loss on forest land

C. Forest Land

Event date	Rainfall (mm)	Runoff [m^3/ha]	Soil Loss[t/ha]	Event date	Rainfall (mm)	Runoff [m^3/ha]	Soil Loss[t/ha]
12/01/2000	35.6	18.97	0.28	22/9/00	22	15.47	0.03
13/01/2000	45.8	19.00	0.23	24/9/00	19	12.80	0.10
14/01/2000	46.7	19.00	0.25	13/03/2001	25.5	8.99	0.04
26/01/2000	34.4	20.00	0.30	28/03/2001	23.5	16.51	0.06
27/01/2000	28.7	15.00	0.26	29/03/2001	25	18.66	0.28
12/05/2000	8	3.23	0.00	30/03/2001	20	17.60	0.24
24/05/2000	16	5.05	0.01	31/03/2001	10	6.39	0.08
30/05/2000	14	9.97	0.00	01/04/2001	32	37.42	0.45
31/05/2000	9	3.20	0.00	17/04/2001	13.5	7.59	0.02
03/06/2000	10	3.41	0.00	18/04/2001	23	6.52	0.01
08/06/2000	6	3.97	0.01	01/05/2001	10.5	8.60	0.05
11/06/2000	22	9.38	0.10	17/05/2001	35.5	74.33	0.39
21/06/2000	19	3.93	0.01	20/05/2001	23	36.90	0.38
23/06/2000	5	3.41	0.02	21/05/2001	20	7.56	0.24
26/06/2000	22	7.30	0.23	05/06/2001	17	24.85	0.18
27/06/2000	26	17.93	0.28	06/06/2001	20	25.24	0.19
29/06/2000	16	8.86	0.01	10/06/2001	74	74.33	0.42
30/06/2000	21	4.97	0.04	16/06/2001	10	5.18	0.03
01/07/2000	43	22.00	0.42	17/06/2001	21	33.48	0.21
03/07/2000	23	10.15	0.06	18/06/2001	10	12.80	0.07
04/07/2000	40	27.91	0.50	24/06/2001	20	19.31	0.15
07/07/2000	17	11.50	0.07	01/07/2001	11	7.69	0.04
08/07/2000	12	15.42	0.00	13/07/2001	30	10.15	0.03
11/07/2000	15	5.10	0.04	16/07/2001	18	7.56	0.03
15/7/00	21	13.00	0.08	17/07/2001	30	15.44	0.06
29/7/00	17.5	8.73	0.19	23/07/2001	85	74.33	0.60
30/7/00	23.3	18.35	0.32	04/08/2001	26	7.72	0.09
31/7/00	26.2	11.53	0.29	15/08/2001	7	1.80	0.01
01/08/2000	23	12.83	0.15	22/08/2001	30	10.28	0.03
02/08/2000	10.5	7.69	0.04	23/08/2001	10	4.97	0.01
03/08/2000	12.5	9.06	0.05	03/09/2001	15	6.32	0.03
10/08/2000	35.5	15.00	0.05	07/09/2001	26	18.32	0.05
11/08/2000	20	4.97	0.07	08/09/2001	13	5.10	0.10
12/08/2000	12	9.09	0.11	12/09/2001	18	3.13	0.10
15/8/00	20	5.05	0.04	13/09/2001	10	3.28	0.10
01/09/2000	13	10.28	0.05	14/09/2001	16	6.47	0.01
07/09/2000	13.5	8.99	0.03	20/09/2001	13	6.37	0.05
08/09/2000	10	8.21	0.38	04/10/2001	9	7.69	0.03
14/9/00	12.5	2.50	0.01	05/10/2001	8	7.69	0.01
20/9/00	100	74.35	0.95	10/10/2001	17	10.28	0.03
21/9/00	30	12.80	0.02	02/11/2001	8.5	2.50	0.00

C. Forest Land

Event date	Rainfall (mm)	Runoff [m³/ha]	Soil Loss[t/ha]	Event date	Rainfall (mm)	Runoff [m³/ha]	Soil Loss[t/ha]
03/11/2001	19	15.47	0.03	20/12/2002	16	5.49	0.06
04/11/2001	11	7.69	0.01	21/12/2002	21	7.82	0.09
14/01/2002	22	5.23	0.00	25/12/2002	20	2.89	0.03
15/01/2002	26	7.04	0.00	31/1/03	21	4.97	0.01
19/02/2002	18	2.12	0.01	16/2/3	10	15.86	0.03
20/02/2002	25	5.49	0.04	17/2/03	40	30.68	0.04
02/03/2002	16	2.37	0.03	18/2/03	45	10.15	0.03
10/03/2002	40	12.95	0.11	19/2/03	48	8.08	0.03
11/03/2002	15	4.97	0.04	20/2/03	46	5.75	0.01
21/03/2002	24	5.56	0.04	27/2/03	22	4.71	0.01
24/03/2002	10	3.10	0.02	01/03/2003	18	11.45	0.04
25/03/2002	19	4.06	0.02	02/03/2003	57	17.41	0.06
07/04/2002	15	3.10	0.01	10/03/2003	40	8.86	0.01
25/04/2002	23	6.47	0.02	15/3/03	20	2.37	0.00
23/04/2002	10	2.89	0.01	28/3/03	20	8.34	0.03
15/05/2002	20	4.97	0.03	30/3/03	60	34.18	0.11
30/05/2002	24	36.90	0.24	04/04/2003	25	3.67	0.01
01/06/2002	18	15.55	0.02	14/4/03	20	1.60	0.00
10/06/2002	20	7.56	0.02	16/4/03	24	8.86	0.02
18/06/2002	10	3.75	0.01	19/4/03	25	11.71	0.01
19/06/2002	15	5.75	0.03	20/4/03	32	6.52	0.01
21/06/2002	10	6.39	0.02	01/05/2003	45	26.79	0.05
24/06/2002	30.5	15.47	0.04	02/05/2003	34	26.27	0.29
26/06/2002	18	4.66	0.01	29/5/03	18	1.60	0.00
29/06/2002	15	5.18	0.04	09/06/2003	25	4.97	0.12
08/07/2002	26	50.82	0.33	20/6/03	23	7.56	0.15
21/07/2002	9	3.80	0.03	28/6/03	32	23.16	0.23
23/07/2002	18	8.99	0.07	29/6/03	10	17.93	0.06
22/07/2002	10	5.18	0.03	05/07/2003	35	37.68	0.11
10/07/2002	18	10.15	0.10	12/07/2003	30	32.24	0.11
11/07/2002	15	14.10	0.13	16/7/03	40	29.64	0.11
18/07/2002	17	2.89	0.03	22/7/3	28	10.15	0.01
20/07/2002	12	6.39	0.07	27/7/3	15	3.67	0.01
30/07/2002	16.5	10.15	0.15	04/08/2003	52	19.75	0.07
05/08/2002	15	4.45	0.04	13/8/3	16	2.37	0.38
07/08/2002	18	11.45	0.11	19/8/03	55	78.09	0.52
12/08/2002	62	74.33	0.59	30/8/03	70	78.48	0.28
13/08/2002	32	31.72	0.38	06/09/2003	9	2.24	0.00
14/08/2002	50	74.59	0.56	08/09/2003	18	3.54	0.12
15/08/2002	15	8.99	0.02	24/9/03	36	8.08	0.12
24/08/2002	18	7.77	0.06	25/9/03	29	8.34	0.02

C. Forest Land

Event date	Rainfall (mm)	Runoff [m³/ha]	Soil Loss[t/ha]	Event date	Rainfall (mm)	Runoff [m³/ha]	Soil Loss[t/ha]
25/08/2002	28	12.90	0.06	16/9/04	29	4.87	0.20
21/10/2002	11	1.60	0.01	10/10/2004	23	9.19	0.12
08/11/2002	30	55.36	0.26	11/10/2004	33	22.58	0.13
18/11/03	12	4.97	0.00	19/10/04	24	10.67	0.25
13/12/03	33	11.53	0.01	27/10/04	30	8.04	0.25
14/12/03	44	13.53	0.25	23/12/04	23	9.69	0.12
15/12/03	32	8.86	0.13	28/12/04	12	2.89	0.06
17/1/04	13	1.60	0.01	29/12/04	15	5.49	0.06
18/1/04	14	1.70	0.01	31/12/04	19	3.67	0.20
22/1/04	6	2.12	0.01	09/10/2003	22	3.67	0.01
09/02/2004	35	3.02	0.01	12/10/2003	20	2.89	0.01
10/02/2004	37	8.18	0.05	17/11/3	33	14.30	0.00
18/2/04	20	4.76	0.02	09/02/05	30	14.56	0.19
27/2/04	20	2.37	0.01	10/02/05	30	16.12	0.13
20/4/04	10	1.67	0.01	11/02/05	32	17.49	0.26
21/4/04	8	2.43	0.01	12/02/05	34	15.86	0.28
22/4/04	12	3.15	0.01	13/02/05	30	17.34	0.25
23/4/04	12	4.45	0.03	04/03/05	4	4.19	0.01
27/4/04	35	14.10	0.08	05/03/05	13	6.00	0.03
29/4/04	37	16.14	0.08	17/3/2005	11	5.49	0.03
30/4/04	32	9.95	0.06	18/3/2005	34	28.67	0.18
28/5/04	7	2.43	0.02	19/3/2005	62	73.83	0.36
07/06/2004	14	3.02	0.10	21/3/2005	12	5.36	0.02
12/06/2004	12	3.46	0.03	22/3/2005	14	7.41	0.03
15/6/04	13	2.71	0.02	28/3/2005	10	7.82	0.03
18/6/04	12	2.56	0.03	06/04/05	20	16.22	0.03
21/6/04	14	2.56	0.03	14/4/2005	15	6.34	0.00
24/6/04	11	2.53	0.04	26/4/2005	10	8.36	0.01
26/6/04	30	16.04	0.43	27/4/2005	27	16.64	0.12
28/7/04	29	16.25	0.03	29/4/2005	34	28.68	0.12
29/7/04	19	14.12	0.02	01/07/05	24	10.72	0.09
11/08/2004	11	5.36	0.01	02/07/05	23	16.20	0.10
16/8/04	70	48.51	0.56	03/07/05	19	11.01	0.05
18/8/04	30	15.24	0.19	11/07/05	24	10.44	0.12
19/8/04	8	11.99	0.06	12/07/05	17	13.53	0.04
20/8/04	10	1.47	0.06	13/7/2005	34	34.57	0.32
25/8/04	47	33.06	0.42	14/7/2005	28	17.93	0.02
02/09/2004	30	37.68	0.09	15/7/2005	33	30.21	0.35

Table B4 - Event base rainfall, runoff and soil loss on agriculture land

D. Agriculture Land

Event date	Rainfall (mm)	Runoff [m^3/ha]	Soil Loss[t/ha]	Event date	Rainfall (mm)	Runoff [m^3/ha]	Soil Loss[t/ha]
12/01/2000	55.0	35.00	0.25	16/07/2001	18	6.89	0.01
13/01/2000	30.0	12.83	0.12	17/07/2001	30	16.56	0.21
14/01/2000	3.0	9.05	0.10	23/07/2001	72	77.15	0.53
26/01/2000	30	15.00	0.23	24/07/2001	14	11.63	0.02
27/01/2000	25	7.59	0.13	29/07/2001	15	8.78	0.03
12/05/2000	7	3.33	0.02	30/07/2001	12	2.35	0.00
24/05/2000	15	2.71	0.00	04/08/2001	21.5	11.00	0.12
30/05/2000	12	1.62	0.00	07/08/2001	13.5	2.37	0.10
31/05/2000	21	8.18	0.12	15/08/2001	9	1.86	0.00
04/06/2000	13.5	11.53	0.01	22/08/2001	22	12.00	0.12
09/06/2000	5	8.86	0.07	23/08/2001	13.5	8.00	0.05
11/06/2000	22	29.90	0.22	03/09/2001	14	3.28	0.02
21/06/2000	32	46.74	0.40	04/09/2001	7	1.08	0.05
27/06/2000	21	29.20	0.10	07/09/2001	16	11.00	0.06
29/06/2000	19	36.49	0.13	12/09/2001	17	10.00	0.05
30/06/2000	21	15.63	0.02	13/09/2001	12	8.00	0.00
01/07/2000	19	30.24	0.18	14/09/2001	19	10.33	0.12
01/08/2000	21	17.44	0.00	20/09/2001	13	2.24	0.05
02/08/2000	13	8.11	0.01	04/10/2001	11	1.86	0.00
03/08/2000	15	5.85	0.01	02/11/2001	19	2.24	0.06
10/08/2000	23	14.41	0.12	03/11/2001	22	12.75	0.22
11/08/2000	5	7.34	0.04	04/11/2001	18	4.97	0.09
12/08/2000	16	8.39	0.30	14/01/2002	20	9.12	0.12
15/8/00	22.5	7.43	0.12	15/01/2002	25	9.06	0.15
07/09/2000	17	9.00	0.09	22/02/2002	12	5.02	0.04
08/09/2000	10	6.63	0.03	23/02/2002	21	9.30	0.12
14/9/00	3	3.77	0.00	02/03/2002	13	2.89	0.00
20/9/00	61	47.42	0.56	10/03/2002	39	15.34	0.45
21/9/00	21	13.97	0.14	11/03/2002	15	2.37	0.00
24/9/00	12.5	31.93	0.05	21/03/2002	22	12.36	0.12
26/9/00	24	54.19	0.22	24/03/2002	10	2.12	0.00
13/03/2001	26	20.01	0.10	25/03/2002	16	2.89	0.00
28/03/2001	20	12.72	0.12	06/04/2002	8	2.37	0.00
29/03/2001	28	13.11	0.12	07/04/2002	13	2.12	0.00
30/03/2001	12	14.02	0.11	23/04/2002	9	1.21	0.00
31/03/2001	8	2.82	0.01	25/04/2002	21	1.34	0.12
01/04/2001	28	31.98	0.13	15/05/2002	23	3.67	0.16
17/04/2001	12	3.28	0.01	30/05/2002	15	14.04	0.12
18/04/2001	22.5	4.63	0.21	02/06/2002	17	3.41	0.12
01/07/2001	15	2.69	0.12	10/06/2002	25	1.86	0.17
03/07/2001	13	6.89	0.02	17/06/2002	30	3.15	0.14
13/07/2001	28	15.65	0.18	21/06/2002	10	2.76	0.06

D. Agriculture Land

Event date	Rainfall (mm)	Runoff [m^3/ha]	Soil Loss[t/ha]	Event date	Rainfall (mm)	Runoff [m^3/ha]	Soil Loss[t/ha]
24/06/2002	25	6.26	0.23	20/6/03	8	1.86	0.00
26/06/2002	15	2.63	0.10	28/6/03	25	25.75	0.25
29/06/2002	13	2.50	0.00	29/6/03	10	19.49	0.07
08/07/2002	33	23.94	0.34	05/07/2003	35	52.00	0.27
10/07/2002	25	1.86	0.12	12/07/2003	30	36.00	0.17
11/07/2002	15	24.46	0.01	16/7/03	40	80.55	0.31
20/07/2002	13	1.99	0.00	22/7/03	28	10.15	0.03
22/07/2002	20	3.15	0.21	27/7/03	15	2.63	0.00
23/07/2002	18	2.89	0.22	04/08/2003	54	17.93	0.33
28/07/2002	15	6.22	0.01	19/8/03	23	4.19	0.01
30/07/2002	22	3.67	0.21	20/8/03	30	80.55	0.19
06/08/2002	15	2.50	0.12	30/8/03	60	80.55	0.34
07/08/2002	28	5.49	0.22	06/09/2003	6	2.89	0.00
12/08/2002	58	19.49	0.45	08/09/2003	15	4.19	0.00
13/08/2002	36	6.52	0.21	24/9/03	17	6.26	0.01
14/08/2002	50	79.77	0.35	25/9/03	18	4.45	0.01
25/08/2002	16	4.97	0.08	09/10/2003	20	1.60	0.00
01/09/2002	5	3.41	0.02	17/11/03	25	5.49	0.01
13/10/2002	6	1.73	0.01	13/12/03	23	7.56	0.02
08/11/2002	43	46.54	0.35	14/12/03	21	10.15	0.03
20/12/2002	33	18.00	0.29	15/12/03	25	4.97	0.01
21/12/2002	35	13.00	0.23	17/1/04	15	2.37	0.00
25/12/2002	8	1.86	0.01	18/1/04	16	3.41	0.00
31/1/03	19	3.41	0.13	22/1/04	10	7.56	0.01
17/2/03	35	15.34	0.23	23/1/04	10	3.15	0.00
18/2/03	40	27.05	0.33	09/02/2004	31	15.34	0.04
19/2/03	48	22.33	0.21	10/02/2004	10	2.37	0.00
20/2/03	45	13.25	0.23	18/2/04	30	4.19	0.13
21/02/2003	35	12.36	0.25	27/2/04	16	2.37	0.00
02/03/2003	52	26.22	0.14	09/04/2004	6	1.73	0.00
10/03/2003	15	8.26	0.01	20/4/04	10	1.47	0.00
15/3/03	18	9.37	0.00	21/4/04	4	1.08	0.00
29/3/03	60	35.33	0.36	23/4/04	30	2.12	0.12
30/3/03	31	24.98	0.14	27/4/04	20	15.34	0.03
03/04/2003	11	1.73	0.00	29/4/04	15	5.23	0.01
04/04/2003	15	2.12	0.01	30/4/04	12	3.67	0.00
14/4/03	20	2.76	0.14	01/05/2004	15	2.12	0.01
16/4/03	24	7.56	0.03	28/5/04	11	1.60	0.01
19/4/03	20	10.15	0.05	07/06/2004	13	1.73	0.01
20/4/03	30	7.04	0.02	12/06/2004	7	3.93	0.04
01/05/2003	21	19.49	0.07	15/6/04	10	3.02	0.01
02/05/2003	46	38.98	0.21	18/6/04	7	1.60	0.00
29/05/2003	18	3.15	0.01	21/6/04	10	2.63	0.00
09/06/2003	17	4.19	0.01	26/6/04	23	14.04	0.12

D. Agriculture Land

Event date	Rainfall (mm)	Runoff [m^3/ha]	Soil Loss [t/ha]	Event date	Rainfall (mm)	Runoff [m^3/ha]	Soil Loss [t/ha]
27/6/04	20	10.67	0.03	12/02/2005	25	3.67	0.01
02/07/2004	11	7.56	0.01	13/2/2005	28	7.56	0.02
04/07/2004	16	15.34	0.05	04/03/2005	8	1.60	0.00
09/07/2004	41	77.96	0.36	05/03/2005	3	2.12	0.00
14/7/04	13	17.93	0.07	17/3/2005	6	3.41	0.01
16/7/04	32	43.17	0.19	18/3/2005	30	23.42	0.15
28/7/04	11	5.49	0.01	19/3/2005	60	75.11	0.32
29/7/04	7	3.15	0.00	20/3/2005	7	17.93	0.02
30/7/04	10	4.19	0.00	24/3/2005	4	6.26	0.01
11/08/2004	4	1.86	0.00	28/3/2005	3	16.64	0.01
16/8/04	34	31.72	0.11	26/4/2005	10	19.49	0.09
18/8/04	12	4.97	0.01	27/4/2005	27	14.04	0.05
19/8/04	2	1.86	0.00	06/05/2005	3	2.37	0.00
25/8/04	44	19.23	0.22	08/05/2005	3	1.60	0.00
28/8/04	9	3.41	0.01	23/5/2005	16	3.93	0.01
02/09/2004	29	25.75	0.11	26/5/2005	10	1.86	0.00
16/9/04	21	4.19	0.12	12/06/2005	8	4.45	0.01
21/9/04	6	1.34	0.00	14/6/2005	11	1.86	0.00
22/9/04	7	1.60	0.00	19/06/2005	5	1.60	0.00
10/10/2004	19	6.26	0.02	28/06/2005	20	2.37	0.10
11/10/2004	46	17.93	0.24	29/6/2005	27	4.97	0.01
19/10/04	16	4.97	0.00	30/6/2005	17	58.47	0.23
21/10/04	5	1.73	0.00	01/07/2005	18	15.34	0.06
27/10/04	12	5.49	0.01	02/07/2005	32	19.49	0.09
27/11/2004	15	3.67	0.00	03/07/2005	22	7.56	0.04
20/12/04	23	5.23	0.02	11/07/2005	25	12.75	0.12
23/12/04	19	3.67	0.01	12/07/2005	17	19.49	0.20
26/12/04	8	1.86	0.00	13/7/2005	30	19.49	0.19
28/12/04	7	1.86	0.00	14/7/2005	23	27.05	0.22
31/12/04	15	2.37	0.00	15/7/2005	33	7.56	0.03
01/01/2005	30	11.45	0.03	23/7/2005	15	8.86	0.03
02/01/2005	36	2.12	0.20	27/7/2005	27	10.15	0.04
08/02/2005	25	4.97	0.01	02/08/2005	30	3.67	0.00
09/02/2005	30	11.45	0.03	05/08/2005	4	2.89	0.01
10/02/2005	20	16.64	0.05	06/08/2005	45	4.97	0.21
11/02/2005	20	17.93	0.06	08/08/2005	7	38.98	0.16

Appendix C

Table C1 - Suspended sediment concentration at different levels at hydrostation

Main Hydrostation (Watershed Outlet)							
Water Level (cm)	**Sed conc.(g/l)**	**Water Level (cm)**	**Sed conc.(g/l)**	**Water Level (cm)**	**Sed conc.(g/l)**	**Water Level (cm)**	**Sed conc.(g/l)**
26.7	3.6	25	0.5	26.73	0.5	36	0.2
16.34	0.6	25	0.4	14.85	0.5	35	0.6
21.7	0.3	30	7	20	0.5	30	1.7
30.7	0.7	25	3.7	17.8	0.3	28	0.9
37.6	3.7	20	1.8	23	2.1	27	0.2
25.45	0.2	51	14.7	20	1.5	29	0.2
21.78	0.2	41	10.7	19	4	30	0.5
38.68	4.4	41	7.6	22	0.4	27	0.3
20	0.1	20	2.3	21	2.2	35	0.4
16.34	0	15	3.5	20	2.3	33	0.7
14.48	0.2	100	10.2	18	1.7	32	1.2
30	0	121	7.8	25	1.1	41	1.6
13.86	0.2	91.5	9.8	20	0.7	43	2.2
22.77	0.2	36	4.1	18	0.6	40	1.6
36.63	0.3	32	2.5	27	0.6	45	2.7
31.68	0.5	35	6.9	25	0.2	65	4.6
33.66	0.9	71	11.3	25	4.1	67	4.2
34.66	6	52	6.8	50	5.3	36	2.1
36.64	10.8	41	3.7	45	2.9	35	1.9
37.62	7.8	36	4.2	36	1.6	35	1.7
19.8	1.2	30	2.2	30	3.1	25	1.7
20.7	1	26	1.9	25	1	28	2
23.75	0.6	44	3.1	20	0.9	30	2.1
30.6	2.5	38	1.7	48	3.1	46	2.1
35.64	3.6	35	0.7	49	2.7	45	2.2
37.62	5.5	65	2.2	50	3.6	42	1.1
39	0.6	61	1.9	49	5.1	42	1.7
41.58	0.5	50	1.1	50	4.7	43	1.7
37.13	6.8	45	2.7	50	2.1	45	2.2
31.68	2	41	2.5	42	1.2	32	3.6
17.82	11.4	36	3	40	0.1	35	4.2
25.74	5.7	43	0.4	42	2.2	32	2.1
29.7	8.1	35	0.7	45	1.7	24	3.6
36.63	5.7	27	0.1	50	2.8	35	4.2
32.67	3.1	36	1.2	50	1.1	36	4.1

Table C2 - Measured discharge data at main hydro station at different water levels

Main Hydrostation			
H(cm)	**Q (l/s)**	**H(cm)**	**Q (l/s)**
6.5	20.5	15.5	203.62
8.5	48.3	9	49.3
23	883.47	11	77.61
24	957.39	17	275.41
27	1212.83	41	2718
25	1159.63	28	1493
20	554.57	26	1410
21	565.15	25	1356
22	606.52	12	115
25	1321.02	12	97
31	1670.86	6.5	17
29.5	1588.78	70	14808
28	1242.96	66	12270
34	2152.98	15.5	175.86

H= water level Q= measured discharge