Assessing Soil Erosion and Conservation in the Loess Area of Faizabad Western Tajikistan

Integrating WOCAT Methods with a GIS-based RUSLE Model

Diploma Thesis

Submitted to the Faculty of Natural Sciences
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by
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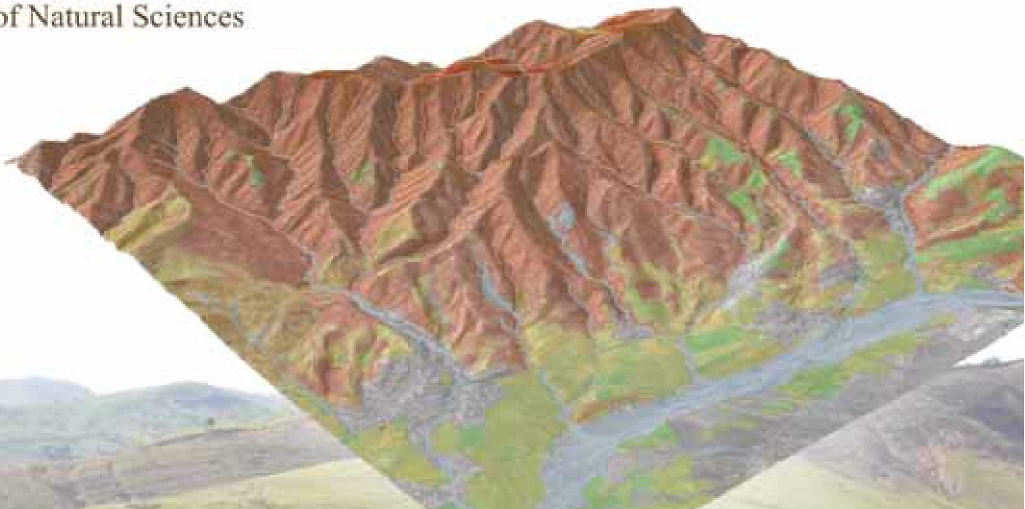

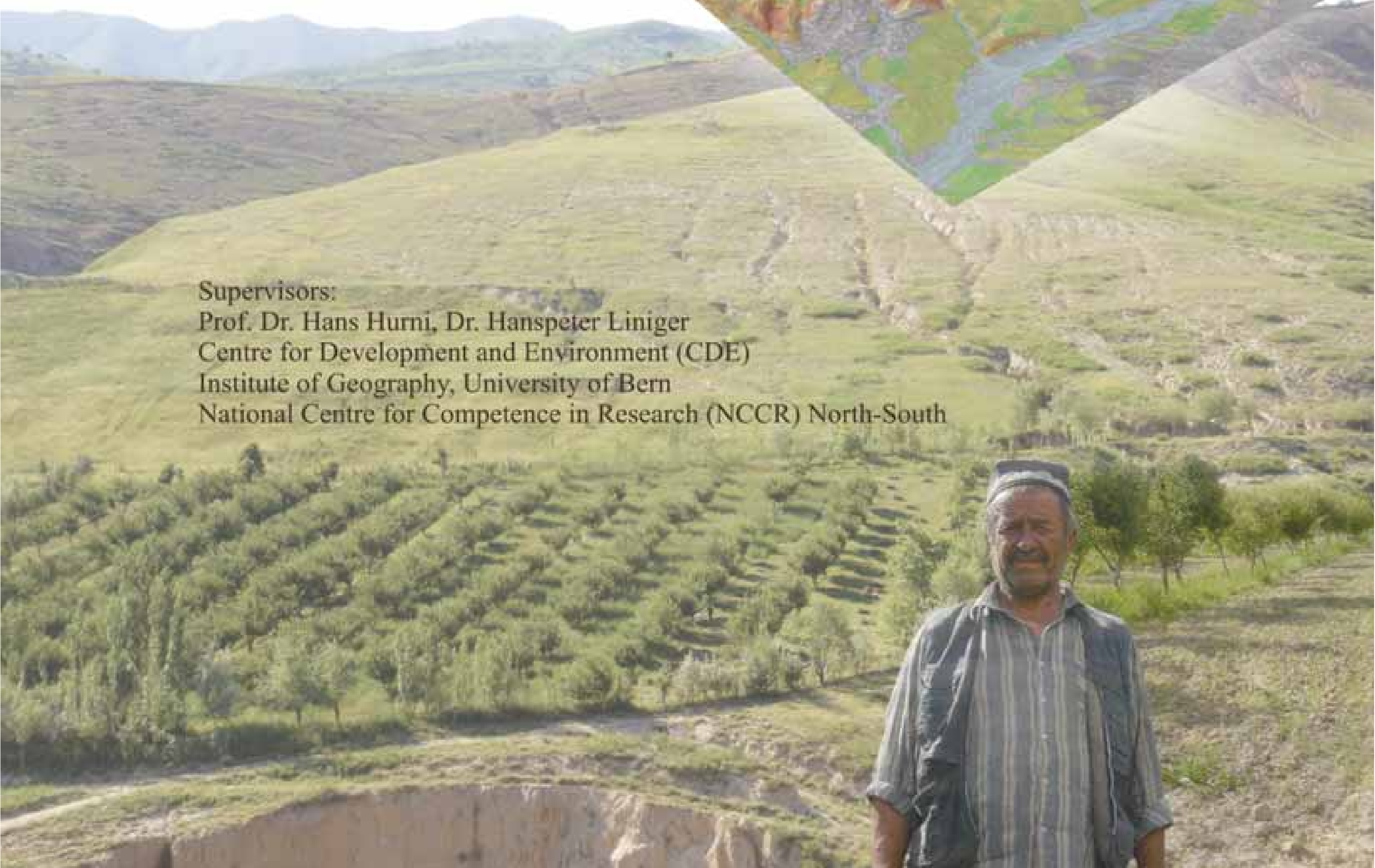

Supervisors:
Prof. Dr. Hans Hurni, Dr. Hanspeter Liniger
Centre for Development and Environment (CDE)
Institute of Geography, University of Bern
National Centre for Competence in Research (NCCR) North-South

Diploma Thesis submitted to the
Faculty of Sciences, University of Bern, Switzerland
by Erik Bühlmann

Supervisors:
Prof. Dr. Hans Hurni
Dr. Hanspeter Liniger
Centre for Development and Environment (CDE),
Institute of Geography, University of Bern

Contact:
Erik Bühlmann
Hallerstrasse 32
CH – 3012 Bern, Switzerland
erik.buehlmann@googlemail.com

Cover: 3D Erosion Map (study area), Orchard System on Degraded Hill Slope, Interviewed Land User

ASSESSING SOIL EROSION AND CONSERVATION IN THE LOESS AREA OF FAIZABAD, WESTERN TAJIKISTAN

INTEGRATING WOCAT METHODS WITH A GIS-BASED RUSLE MODEL

Diplomarbeit

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Erik Bühlmann

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Leiter der Arbeit:
Prof. Dr. Hans Hurni, Dr. Hanspeter Liniger
Centre for Development and Environment (CDE)
National Centre of Competence in Research (NCCR) North – South
Geographisches Institut

PREFACE

Besides the very interesting topic, the chance to get in touch with a foreign region and a different culture motivated me to choose this theme. A personal objective was writing a thesis that may be used as a practical guideline for further projects aiming to improve the livelihood of rural people in western Tajikistan. Such knowledge is of little value if it cannot be transferred and made available to local organisations and the land users themselves. I hope that the results of this study will provide tools for these actors to ensure sustainable yields and fertility on their agricultural land.

This thesis is linked to the PhD thesis by Bettina Wolfgramm focussing on the assessment of impacts of land use on natural resources in the hill zone of western Tajikistan. Three other Master theses and the PhD thesis of Gulniso Nekushoeva are currently beeing carried out in this context. The studies are integrated in (and financed by) the Work Package *Natural Resources in Sustainable Development* (WP4) and also the National Centre of Competence in Research (NCCR) North-South. The NCCR North-South is one of fourteen long-term research programmes implemented by the Swiss National Science Foundation (SNSF).

Without the valuable support, assistance and contributions of numerous people, this thesis could not have been written. To these people I would like to express my gratitude. I am very grateful to my parents for their irreplaceable interest and support throughout my studies.

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Erik Bühlmann

ABSTRACT

The study was conducted within the framework of the National Centre of Competence in Research (NCCR) North–South. It assesses farmer innovations for Soil and Water Conservation (SWC) in the Loess zone of Faizabad, western Tajikistan. Soil erosion by water is a major problem in the hill zone of western Tajikistan. Inappropriate land use in this area accelerates water erosion entailing soil loss and land fertility decline. Since the food crisis during the civil war in the mid-1990s, the share of people engaged in agriculture rose to almost 60 percent in Tajikistan. Until the collapse of the Soviet Union in 1991, farmers were employed in state farms, and it was not within their responsibility to choose the way of farming. Due to this lack of experience, knowledge on necessity and opportunities for sustainable land use is scarcely available.

Even though considerable environmental research on the Tajik hill zone had been conducted during Soviet times and has been resumed during the past few years, empirical erosion models have not been applied. Until now, much attention has been given to monitoring of natural resources, often excluding stakeholders from the approach. To offer an effective basis for decision making, scientific information must be coupled with knowledge of local land users. The overall goal of the present study is to evaluate the effect of local SWC innovations on soil erosion, and to identify priorities for conservation on Tajik loess soils. The research questions of the thesis are: (i) Where does soil erosion occur, and to what extent do current land use practices reduce/increase it? (ii) Can soil erosion on cropland be reduced to sustainable levels by extending local SWC innovations? (iii) How can soil loss reduction be achieved in an efficient and cost-effective way? (iv) Is the GIS-based RUSLE model a suitable tool for erosion risk assessment and for modelling of conservation scenarios? (v) Is the WOCAT methodology suitable for combination with ACED and RUSLE and for the assessment and evaluation of different land use practices / SWC technologies?

The field work for this study was carried out between April and July 2005 in a 10km x 10km study area, approximately 50km east of the capital Dushanbe. Six case studies on local SWC technologies were assessed on a field-scale. Field measurements and land user interviews were conducted using WOCAT (World Overview of Conservation Approaches and Technologies) questionnaires; in the process a special focus was given to SWC on cropland. 57 field plots (grouped into six test sites) were mapped to evaluate the main impacts on erosion. On these fields rill measurements were conducted to validate the outputs of the erosion model at a later stage of the study. Besides, land use was visually classified for the entire test area during the field stay. Information derived from digital topographic data and from high resolution satellite imagery allowed area-wide erosion risk assessment with the RUSLE (Revised Universal Soil Loss Equation) model. Moreover, integrated in a Geographic Information System (GIS), the erosion prediction model served as tool to model the potential effect of local SWC technologies on current soil loss rates. Conservation scenarios were computed, applying local SWC innovations to fields affected by soil erosion.

Soil loss predictions ranges from 0.8 to 378 t/ha*year, averaging 79 t/ha*year. High to very high erosion rates (>30 t/ha*year) are predicted for 35% of the cropland area. The distribution map of soil erosion risk shows the fields where conservation measures should be taken.

Furthermore, the erosion map indicates that the marginal cropland farmed by peasants shows generally higher erosion rates than the relatively flat land cultivated by state farms.

Evaluation of field sampling data reveals that agricultural causes and topographic effects are more often responsible for soil losses in the mapped fields than runon. Besides, the importance of topographic factors is underlined by multivariate statistical analysis of field protocol variables and rill erosion measurements. The study implies that topographic variables (slope length and slope steepness) correlate better with soil erosion than runon-situation and canopy cover. WOCAT case studies on local SWC innovations as well as erosion/conservation modelling suggest that local SWC technologies have a promising potential to control soil erosion: tilling and planting on contour (average soil loss reduction predicted at -11%), zero weeding of chickpea fields and cultivation of perennial fodder plants (-16%), graded drainage ditches
(-53%), intercropping in orchard systems (-63%) and terracing (-93%). For each of these technologies, its potential effect on current soil loss rates is modelled using the RUSLE. In general, the predicted soil loss reducing effects of local SWC innovations correspond well with field observations and farmer statements gathered in the case studies. Combining terraces with intercropped orchard systems results in the greatest reduction in soil loss.

Modelling of conservation scenarios illustrates that soil erosion on cropland may be more than halved if land users start implementing cost-extensive agricultural measures such as contouring, zero weeding, drainage ditches and cut-off drains. However, agricultural technologies often have to be implemented or reconstructed annually, entailing the risk that an achieved reduction may be reversed in another year. To reduce soil erosion below sustainable soil loss tolerance, virtually all fields steeper than 12% gradient would have to be terraced. Since terracing (T) is a labour and cost intensive measure, it is unlikely that land users will follow such recommendations at a voluntary basis, i.e. without public investment. Even though the reduction of soil loss to sustainable levels remains a long-term goal, this scenario seems not to be practicable under the current economic situation. A middle way is proposed for which average soil erosion is believed to decrease to 13 t/ha*year, only 3 t/ha*year above the often quoted limit of tolerable soil loss of 10 t/ha*year. To achieve this, on many fields soil erosion can be sufficiently reduced by cost and labour extensive measures. Cost intensive orchard intercropping systems and terraces are only proposed where slope steepness exceeds 18% and where other measures do not bring about required reduction.

Presently, many farmers lack knowledge on necessity and opportunities for sustainable land use. Hence, knowledge on appropriate land management should be made available to land users in the area. Furthermore, insufficient short-term benefits of the assessed SWC practices may explain their low rate of adoption in practice: short-term effects of soil and water conservation practices are limited and their long-term effects uncertain and too far a way in the future to convince farmers to adopt them. Although the discussed SWC measures are in the long run financially attractive to farmers in Faizabad, the majority of them have often limited capital to invest in SWC. Considerable public investments in SWC practices are required to advance their implementation in areas with steep slopes and low yields such as Faizabad. Farmers can also increase benefits of SWC measures by growing crops with improved management practice.

CONTENTS

ABBREVIATIONS

ACED	Assessment of Current Erosion Damage
AML	Arc Macro Language
DEM	Digital Elevation Model
EUROSEM	European Soil Erosion Model
FAO	Food and Agriculture Organization (United Nations)
GIS	Geographic Information Systems
GPS	Global Positioning System
LISEM	Limburg Soil Erosion Model
MFI	Modified Fournier Index
MUSLE	Modified Universal Soil Loss Equation
NCCR	National Centre of Competence in Research
NDVI	Normalised Difference Vegetation Index
OSAVI	Optimised Soil Adjusted Vegetation Index
RUSLE	Revised Universal Soil Loss Equation
SNCF	Swiss National Science Foundation
SWC	Soil and Water Conservation
USLE	Universal Soil Loss Equation
WEPP	Water Erosion Prediction Project
WOCAT	World Overview of Conservation Approaches and Technologies
WP4	NCCR – Work Package (Natural Resources in Sustainable Development)

SYMBOLS

A	average annual soil loss (t/ha*year)
Band 3	band of a satellite image covering the red spectrum
Band 4	band of a satellite image covering the near-infrared spectrum
C	cover management factor (dimensionless)
c	seasonal ratio of $F_{c,max}$ for each crop
CC	canopy cover expressed in percent or the fraction of the area covered canopy cover subfactor (for C factor calculation)
CC_{max}	canopy cover subfactor at the stage of maximum vegetation height
E	total storm energy (MJ/ha*mm)
EI_{30}	storm erosivity (MJ*mm/ha*h)
em	rainfall kinetic energy (MJ/ha*mm)
$F_{c,max}$	canopy cover fraction at the stage of maximum vegetation height
i	subscript indicating a particular segment
i_m	rainfall intensity (mm/h)
I_{30}	maximum 30-minutes rainfall intensity (mm/h)
K	soil erodibility factor (t*ha*h/ha*MJ*mm)
L	slope length factor (dimensionless)
M	monthly values for the month of interest
M+1	subsequent month (month following M)
M-1	previous month (month previous to M)
P	support practice factor (dimensionless)
P_1	first half-monthly period of a month of interest
P_2	second half-monthly period of a month of interest
P_b	base value of the P factor for contouring (dimensionless)
PLU	prior land use subfactor (dimensionless)
P_{mb}	minimum P factor (contouring) for a given ridge height (dimensionless)
R	average annual erosivity factor (MJ*mm/ha*h*y)
$rain_{10}$	amount of rainfall for days with precipitation >= 10.0 mm
s	slope steepness (%) slope steepness (sine of slope angle)

S	slope steepness factor (dimensionless)
s_c	slope steepness for which a value of P_b is desired (sine of slope angle)
SC	surface-cover subfactor (dimensionless)
s_e	slope steepness above which contouring is ineffective (sine of slope angle)
SLR	soil loss ration (dimensionless)
s_m	slope steepness at which contouring is most effective (sine of slope angle)
SM	soil-moisture subfactor (dimensionless)
λ	slope length (ft)
Θ	slope angle (degrees)

1 INTRODUCTION

Soil erosion by water is a major problem in mountainous areas with steep slopes. Inappropriate land use in these areas is likely to accelerate water erosion entailing soil loss and land fertility decline (Hurni et al., 1996; Liniger and Thomas, 1998). Suspension from the eroded material damages the water quality in downstream areas and its subsequent sedimentation decreases the reservoirs' capacity. Therefore, controlling erosion is crucial to sustain agricultural yields and to reduce environmental damage. Spatial and quantitative information on soil erosion on a regional scale contributes to conservation planning, erosion control and management of the environment. However, neither accurate measurements of soil loss from crop fields nor a documentation of sustainable land management practices are available in Tajikistan. The present study addresses this gap.

1.1 Problem Statement

Tajikistan's foothills and mountainous valleys comprise one of the most fertile and most populated areas of Central Asia. Irrigated cropland on planes and valley floors is the most suitable for cultivation of food crops. However, during soviet times, it was turned into a cotton monoculture farming system weeping out the region's agrarian diversity (Gleason, 1997; Kulchik et. al., 1996). Before its independence, food supply problems in Tajikistan were unknown, since it received considerable food deliveries from the Soviet state. When it became autonomous, these deliveries were terminated, besides the consequent food crisis was aggravated by the civil war (Breu and Hurni, 2003). Subsequently the share of people engaged in agriculture rose from 46.8 percent in 1992 to almost 60 percent in 1996. Because of food shortage, the rural population had no choice but expanding its cultivated land to steep slopes highly at risk of soil degradation (Abdullaev and Akbarzadeh, 2002; Johnes, 2002). This trend is aggravated by the slow progress of land reforms which can be observed particularly within the Faizabad District (State Land Committee, 2004). While a number of studies state that some success has been achieved during the ongoing land reform process (Nissen, 2004), the British NGO Action Against Hunger went so far as to say that the reorganization of farms was "a success only on paper" (Action Against Hunger, 2003). Today, land in Faizabad District is still exclusively state owned but can be leased.

Since the civil war, Tajikistan is designated as a low-income/food-deficit country and can be considered as particularly vulnerable to food insecurity and to fluctuations of global food prices. Hence, sustainable increases in agricultural productivity are essential for short-term poverty reduction and long-term food security (Goletti and Chabot, 2000; Babu and Tashmatov, 2000). Until the collapse of the Soviet Union, farmers were employed in kolkhozes and it was not within their responsibility to choose the way of farming (Tashmatov et al., 2000). Due to this lack of experience, knowledge on necessity and opportunities for sustainable land use is scarcely available (Duncan, 2000).

1.2 Site Description

The 10x10km study area, selected by Bettina Wolfgramm, is located in the hill zone of Tajikistan, approximately 50km east of the capital Dushanbe (for more details on the selection procedure of the study area see Wolfgramm and Hett, 2004). Within the catchment, two distinct landforms are represented: a hill slope region with moderate to steep slopes and the flat to gently sloping floodplain, both with deep calcareous brown soils from loess deposition (Ding et al., 2002). The site is located at an elevation ranging from 1,200 to 2,500 metres above sea level. Annual precipitation averages slightly below 900 mm, of which 90% occurs from November to May leaving the summer months nearly dry. From the end of December to the beginning of March, snow accounts for most of the precipitation.

The crop–livestock farming system in the area is typical for the hill zone of the country. Most annual cropland is located on the valley floor and on the passage from the floodplain to the hill slope zone. While large fields, located in the valley floor, are mostly cultivated by state farms or private farm enterprises, peasant farmers do not have the choice but cultivating the rather small and often sloping field plots on hill slopes near the villages. Figure 1 represents a typical hill slope of the study area.

Figure 1: Typical hill slope of the study area: former pastures were turned into annual cropland which is now farmed by peasants (foreground) and orchards on terraced land established during Soviet times (in the upper left corner)(Photo by: E. Bühlmann, April 2005)

Various sheet and gully erosion features can be observed in Figure 1, documenting the extremely high risk of soil erosion on these hill slopes. Even though most land users are aware of soil erosion problems and related fertility decline, only few farmers started implementing effective measures to control soil erosion. Figure 2 shows one of these conservation initiatives which will be further described at a later stage of this study.

Figure 2: Conservation initiative of peasant farmers in Faizabad: three smallholders established an orchard system with runon prevention to increase farm production and to reduce soil erosion; the pasture next to it faces severe rill and gully erosion (Photo by: E. Bühlmann, May 2005)

The picture documents that SWC, in combination with appropriate land management, has the potential to control soil erosion. Where no measures are taken erosion removes the topsoil which adversely affects fertility of the land.

1.3 Theory and Methodology

1.3.1 Erosion

"Erosion has always taken place, and always will" states Hudson (1995) in respect of the constantly changing earth surface. He considers erosion as one of the aspects of the constant process of change which is fundamental to the formation of alluvial soils and sedimentary rocks. Human's activities seldom slow down or halt the process but frequently speed it up. Hence, it is important to distinguish between erosion resulting exclusively from the forces of nature, referred to as *natural erosion* and erosion processes influenced by man, referred to as *soil erosion* or *accelerated erosion* in this study.

Soil Erosion. On a world scale human's non-agricultural activities which accelerate the erosion processes have little significance. Agriculture is so widespread that its activities, materially altering speed of the erosion process, are much more important. Livestock trampling on soil break it down and make it easier to be carried away by wind or water. By ploughing and tilling the soil, man disturbs and aerates the soil. Whenever vegetation is cleared and the ground is more exposed, there is less canopy cover to absorb the energy of the falling rain, thus entailing more rainfall erosion and more surface runoff. Different reports indicate that soil degradation is increasing world wide (FAO, 2000; Hudson, 1995; Mosimann et al. 1991).

Erosion Process. Soil erosion is the detachment and movement of the mineral particles and organic material of the soil through the action of water or wind. Soil erosion by water is the most important single agent of erosion. It generally begins when raindrops and their splash strike bare or incompletely vegetated soil on sloping land. The energy of raindrops detaches and transports soil short distances to nearby rills. Detachment, transport and deposition of soil may occur in these rills and in progressively larger drainage channels as runoff water accumulates from many smaller channels and moves down slope toward reservoirs or oceans (Laflen et al., 1990; Miller et al., 1999).

Classification of water erosion. (i) *inter-rill* erosion, meaning both movement by rain splash and the transport of raindrop-detaches soil by thin surface flow. Because splash erosion and thin surface flow act uniformly over the land surface, its effects are seen only where stones of tree roots selectively protect the underlying soil and splash pedestals or soil pillars are formed. (ii) *Rill erosion* is usually defined as small washes which can be eliminated by normal cultural methods and *gullies* when the channels are so large and well-established that they cannot be crossed by farm implements. Rills from one storm are often eliminated during the next high intensity rain storm. The new channels may form an entirely fresh network, unrelated to the positions of previous rills (Hudson, 1995). This phenomenon is documented in Figure 3 which shows rill erosion on annual cropland before ploughing.

Figure 3: Active rill network on cropland formed during rainstorms in winter and early spring (Photo by: E. Bühlmann, April 2005)

As expected from the greater erosive power of concentrated flow, rill erosion may account for a main share of the soil removed from a hillside. (iii) *Gullies* are relatively permanent steep-sided water courses which experience temporary flows during rainstorms. They are almost always associated with accelerated erosion (Hudson, 1995; Morgan, 1979).

Consequences of Erosion. The consequences of erosion can be grouped into (i) onsite impacts, which includes loss of crop, seeds, fertilizer and thinning of the soil layer thus directly affecting present and future productivity; and (ii) off-site impacts, including dam sedimentation, pollution of water courses and property damage by moody floods (Boardman, 2002). Even though both implications are likely to affect rural peoples' lives, this study focuses on on-site impacts. Erosion of any soil usually results on-site in a net decrease of long-term productivity: erosion removes the topsoil which has the highest organic matter content, has the most stable soil structure and offers the most optimal seedbed for germinating and emerging plants. Several studies have demonstrated that the material removed by erosion is commonly from 1.3 to 5 times richer in organic material than the soil left behind. Furthermore, removal of the topsoil reduces the water-holding capacity of the soil and further reduces the available rooting depth of the crop which increases the negative impact on soil productivity (Hatfield, 2002; Pimentel et al., 2003). The productivity of soils with deep rooting potential is not as sensitive to erosion as other soils. The productivity of those soils, formed in permeable parent materials with favourable subsoil characteristics, will not be adversely affected by successive minor increments of erosion. The deep soils developed on loess deposits in Faizabad and some other parts of western Tajikistan may have these characteristics. Crop yields can be somewhat lower on these eroded soils but with a management above average, yields from eroded and uneroded sites will be similar (Miller et al., 1999).

Soil Loss Tolerance. The objective of soil conservation is to ensure that land is cultivated in such a way that the use can be sustained indefinitely, i.e. there is no progressive deterioration. Hence, the criterion for tolerable soil loss should be when soil loss is no greater than the rate of formation of soil. Since formation rates are usually very low and difficult to measure, soil loss tolerance would need to be set close to zero which seems rather unrealistic, although remaining a long-term objective. The level of erosion which has for many years been taken in the US as the upper limit of tolerable soil loss is 11.2 t/ha*year (5 t/acre*year) which is equivalent to a formation rate of 25 mm in 30 years (in undisturbed conditions scientists estimated that an average of 300-1000 years, and if soil is tilled about 100 years, are needed to form 25 mm of soil) (Hudson, 1995; Laflen et al., 1990). In this case, the term *soil loss tolerance* denotes the maximum rate of soil erosion that can occur and still permit crop productivity to be sustained economically over a longer-term (here between 300-500 years). Hence, the term considers the loss of productivity due to erosion but also considers the rate of soil formation from parent material, role of topsoil formation, loss of nutrients and the cost to replace them as well as erosion control practices that farmers might reasonably be able to implement (Renard et al., 1997). In this light, Renschler et al. (1998) assumed that a soil loss tolerance of 5 to 10 t/ha*year is acceptable for soil depths of more than 1 metre while Schwertmann (1987) argues that the upper limit should be set to 10 t/ha*year for very deep brown soils from loess formation. Bakker et al. (2004) analysed productivity-erosion relationships and found that erosion rates of 10 t/ha*year will entail average yield losses of 0.4% per decade. He predicts that for areas suffering from more severe erosion yield decline can easily become 10-fold greater. Even though erosion may not have resulted everywhere in severe productivity losses so far, future erosion will show increasingly severe losses with current erosion rates. Hence, attention should be paid to soils that have already suffered from erosion too, even though they are still productive at this stage.

1.3.2 Soil Erosion Modelling and GIS

Model Selection. For conservation mapping, reliable information on soil loss from fields, catchments and watersheds is required. Many models exist for the consideration of these processes. However, these models differ greatly in terms of their complexity, their inputs and requirements, the processes they represent and the manner in which these processes are represented, the scale of their intended use and the types of output information they provide. Determining the appropriate model for an application requires consideration of these elements in the context of the objectives set up by the researcher (Merrit et al., 2003). Various authors conducted research comparing performance of empirical, physical and conceptual models in specific environments (e.g. Bacchi et al., 2003; Hengsdijk et al., 2005; Laflen, 2002; Merrit et al., 2003; Nearing et al., 2005, Yu et al., 2001). Physically based soil erosion models like WEPP (Flanagan and Nearing, 1995), EUROSEM (Morgan et al., 1998) or LISEM (de Roo, 1996) apply simulations of abstract topographic units to derive runoff and sediment yield. Jakeman and Hornberger (1993) state that complex models suffer from problems with error accumulation due to over-parameterisation. Beven (2001) argues that over-parameterisation of physical models often leads to the problem that single parameters cannot be estimated independently anymore.

Empirical models as the USLE (Wischmeier and Smith, 1978) or its revised form the RUSLE (Renard et al., 1997) require a smaller number of input parameters. When used within the developed framework, simple empirical models can be more accurate than physical models with more complicated structures (Bacchi et al., 2003; Laflen, 2002; Merrit et al., 2003). While the Modified Universal Soil Loss Equation MUSLE (Williams et al., 1971) was developed to predict individual storm sediment yield, USLE and RUSLE are the most widely used erosion prediction models estimating average annual soil loss caused by sheet and rill erosion in specific climatic, pedologic, topographic and cultivation conditions (Laflen, 2002; Kesley, 2002). Furthermore, the described empirical models are applied to identify areas needing soil erosion control measures and to select appropriate practices to minimize damages resulting from soil erosion (e.g. Cohen et al., 2005; Hengsdijk et al., 2005; Hurni, 1985; Pertiwi et al., 1998; Sarangi et al., 2004; Shi et al., 2004).

The (R)USLE Model. The methodology was empirically obtained by a great number of experimental observations and is based on a highly schematic representation of erosive phenomena (Mendicino, 1999). The USLE and RUSLE equation is given by

$$A = R * K * L * S * C * P$$

in which A represents average annual soil loss (t/ha*year), R is a climatic factor which mainly takes into account the erosive capacity of rainfall (MJ*mm/ha*h*y), K is the soil erodibility which expresses the intrinsic capacity of the soil for being eroded (t*ha*h/ha*MJ*mm). The quantities L, S, C and P are dimensionless factors that take into account slope length, slope angle, vegetation cover and management practices (Wischmeier and Smith, 1978; Renard et al., 1997).

Although the original USLE has been retained in RUSLE, the technology for factor evaluation has been altered and new data have been introduced, supporting the evaluation of the terms in specified conditions. Major improvements of the RUSLE (compared to the USLE) include time variation in soil erodibility, improved LS factor that incorporates recent science and a subfactor approach for computing the cover and management factor. Furthermore, the conservation factor P was diversified based on modelling analysis and can now be calculated for terracing, buffer strips, strip cropping, drainage and off-grade contouring (Renard et al., 1997). RUSLE was developed for the purpose of extending its application rather than increasing its predictive accuracy for normal cropping situation. As a consequence, USLE and RUSLE are expected to provide a similar degree of accuracy (Foster et al., 2003; Merrit et al., 2003; Sonneveld and Nearing, 2003; Tran et al., 2001). However, the main advantage of using the RUSLE in this study are its capability of estimating the C factor from information on vegetation type, residues and tillage practices rather than from experimental plot data as practised in the USLE.

Integration with a Geographic Information System (GIS). GIS are an arrangement of computer hardware, software and geographic data that people interact with to integrate, analyse and visualise the data and to identify relationships, patterns and trends (ESRI, 2005; Longley et al., 2001). Standard applications of GIS allow capture, modelling, storage, retrieval, manipulation and analysis of geographically referenced data. GIS, furthermore, provide multiple tools for thematic mapping and data display (Ormsby et al., 2001; Rigaux et al., 2002; Worboys and Duckham, 2005). In this study, a GIS is used for soil erosion modelling and scenario calculation and analysis. Besides, it enables spatial analysis of spectral and topographic information allowing consideration of spatial variability of the environment.

1.3.3 Soil and Water Conservation and WOCAT Methodology

For a given tract of land, a land user has little control over climate, the soil and the topography or slope that affects soil erosion. However, the impact of these factors can be reduced by conservation practices. Some farmers started implementing measures to control soil erosion on their own initiative, which is referred to as *farmer innovation* in this study. The term *soil- and water conservation* (SWC) is defined according to WOCAT as "activities at the local level which maintain or enhance the productive capacity of the land in areas affected by or prone to degradation". SWC technologies are categorised into agronomic-, vegetative-, structural- as well as management measures or a combination of these (WOCAT, 2005abc).

WOCAT is a tool that aims at promoting improved decision making on land management and transfer of appropriate technology through collection, presentation and dissemination of knowledge on SWC worldwide (FAO, 2000). A set of three comprehensive questionnaires and a database system have been developed to document all relevant aspects of SWC technologies and approaches. WOCAT defines *SWC technologies* as "measures that control soil degradation and enhance productivity in the field". *SWC approaches* are defined as "ways and means of support that help to introduce, implement, adapt and apply SWC technologies in the field" (Liniger et al., 2002a). The advantage of using WOCAT methods is that it provides standard tools which enable documentation, analysis and better decision-making. Furthermore, it allows identifying options for overcoming land degradation from the field to the national and international level (Hurni, 1997; Liniger et al., 2002b, Liniger and Schwilch, 2002). In the present study, the WOCAT methodology was used to gather and assess information on farmer innovations for SWC.

1.4 Objectives, Research Questions and Overall Approach

Soil erosion modelling is a potentially powerful tool for assessing soil erosion and impact of land management. It improves our understanding of erosion, helps us locating erosion hotspots, predicting erosion and evaluating the effect of different soil and water conservation methods. Even though considerable environmental research on the Tajik hill zone had been conducted during Soviet times and has been resumed during the past few years, empirical erosion models have not been applied. Until now, much attention has been given to monitoring, often excluding stakeholders from the approach. To offer an effective basis for decision making, scientific information must be coupled with knowledge of local land users.

The overall aim of this thesis is:

> **To evaluate the effect of local SWC innovations on soil erosion and to identify priorities for conservation on Tajik loess soils.**

Following objectives were set up to achieve the overall goal:

1. To estimate soil loss and its spatial distribution under current cropping conditions using an adapted RUSLE model combined with GIS tools and information derived from high resolution satellite imagery.
2. To get a better understanding of erosion processes on Tajik loess soils through rill erosion assessment in combination with agricultural, topographical and environmental information gathered in a field protocol.
3. To assess local SWC innovations and their potential for a wider application using WOCAT methods.
4. To use the RUSLE for modelling the potential effect of local SWC innovations on current soil loss rates
5. To develop scenarios for reduction of current soil loss by applying local SWC innovations to fields affected by soil erosion in the study area (rule based RUSLE computations).

The combination of these methods may provide an integrated and effective tool for resource management within the scope of sustainable development in developing countries.

Following research questions were developed for this thesis:

> Where does soil erosion occur, and to what extent do current land use practices reduce/increase it? Can soil erosion on cropland be reduced to sustainable levels by extending local SWC innovations? How can soil loss reduction be achieved in an efficient and cost-effective way?
>
> Is the GIS-based RUSLE model, as used in this study, a suitable tool for erosion risk assessment and for modelling of conservation scenarios? Is the WOCAT methodology suitable for combination with ACED and RUSLE and for the assessment and evaluation of different land use practices / SWC technologies?

To achieve these objectives and research questions, the study is carried out at three different spatial scales. Figure 4 provides an overview of the study components and points out the linkages within and between these scales.

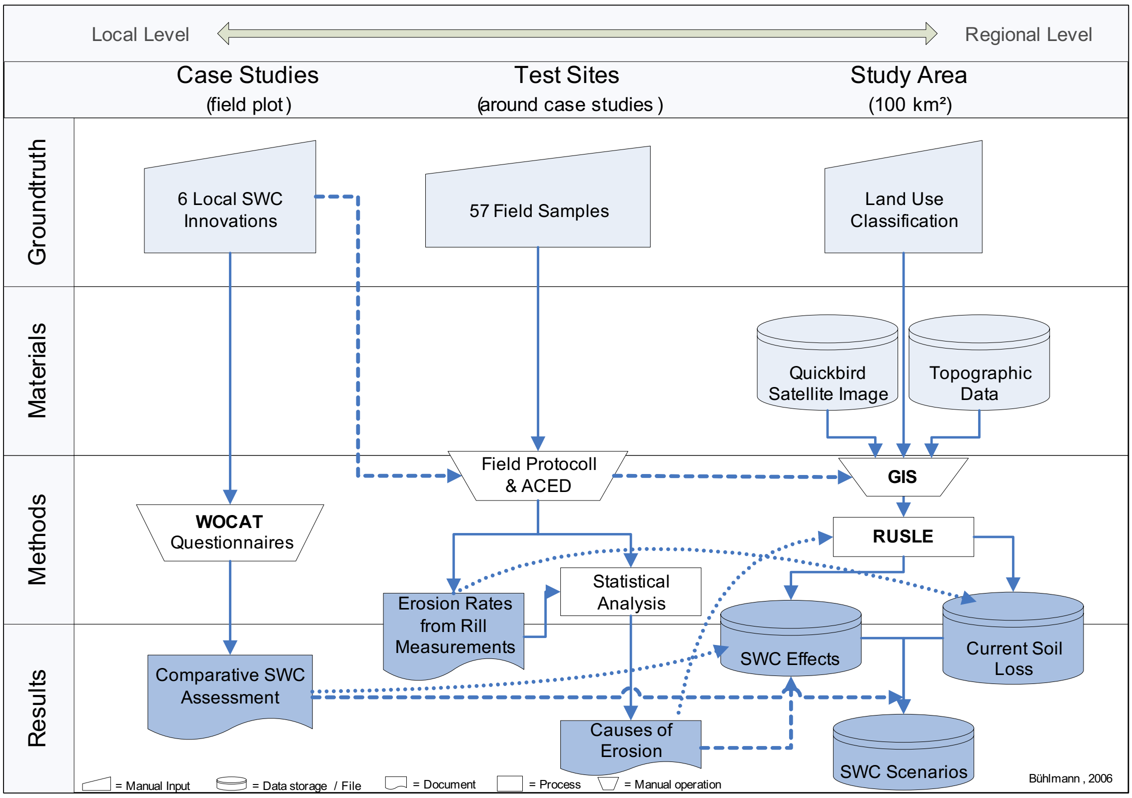


Figure 4: Overall Approach of the study and integration of three spatial scales (solid blue lines = links within a scale level; dashed blue lines = links between scale levels; dotted blue curves = validation and verification processes)

The resolution of the data collected in the field increases towards the case study level. Case studies and field sampling are intended to increase the level of detail at study area scale. The findings from information gathered at large scales are essential inputs for scenario calculation. Furthermore, ground truth data at field level are used to verify and validate model structure and model outputs.

Section 2 examines the abilities of current erosion models to deal with the characteristics of the study area and describes methods used for rill erosion estimation as well as the approach used for assessment of local SWC technologies. Section 3.1 gives details on the calculation procedures of the single model factors for erosion mapping, so that hot spots, areas high at risk of soil erosion, can be located and analysed. The model outputs are validated and assessed in section 3.2 allowing conclusions concerning the effect of particular crops on soil erosion. Analysis of main causes of soil erosion, in section 3.2.3, is derived from field protocol data, suggesting priorities for conservation. Local SWC measures are assessed in section 3.4 for which amendments are proposed. Finally, all these findings serve as basis to establish criteria for scenario calculation. Following simulation of SWC technologies' effects on soil loss rates, section 3.5 concludes proposing a conservation map.

2 MATERIALS AND METHODS

The present study was carried out on three different spatial scales. (i) Digital topographic information and a high resolution satellite image were available for the entire study area, allowing area wide assessment with a soil loss prediction model. For this purpose, land use was visually classified for the entire test area during the field stay. On the same scale, priorities for conservation will be suggested. (ii) 57 field plots (grouped into six test sites) were mapped to evaluate the main impacts on erosion. Measurements of erosion features observed in the mapped fields will be used to validate the outputs of the erosion model. In the mapping approach, every land use and crop predominant in the study area was considered. The criteria on which basis the field plots were selected, are closely linked to the selection procedure of SWC case studies described below. (iii) Six case studies on local SWC technologies were assessed on a field-scale. The main criterion for the selection of the case studies was to cover the full range of SWC innovations observed within the study area. In general, only SWC plots with close by fields in a comparable physical environment were chosen. Only SWC measures on cropland were analysed.

This section will provide details on the materials and methods used in this thesis. It will illustrate why and how particular methods were applied and what adaptations and modifications were made. Literature reviews are presented, discussing the strengths and weaknesses of the the used approaches. Calculation processes to derive the factors for RUSLE soil erosion modelling are documented in this part of the study providing an initial analysis of these factors to ensure validity of the model. The outcomes of these methods will be displayed and evaluated in section *Results and Discussion.*

2.1 Digital Elevation Model

Usually, Digital Elevation Models (DEM) provide spatial information on elevation, slope and watershed aspect in the modelling process (Hickey et al., 1994). Van Remortel et al. (2001) demonstrated that a high-quality DEM input grid is the key element for ensuring reliable topographic factor computations. Kankrida and Dwivedi (2003) argue that most DEMs do not portray true field conditions, often resulting in inaccuracies in the prediction of deposition zones due to interpolation errors. While field estimates of slope steepness and cumulative slope length may be more accurate than model calculations, for larger areas they are generally not practical nor affordable (Hickey et al., 1994; Millward and Mersey, 1999). Wang et al. (2001) and Wu et al. (2005) proved that DEM resolution has a profound effect on the spatial pattern of the topography factors. According to the authors, the computed total soil erosion decreases with the increasing grid sizes since the spatial variability of the topography is essentially the determining factor. Boggs et al. (2001) argued that spatial variability should be well represented in the DEM to assure that risky spots are located and high priority areas for SWC are identified. Therefore, it can be concluded that the smallest available grid size represents the best DEM resolution for this kind of study. However, the size and spatial distribution of the original elevation data limit the minimum precision of a DEM. The most effective DEM resolution will ensure that precision is not lost due to choice of an overly large grid size. Similarly, a grid size that is too small may result in an estimate of slope variation at a much higher level of detail than is relevant for the process being modelled. Best slope estimates can be obtained by computing the DEM at high resolution, but with sufficient smoothing, using elevation data from larger areas (Warren et al., 2004).

In the present study, a DEM of five metre grid size was generated from 20 metre contour lines digitised from a Russian 1:50,000 topographic map (Russian Military Topographic Map, 1983). Next to the contour lines, about fifty points representing additional surface elevation and digitised streams for drainage enforcement served as input into the *topo to raster* function in ArcGIS. Smoothing parameters were used to reduce steps in the output model resulting from inappropriate interpolation of contour information. Function fill was used to remove unwanted sinks in the elevation model. The generated DEM served as a basis to compute topographic factors for soil loss modelling and was used to orthorectify satellite images.

2.2 Quickbird High Resolution Satellite Image

A Quickbird satellite image was ordered to allow field-wise land use, vegetation, SWC and erosion mapping of the 100 km^2 study area. The high resolution of 0.6 metre offered by Quickbird satellite images, allows mapping of the small field plots observed in the study area. The Quickbird satellite image was taken 22^{nd} of June 2005, which is considered to be around the stage of maximum vegetation height. The received satellite image is cloud-free and is almost free of atmospheric distortion. Unfortunately the image was taken with an off-nadir view angle of 24.4 degree. The resulting spatial distortion can be corrected through image orthorectification.

At first, the multispectral image (2.4 m resolution) and the panchromatic image (0.6 m resolution) were merged. The pan-sharpened image was then orthorectified using a DEM and around 40 ground control points gathered in the field with a GPS (Global Positioning System). As described above, DEMs are subject to data uncertainty due to generalization or imperfections in the creation process. The quality of the digital orthoimage is significantly affected by this uncertainty. For different image data, specific accuracy levels of DEMs are required to limit the uncertainty-related errors within a controlled limit. For aerial photographs with a scale larger than 1:60000, for instance, elevation data accurate to 1 meter is recommended. The 1 metre accuracy reflects the accuracy of the Z coordinates in the DEM, not the DEM resolution (ERDAS, 2003). Since the DEM used in the present study is generated from contour lines with 20 metres equidistance, it is questionable whether the resulting DEM accuracy is entirely sufficient for orthorectification of high resolution satellite images.

Digital imagery from mountainous regions often contains a radiometric distortion known as *topographic effect* which results from the differences in illumination due to the angle of the sun and the angle of the terrain (ERDAS, 2003). In vegetation mapping and land use change detection atmospheric correction is often unnecessary as long as all data is in the same relative scale (Carpenter et al., 1999; Song et al., 2001). For detailed information on image pre-processing of high resolution satellite images see Jakobsen (2003), Kadota and Takagi (2002), Li (1998), Li et al. (2005), Schmidt (2003), Song et al. (2001) and Yilmaz et al. (2004).

2.3 Land Use Classification

Information on spatial distribution of land use is essential for erosion modelling and the development of land use dependent SWC scenarios. To create a land use map, field boundaries were digitized from Quickbird high resolution satellite images. During a three day walk through the study area, the crop currently cultivated was determined for each polygon. The resulting land use map includes 15 land use types which can be summarised, based the WOCAT classification scheme, into 8 main land use categories: *annual cropland* (wheat, flax, chickpeas, vegetables, safflower), *perennial cropland* (alfa alfa, exparzet), *tree/shrub cropping* (orchards, vineyards, mulberry groves), *mixed cropping* (agroforestry), *fallow/abandoned land*, *grazing land* (intensive grazing land, extensive grazing, grazed alluvial cone with sparse vegetation), *natural forests* and *other* (streams and gullies, settlements, industrial zone). The vegetable crop class includes various, often irrigated crops which are part of an annual crop rotation system. Vegetables frequently cultivated in Faizabad are, for instance, tomatoes, onions, potatoes, carrots, maize, cucumber and herbs. In this study, the land use category *mixed cropping* comprises of orchard systems in which an annual crops are cultivated in the area between the tree rows. With the above listed land use classes, all fields within the study area could be classified.

2.4 Field Sampling and Rill Erosion Assessment

In order to evaluate the main impacts on soil erosion and for model validation purposes, 57 field plots (grouped into six test sites) were mapped with a field protocol. The protocol was developed according to the objectives of this study and included following features: (i) the Assessment of Current Erosion Damage (ACED) method developed by Herweg (1996) allowing estimation of annual soil losses based on rill measurements and identification of main factors of erosion; (ii) WOCAT-Mapping (WOCAT, 2005c) classifying erosion processes and gathering information on SWC; and (iii) elements of the FAO Field Assessment Tool (FAO, 2004) to complement the two previous features.

For each test site, a form was filled lining the fields up in rows to facilitate comparison of features within the test site. The protocol classifies topographic factors, soil surface conditions and visible erosion features. The layout of the field plot is described on the basis of the field gradient, measured using an inclinometer, slope form and tillage direction. Gathered soil surface properties were crop cover, crop residue cover, area covered by stones, surface roughness and presence of soil crusting. Furthermore, SWC practices were classified and visually assessed. Besides, length, width and depth of rills and gullies were measured. Similar features were then assigned to rill classes which were redefined for each field plot. In order to estimate annual soil loss, the field plots were revisited at the end of the rainy period to update rill measurements. Information on land management practices and land use history was gathered through land user interviews. The collected field data was then entered as attribute information in a GIS; additional spatial information was then added: field size was generated from a land use map based on field boundaries digitised from satellite imagery. All field plots were documented with several pictures in order to allow reconstruction of conclusions made in the field.

Recent studies on soil erosion have shown that particles are transported only over short distances in interrill areas before under some circumstances deposition can occur (Abrahams et al., 1998; Rejman and Usowicz, 2002; Zhang et al., 2003). Rill erosion, however, exports sediments from the field and is thus directly affecting the soil resource. Various authors found that rill erosion accounts for more than 80% of the total erosion at all slope gradients (Chaplot et al., 2005; Fox and Bryan, 1999, Herweg, 1992; Morgan, 1979). Hence, soil loss rates can be estimated from rill erosion measurements. The method used in this study, was proposed by Herweg (1996): He multiplied the volume of observed rill features by the bulk density of the topsoil, which was assumed to be 1gr/cm3 for field plots cultivated by hand and 1.3gr/cm3 for land cultivated by tractor. Rills with a depth of more than 30 cm had to be excluded from the calculations, since they do not disappear entirely after tillage activities. Fields with unequal spatial distribution of erosion features were not included in this study, as they may lead to overestimation of soil loss rates when soil losses are scaled up to the hectare. Since erosion features on fields with steady vegetation cover may become permanent, soil loss rates can only be estimated on annual crop land (Boardman, 2002).

Since the measured rills may have replaced rill networks developed during previous rainstorms (see Figure 3), the ACED method may not account for the total annual linear erosion and, hence, may rather underestimate soil losses. However, various authors found that results from the ACED erosion survey are within 15% accuracy for careful measurements (e.g. Herweg and Stillhardt, 1999; Bewket and Stirk, 2003; Dijk van et al., 2005). Okoba (2005) proved significant correlations between soil loss and all the rill attributes. Rill attributes also correlated significantly among each other, suggesting a linear influence of rill dimensions on soil loss rates. Vigiak et al. (2005) compared soil loss rates predicted by the empirical soil loss model Morgan, Morgan and Finney with an ACED erosion map classifying soil loss rates into five categories. The results of their statistical analysis indicated almost perfect agreements between the two maps. However, being a semi-quantitative and qualitative erosion assessment method, survey results cannot be taken as accurate estimations of soil loss from runoff plots.

2.5 Assessing SWC Case Studies with WOCAT

Only a small range of SWC technologies can be observed in the study area. Farmers' acceptance and adoption of SWC measures may be enhanced if the technologies suggested by conservationists or proposed by the land committee are extensions and outgrowths of indigenous practices. Therefore, six case studies on local SWC technologies were conducted using World Overview of Conservation Approaches and Technologies (WOCAT) methods. A set of three comprehensive questionnaires and a database system have been developed to document all relevant aspects of SWC technologies and approaches: (i) The questionnaire on SWC technologies (WOCAT, 2005a) addresses the specification of the technology (purpose, classification, design and costs) and the natural and human environment where it is used. It also includes an analysis of benefits, advantages and disadvantages, economic impacts, acceptance and adoption of the technology. (ii) The questionnaire on SWC approaches (WOCAT, 2005b) focuses on implementation, with questions on objectives, operation, participation by land users, financing and direct and indirect subsidies. Analysis of the described approach involves monitoring and evaluation methods as well as an impact analysis. (iii) Questionnaire WOCAT mapping (WOCAT, 2005c) is the spatial component of the methodology and should be considered complementary to the technology questionnaire and the approach questionnaire.

In this study, 6 technology questionnaires and two questionnaires on approaches were completed, gathering information on local SWC initiatives from farmer-interviews and from field observations. Besides, the SWC fields were mapped with the field protocol which includes several features of WOCAT mapping. The results of these studies are illustrated and discussed in section 3.4. Additional information on the conducted SWC case studies can be found in the four page summaries and by browsing the full database in Appendix 4 of this thesis.

2.6 Soil Loss Factor Calculation

The model structure of the RUSLE by Renard et al. (1997) serves as a basis for soil loss prediction in this study. The methodology to derive factors was adapted according to the data available and considering the newest findings in the literature. To ensure the validity of the model output, adaptations with regard to specific local conditions were made. The basic model structure of the used model is illustrated in Figure 5.

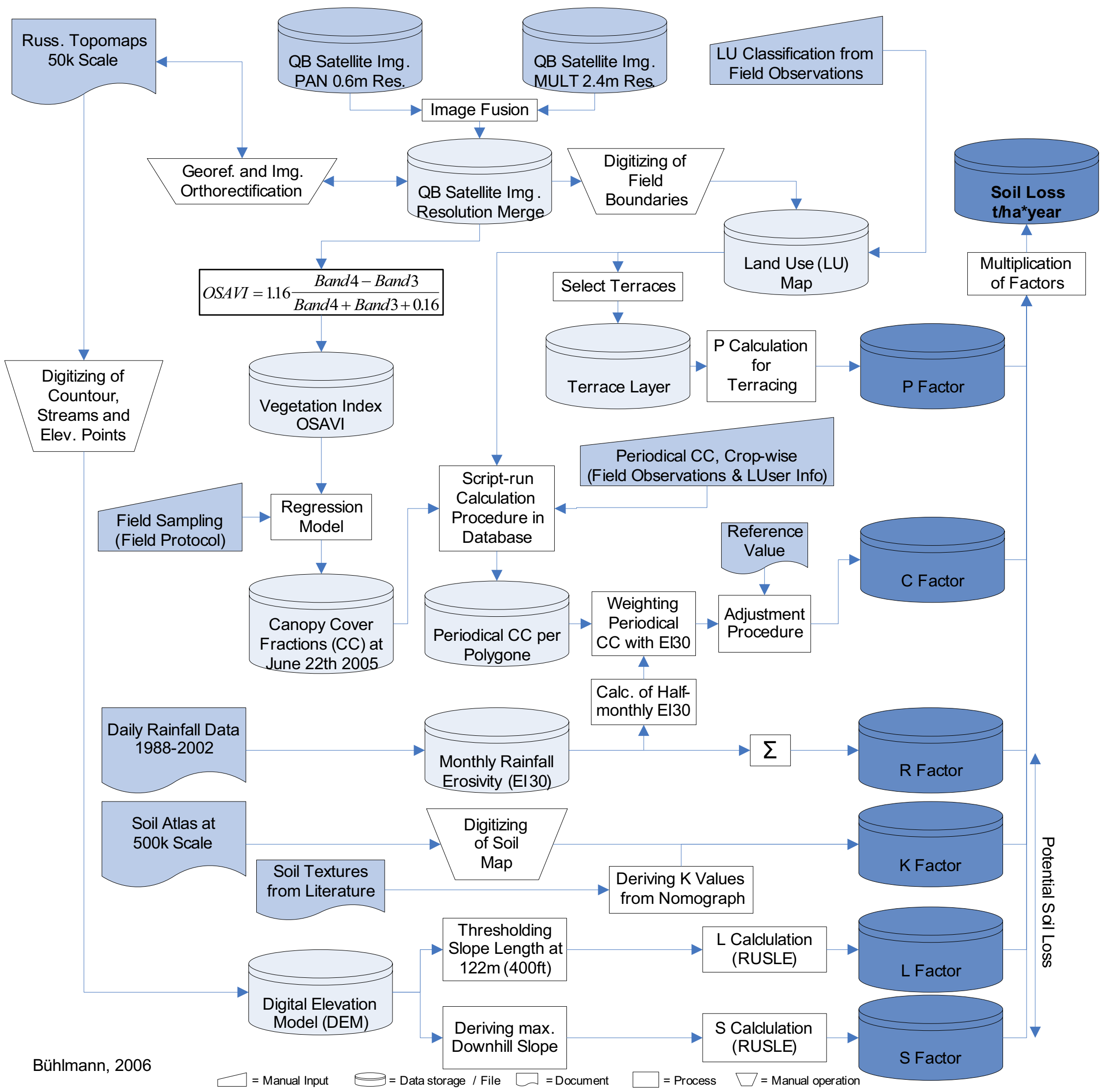


Figure 5: Overview of model inputs and the factor calculation procedure: factors and model output are displayed in deep blue, model inputs in medium tone, intermediate steps in light blue

The ecological condition, known as potential soil loss is expressed as a product of the following factors: rainfall erosivity *R*, soil erodibility *K*, slope length *L* and slope steepness *S*. Potential soil loss is reduced to predicted annual soil loss by multiplication with factors *C* (crop management) and *P* (support practice).

2.6.1 Rainfall and Runoff Factor *R*

The rainfall-runoff erosivity factor *R* of the RUSLE is generally recognized as one of the best parameters for prediction of raindrop impact and therefore of the potential transport capabilities of runoff generated by erosive rainstorms (De Santos and De Azevedo, 2001; Early et al., 2003; Laflen, 2002). Various empirical and physical models predicting rainfall erosivity were assessed by Van Dijk et al. (2002). The authors found that only fourteen out of the 23 equations predicted total kinetic energy within 10% of the measurements. The predictions by the USLE and the RUSLE were within these margins; the two models performed equally well. With more than 30 years of measurements in many States, Wischmeier and Smith (1972) proved that soil losses from cultivated fields are directly proportional to the total storm energy (E) times the maximum 30-minutes intensity (I_{30}) of a rainfall event. The accurate computation of each storm rainfall erosivity (EI_{30}) calls for high resolution rainfall measurements on a small time step. Generally, this kind of record is not available, particularly over the large periods recommended for *R* factor calculation. To circumvent these data limitations, various authors, e.g. Cohen et al. (2005) for Kenya, Schwertmann (1987) for Bavaria and Sonder (2002) for Colombia, established relationships between annual rainfall or the Modified Fournier Index (MFI) and *R*. However, using annual precipitation to compute the *R* factor ignores regional seasonality. Seasonal effects are considered to be crucial in determining annual soil loss rates for a region as Faizabad with a great variability in rainfall throughout the year.

In order to take into account seasonal fluctuations of rainfall erosivity, EI_{30} values were estimated following an approach of Mannaerts and Gabriel (2000). A daily database from January 1988 until December 2002 was created with rainfall parameter $rain_{10}$ (amount of rainfall for days with precipitation $\geq$ 10.0 mm) and an estimated average storm duration as second independent predictor variable. The maximum 30-minute intensity of a rainfall event (I_{30}) was predicted, dividing $rain_{10}$ by estimated average storm durations. For months January-March and October-November, average storm duration was assumed to be 3 hours; for April and September and average of 2 hours was assumed. In May-August very high rainfall intensities were observed. Since precipitation during these months exclusively falls during air mass thunderstorms, an average storm duration of 1 hour is suggested. The estimates of average monthly storm duration are based on field observations and farmer-information and proved to be consistent with figures from areas with similar climatic conditions (e.g. Hevesi et al., 2003; Lebel and Amani, 1999; Marai, 2003). Calculating rainfall intensities, the assumption was made that two third of the total precipitation of a storm event fall during half of its duration.

The kinetic energy of a given amount of rain depends on the sizes and terminal velocities of the raindrops which are related to rainfall intensity (Renard et al., 1997). Unit energy was calculated according to an energy-intensity-relationship proposed in the RUSLE. It determines the energy of rain fall (e_m) for a short interval within a rainstorm event in which rainfall intensity is assumed to remain constant,

$$e_m = 0.29\left[1 - 0.72\exp\left(-0.05 i_m\right)\right]$$

where e_m has units of MJ/ha*mm of rain and i_m is rainfall intensity and has units of mm/h. Total storm energy E was then calculated by summing up the e_m values of a rainstorm. The fifteen year average of monthly rainfall erosivity ($EI_{30,month}$) is the sum of computed EI_{30} values for all rain periods within that time. Thus

$$R = \sum EI_{30}\left(10^{-1}\right)$$

where R = average annual rainfall erosivity in MJ*mm/ha*h (Renard et al., 1997). Smooth half-month values were calculated to be included in the computation of the time-varying crop and management factor C which requires weighting with 24 seasonal EI_{30} values:

$$P_1 = M\left(\frac{0.75(M-1)+0.25(M+1)}{(M-1)+(M+1)}\right)$$

$$P_2 = M\left(\frac{0.25(M-1)+0.75(M+1)}{(M-1)+(M+1)}\right)$$

M, (M-1 and (M+1), which are monthly values for the month of interest (M), the previous month (M-1) and the subsequent month (M+1). P_1 and P_2 are calculated values of the variable for the first and second half-month periods in the month, leaving the sum of the two period rainfalls equal to the monthly rainfall (Renard et al., 1997).

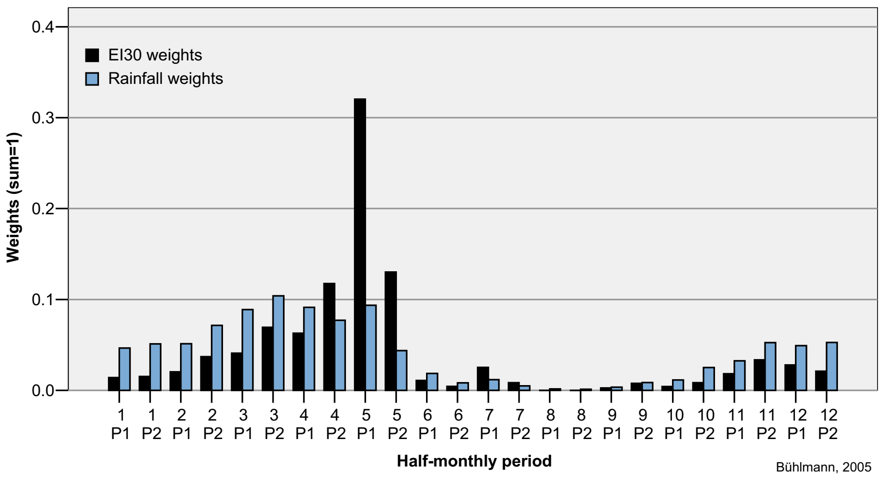


Figure 6: Rainfall erosivity (EI_{30}) weights in comparison to weights of average rainfall per half-monthly time interval (P_1 and P_2)

With the proposed method an average annual R factor of 244.1 MJ*mm/ha*h was predicted for Faizabad. The obtained R factor corresponds with an R value of 277.9 MJ*mm/ha*h derived for this dataset using a direct regression relationship between average annual rainfall and the R factor by Renard and Freimund (1994) which was based on measurement data of 155 stations in the United States. Yang et al. (2003) and Zhang et al. (2005) proved the validity of this regression to be applied on a global scale. Hurni (1985) showed that monthly EI_{30} correlates fairly good with monthly rainfall in the Ethiopian highland (r = 0.88). The relationship between the monthly EI_{30} and monthly rainfall amounts in Faizabad (monthly EI_{30} = 0.35*monthly rainfall) corresponds with observed relationships in areas with similar climatic characteristics.

2.6.2 Soil Erodibility Factor *K*

The soil erodibility factor *K*, in both the USLE and the RUSLE, is a quantitative value which is a function of soil properties, such as particle size distribution, organic matter content, structure and permeability. Wischmeier and Smith (1978) recommend computation of the *K* factor using their soil erodibility nomograph. Parysow et al. (2003) and Kirkby (2001) stated that in some cases the traditional approach for estimating soil erodibility did not account for spatial variability of individual soil properties. However, in tests against measured *K* values, only 5 percent of the nomograph solutions differed from the measure *K* values by more than 0.04 percent (Wischmeier and Smith, 1978).

Figure 7: Spatial distribution of soil types in the study area digitized from a 500k soil atlas
Soil data: Academy of Science Tajikistan, 1984 (Atlas of Natural Resources)
Contour lines: Russian Military Topographic Map, 1983
Map background: DigitalGlobe, 2005 (Quickbird satellite image, 0.6m resolution)

Spatial distribution of soil classes in Faizabad was obtained from the Atlas of Natural Resources in a scale 1:500,000 (Academy of Science Tajikistan, 1984). Two main soil classes, *Calcareous Montane Brown Soils* and *Typical Montane Brown Soils*, were documented within the area of interest, both formed after loess deposition. Kuteminskij and Leonteva (1966) and

Jakutilov et al. (1963) analysed the texture and organic matter content of these soil types in Faizabad taking samples from soils facing different degrees of erosion (see Appendix 4 for details on soil properties). Entering texture classes in the nomograph,

$$K = 2.77 * 10^{-6} * M^{1.14} * (12 - OS) + 0.043 * (A - 2) + 0.033 * (4 - D)$$

where M = (%silt + very fine sand) * (%silt + sand), OS = %organic matter, A = soil structure, and D = permeability, an erodibility factor *K* of 0.37 for *Typical Montane Brown Soils* was determined. *Calcareous Montane Brown Soils* are thought to be slightly more erodible with *K* = 0.42. These results are consistent with findings of Schwertmann (1987) who calculated *K* values of between 0.35 and 0.5 for loess brow soils in Bavaria.

2.6.3 Topographic Factor *LS*

In the RUSLE, the effect of topography on erosion is accounted for by the *LS* factor. The slope length factor *L* is defined as the distance from the source of runoff to the point where either deposition begins or runoff enters a well defined channel that may be part of a drainage network or a constructed channel. The slope steepness factor *S* reflects the influence of slope steepness on erosion (Wischmeier and Smith, 1978). The influence of slope steepness on erosion rate differs for rill and interrill conditions, since rill erosion increases substantially more with increasing inclination than interrill erosion (Renard and Freimund, 1994). Combining the two erosion processes into single data sets, as done in the USLE, led to serious overestimation (see Figure 8) of the effect of slope gradient on erosion rate (Fox and Bryan, 1999). New equations were developed in the RUSLE using distinct slope relationships for different conditions (Renard et al., 1997).

A DEM dataset was used as input in an AML (Arc Macro Language) script by Van Remortel and Martin (2003) which was developed to obtain more accurate *LS* factor values. The *LS* calculation algorithm is based on the RUSLE research of Renard et al. (1997) which corrects slope length for horizontal projection.

Slope Length Factor *L*. The AML script calculates slope length from high points (e.g. ridge tops) towards low points such as the watershed pour point or other outlet while considering both, areas of deposition and converging flows (Van Remortel and Martin, 2003). The slope length calculated by the model ranged from 2.5 to 1295 metres with a mean of 46 metres. Overland flow paths seldom exceed 400 ft (122 metres) due to the interception of natural depressions, flat areas or ditch construction (Renard et al., 1997; Lin et al., 2002; Shiono et al., 2002). Hence, a threshold value of 122 metres was introduced for slope length. The corrected values were averaged for each field and served as input in the slope length factor *L* equation. Plot data have shown that average erosion for the slope length λ (in metres) varies as:

$$L = (\lambda / 22.13)^m$$

where 22.13 equals the RUSLE unit plot length in metres and m = a variable slope-length exponent. The slope length λ is the horizontal projection, not the distance to the soil surface. The slope-length exponent m is related to the ratio β of rill erosion to interrill erosion:

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

while values for the ratio β are computed as follows:

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

where Θ is the slope angle (Renard et al, 1997).

Slope Steepness Factor *S*. Dunn and Hickey (1998) state that the effects of slopes algorithms on slope angle estimation and resulting erosion predictions can vary greatly in accuracy. The AML script addresses overestimation of overall slope angle estimates. The maximum slope angle calculation method, used for instance in the *slope function* in ArcGIS (ESRI, 2005) is replaced by a function which constrains slope angles to the downhill direction (Hickey, 2000). The slope steepness factor was then calculated using the two equations below which are strongly supported by experimental data (Renard et al., 1997).

$$S = 10.8\sin\Theta + 0.03 \qquad s < 9\%$$

$$S = 16.8\sin\Theta - 0.5 \qquad s \geq 9\%$$

where Θ = slope angle and s = slope in percent

The obtained *S* factors are displayed and compared with other calculation methods in Figure 8.

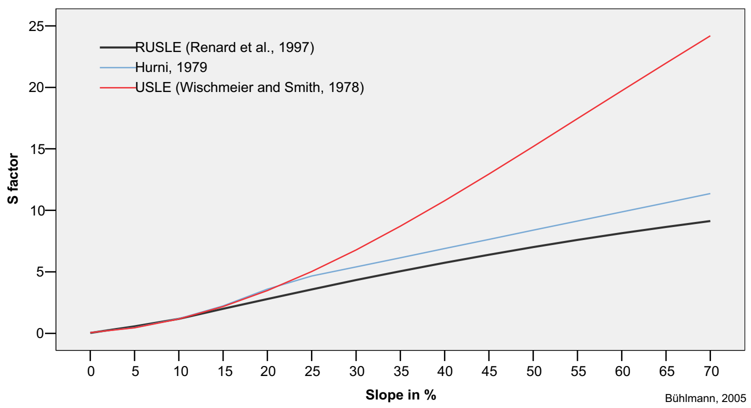


Figure 8: Slope steepness factor (S) computations using different equations

Hurni (1979) calibrated *S* values of Wischmeier et al. (1958) for slopes between 22% and 56% in Ethiopia using runoff plot data. The slope factors calculated by using this method are comparable to the ones computed using the model by Renard et al. (1997). The *S* values computed by the AML script (see *S* values of RUSLE) are slightly lower than those predicted by Hurni (1979), hence, there is no risk of overestimating soil loss at steep slopes.

2.6.4 Crop and Management Factor *C*

The *C* factor is used within RUSLE to reflect the effect of cropping and management practices on erosion rates. Parameters are (i) the impacts of previous cropping and management, (ii) the protection of the soil surface by vegetative canopy, (iii) the reduction in erosion due to surface cover and surface roughness and (iv) in some cases the impact of soil moisture on runoff from low-intensity rainfall. An individual Soil Loss Ratio (SLR) is calculated for each half-monthly time period over which the important parameters can be assumed to remain constant. Each of these SLR values is then weighted by the fraction of rainfall and runoff erosivity (EI_{30}) associated with the corresponding time period. The weighted values are then combined into an overall *C* factor value (Renard et al. 1997). By definition, under standard fallow conditions annual *C* equals 1. As surface cover is added to the soil, the *C* factor value approaches zero. For instance, a *C* factor of 0.15 means that 15% of the amount of erosion will occur compared to continuous fallow conditions (Kesley and Johnson, 2003).

Many authors state that data necessary to calculate the SLR subfactors, as proposed in the RUSLE, are usually not available. Various alternative methods to approximate *C* factor values were developed. Cohen et al. (2005) and Lee (2003) mapped the *C* factor indirectly through vegetation classification which bares the risk that classification errors are introduced into the *C* factor map. Furthermore, the assignment of average *C* factor values to each vegetation type leads to smoothing of estimates and disappearance of spatial heterogeneity and variability (Wang et al., 2002). Lin et al. (2002) as well as Van Leeuwen and Sammons (2004) established linear and polynomial relationships between the *C* factor values and the Normalised Difference Vegetation Index (NDVI) from satellite image data.

In this study, the *C* factor was derived focussing on the impact of plant cover on soil erosion which is expressed best in the canopy cover subfactor (CC) of the RUSLE. Average canopy cover was determined for each field plot using a polynomial relationship between canopy cover fractions and the Optimised Soil-Adjusted Vegetation Index (OSAVI). The effect of interception of rainfall by canopy, which is considered by the canopy-droplet-fall-height in the RUSLE CC subfactor, is extremely variable and thus difficult to predict (Bussière et al., 2002; Crockford and Richardson, 2000). Hence, interception effects were not incorporated in the calculation. The obtained canopy cover fractions subsequently served as input in the RUSLE CC subfactor equation. The results obtained were then adjusted to *C* factors experienced in similar agronomic conditions (see below). To take into account the seasonal variability of the *C* factor, it is essential to consider the plant grown on each field polygon. For this reason, a land use map of the study area was created based on visual land use classification conducted in the field. Visual classification reduces the risk of classification mistakes in comparison to ordinary approaches which classify land use from satellite imagery. This may ultimately result in greater accuracy of *C* values.

Canopy Cover from Satellite Image. Various authors describe procedures to derive canopy cover fractions from multispectral satellite imagery. Witztum and Stow (2004) derived bare ground fractions from the red band alone, reaching agreements of r^2=0.55 with field measurements. Mutanga and Skidmore (2004), Lawrence and Ripple (1998), Leprieur et al. (2000), Steven et al. (2003) and Rondeaux et al. (1996) investigated the sensitivity of different vegetation indices to soil colour and vegetation properties. They recommend to use either NDVI or OSAVI for vegetation mapping with agricultural objectives. In this study, the OSAVI and the

NDVI performed equally well (r^2=0.6799 versus r^2=0.6792). Since soil adjusted vegetation indices proved to reduce soil noise over the full range of canopy covers (Rondeaux et al., 1996), the OSAVI was chosen to determine average canopy cover per field. Soil adjusted vegetation indices are, as is the NDVI, ratio-based indexes derived from near-infrared and red spectral responses. They incorporate an adjustment factor, based on canopy cover observed in the area of interest ranging from 0 (for densely vegetated areas) to 1 (for sparsely vegetated areas). An approach to optimise the adjustment factor for general applications resulted in a recommended adjustment factor of 0.16. Hence, OSAVI is calculated as follows:

$$OSAVI = 1.16 \frac{Band4 - Band3}{Band4 + Band3 + 0.16}$$

where Band 3 covers the red spectrum and Band 4 the near-infrared spectrum (Lawrence and Ripple, 1998).

The established regression relationship between canopy cover observed in the field and calculated OSAVI value per field plot is shown in Figure 9.

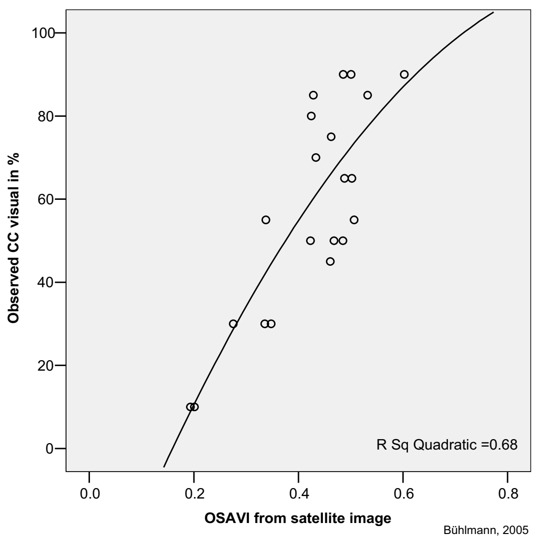


Figure 9: Quadratic regression between observed canopy cover in the field (CC visual) and the optimised soil-adjusted vegetation index (OSAVI); regression equation: $y = -151.73x^2 + 312.44x - 45.88$

The relatively equal distribution of the scatters may ensure high reliability of the regression model even though only few ground truth measurements for very low canopy cover and bare ground plots were sampled in the field. The calculated canopy cover values ranged from –13.2 to 102.6 with 19 negative values and one value above 100. Negative values were replaced with 0, whilst values above 100 were set to 100. The fact that only 20 values (1.1% out of 1808) were outside the percentage range and the relatively high correlation coefficient of 0.68 indicate that the canopy cover estimates are applicable. The obtained canopy cover estimates are displayed per land use class in Figure 10.

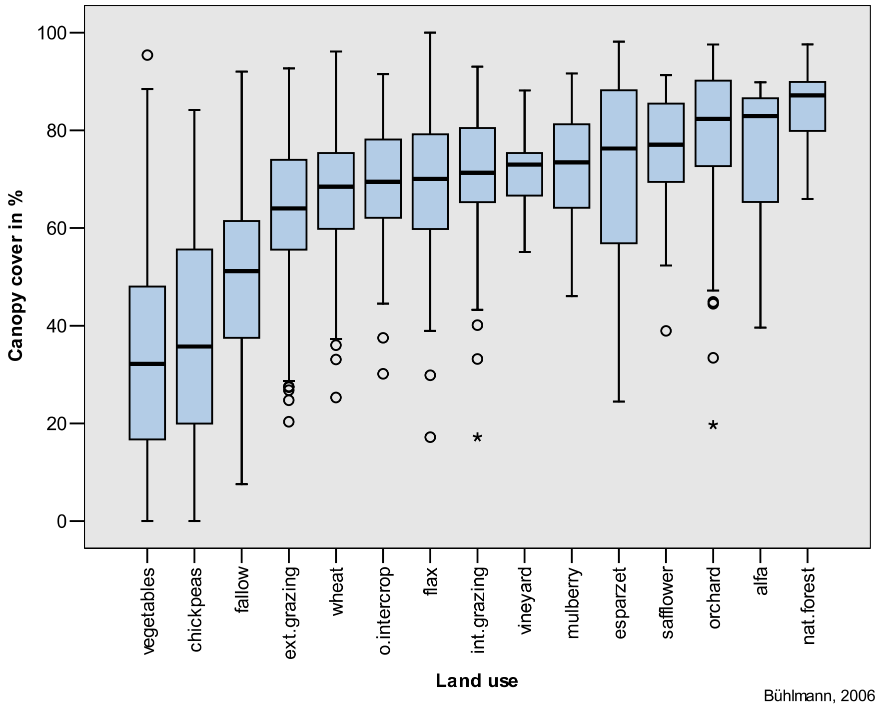


Figure 10: Boxplot showing percentage canopy cover per land use type at the stage of maximum vegetation height (June 22nd 2005): percentage canopy cover is estimated from a regression model established between field measurements and OSAVI

The boxplot shows that the median for vegetables, chickpeas and fallow/abandoned land is lowest whereas orchards, alfa-alfa and forest lands constitute the highest. The greatest variance is observed for vegetables which is due to the heterogeneity of this class. Some vegetable plots were tilled just before the satellite image was taken, which explains the high bare ground fractions in this category. The low canopy cover fractions on chickpea fields are more difficult to interpret: chickpea fields are cultivated at the end of April and are thus expected to be at a maximum stage of vegetation height at the time the satellite picture was taken. Field observations revealed that chickpeas alone account only for a small share of a field's overall canopy cover, while the contribution of weeds within chickpea fields is far higher.

The Quickbird satellite image was taken 22nd of June 2005, which is considered to be around the stage of maximum vegetation height for most crops. Solely haymaking of intensive grazing land and alfa-alfa and esparzet fields had begun before the satellite image was taken. This explains the rather great variances in canopy cover and the unexpectedly low median for intensive grazing land. Before haymaking activities had started, much higher canopy cover fractions were observed for intensive grazing land than for extensive grazing land.

Calculation Procedure. Since no high resolution satellite imagery was available for other time periods, annual canopy cover fractions had to be calculated using estimates of seasonal canopy cover ratios based on field observations. The canopy cover subfactor for the stage of maximum vegetation height (CC_{max}) can be expressed as

$$CC_{\max} = 1 - F_{c,\max}$$

where $F_{c,max}$ is the canopy cover fraction at the stage of maximum vegetation height. Hence, CC subfactors for each half-monthly period (i) can be expressed as

$$CC_i = 1 - F_{c,\max} * c_{i,crop}$$

where $c_{i,crop}$ is the seasonal ratio of $F_{c,max}$ for each crop or land use (Renard et al., 1997).

Arsenault and Bonn (2005), Auerswald (2002) and Greene and Hairsine (2004) consider the impact of crop residues on soil erosion to be significant. Crop residues remaining on the field after harvesting are incorporated in the *C* factor calculation through the periodical canopy cover ratio ($c_{i,crop}$). The obtained seasonal canopy cover fractions ($F_{c,max}$ * $c_{i,\ crop}$) are averaged and displayed per land use type in Figure 11. The seasonal canopy cover fraction of an average wheat field, for instance, reaches its maximum stage of 0.68 in mid-June (average $F_{c,max}$). After harvesting, farmers remove the straw from the field; the remaining stubbles were found to account for around 35% of $F_{c,max}$. In early November wheat fields in Faizabad are tilled and winter wheat is sawn again. For a few weeks the canopy cover fraction remains close to zero, before the freshly sawn wheat germinates. The thin cover remains during winter and augments rapidly in April as spring temperatures boost plant growth.

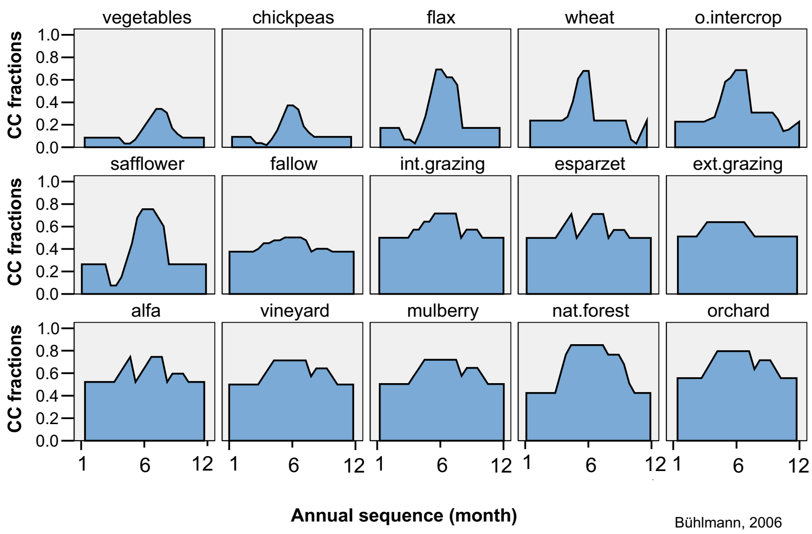


Figure 11: Average periodical canopy cover (CC) fractions per crop and land use type

On harvested wheat and safflower fields, residue cover was found to account 35% of the cover observed during the stage of maximum vegetation height ($F_{c,max}$). Much thinner residue covers were observed on vegetable, chickpea and flax fields. Many farmers cultivate wheat in autumn (winter wheat) leaving recently tilled annual cropland vulnerable to rain storms and snow melting. After ploughing activities, canopy cover fractions drop close to zero on annual cropland. A rapid increase is observed in April and May, marking the main growing period of

Faizabad's rain-fed agricultural system. Intensive grazing land experiences an abrupt decrease in canopy cover after haymaking; esparzet and alfa-alfa field plot, showing two major peaks, are usually harvested twice a year. Canopy cover drops a third time on these fields after being grazed by animals. Similar effects are observed for vineyards, mulberry groves and orchards, since grass between the trees is typically used for haymaking. After fruit harvest in autumn, many farmers let their animals graze in their three/shrub cropping systems.

For each field plot, periodical CC values were computed and weighted by the fraction of rainfall and runoff erosivity (EI_{30}) associated with the corresponding half-month (see section 2.6.1) and summed up to an annual CC subfactor. In a database program, script-run calculation procedures had to be established to process the extensive data volume. Finally, the computed CC subfactors were brought to a level of *C* factors experienced in the Ethiopian Highlands, where land is cultivated under similar physical and agronomic conditions. Wheat was used as reference crop for which an average annual *C* factor of 0.15 was derived by Hurni (1985). During the adjustment procedure, all proportions were kept. Figure 12 shows averages of computed *C* factor values summarised per land use type in comparison to average annual canopy cover fractions.

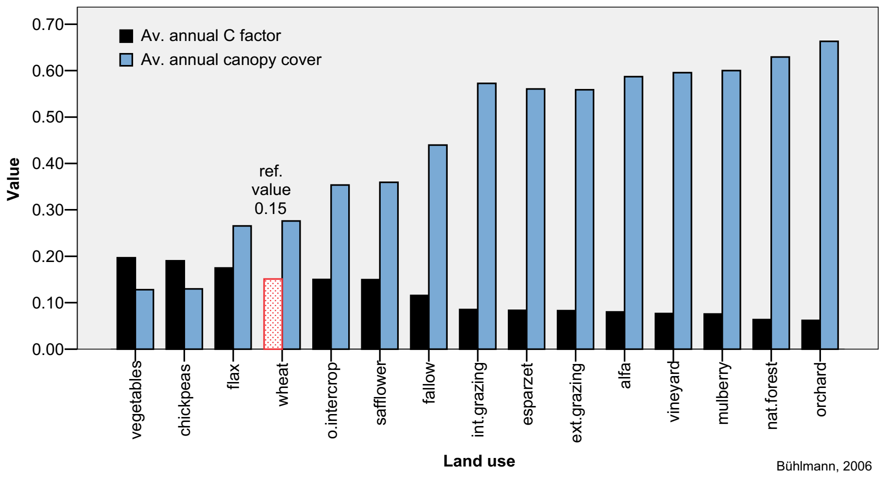


Figure 12: Average annual C values adjusted to the reference value for wheat (0.15) in comparison to average annual canopy cover fractions per land use type

As expected, annual cropland (vegetables, chickpeas, flax, wheat, safflower) have lower *C* factors than perennial herbaceous fodder plants, tree cropping and grazing land. Annual cropland is ploughed at least once a year and often experiences thin canopy cover during months of high rainfall erosivity. Permanent cover on perennial and tree/shrub cropland and the grass cover on grazing land protect the soil from eroding during heavy rainstorms in spring.

The advantage of the proposed method is that every field plot has its own *C* factor depending on its canopy cover at the maximum stage of vegetation height and according to the crop specific seasonal fluctuations. This means that a sparsely vegetated vegetable or chickpea field has a much higher *C* factor than a densely vegetated field plot of the same land use. Hence, assessing canopy cover based on analysis of high resolution satellite images is expected to result in much more differentiated and accurate erosion estimates in comparison to models assigning *C* factors through land use classification.

2.6.5 Support Practice Factor *P*

The *P* factor accounts for control practices that reduce the erosion potential of runoff by their influence on drainage patterns, runoff concentration, runoff velocity and hydraulic forces on soil. The supporting mechanical practices include contouring (tillage and planting on the contour), terracing, establishing strips of close-growing vegetation, subsurface drainage, diversions and other soil-management practices orientated on or near the contour. These practices result in the collection and storage of moisture and reduction of runoff (Renard et al., 1997). Sonneveld and Nearing (2003) stated that values for *P* are generally difficult to determine and proved in their nonparametric/parametric analysis that the support practice factor is the least robust and reliable of all RUSLE factors. Many authors run the RUSLE model with an undifferentiated *P* value ($P = 1$) assuming that no erosion support practices are applied within their area of interest (e.g. Cambazoglu and Gögüs, 2004; Hoyos, 2005; Millward and Mersey, 1999; Renschler et al., 1998; Reusing et al., 2000; Rosewell, 1997; Van Leeuwen and Sammons, 2004).

In order to assign *P* values representing current conservation practices, spatial distribution of terraced fields was derived from high resolution satellite images. The observed contemporary agricultural practices in Faizabad consist mainly of up and down tillage. Since no SWC is practised on the large majority of the fields within the study area, support practice factor *P* was assumed to be 1 for all non-terraced fields. The soil loss reducing effect of intersecting buffer strips, vegetated filter strips and ditches established between fields on soil erosion is accounted for in the calculation of the *LS* factor: slope length was set to a maximum of 400ft (122 metres), under the assumption that surface runoff will be redirected or will concentrate in water carriers after less than 400 ft.

Terraces reduce sheet and rill erosion on the terrace interval by breaking the slope into shorter slope lengths. Properly designed terraces and outlet channels collect surface runoff and convey it off the field at nonerosive velocities. Deposition along the terraces may also trap much of the sediment eroded from the interterrace interval, particularly if the terraces are levelled and include closed outlets, have underground outlets or have a very low grade. Deposited sediment remains on the field and is redistributed over a significant portion of the field, thus reducing soil deterioration caused by erosion (Renard et al., 1997). While sole adjustment of slope steepness and slope length for terraced fields does neglect the effect of interterrace sections, the additional *P* factor for terraces used in conservation planning considers both the benefit of deposition and the amount of sediment deposited. The net soil loss is the soil loss on the interterrace surface minus the amount of deposited soil. Deposited soil is credited as helping to maintain the soil resource by retaining the soil on the terrace (Galetovic, 1998).

To represent the specific situation in the study area, the following model settings were selected: The average terrace in the test area was found to have a horizontal interval of approximately 10 metres which fulfils the criterion for the maximum benefit (< 33.5 metres). Mainly closed outlets were observed within the test area which results in a *P* factor of 0.5 for an average terrace, according to Table 6-15 in Rendard et al. (1997). In the adjusted RUSLE model of this study, the *P* factor for terracing is applied in combination with a reduced slope gradient of 5% and with the threshold for slope length of terraced areas set to 10 metres. The predicted impact of locally emerged SWC practices on soil erosion is displayed and discussed in section 3.5.

3 RESULTS AND DISCUSSION

3.1 Land Use Map

Information on spatial distribution of land use is an important input for C factor calculation and scenario computation. The land use map (Figure 13) is based on visual classification as described in section 2.3. To get an overview, only main land use categories are displayed.

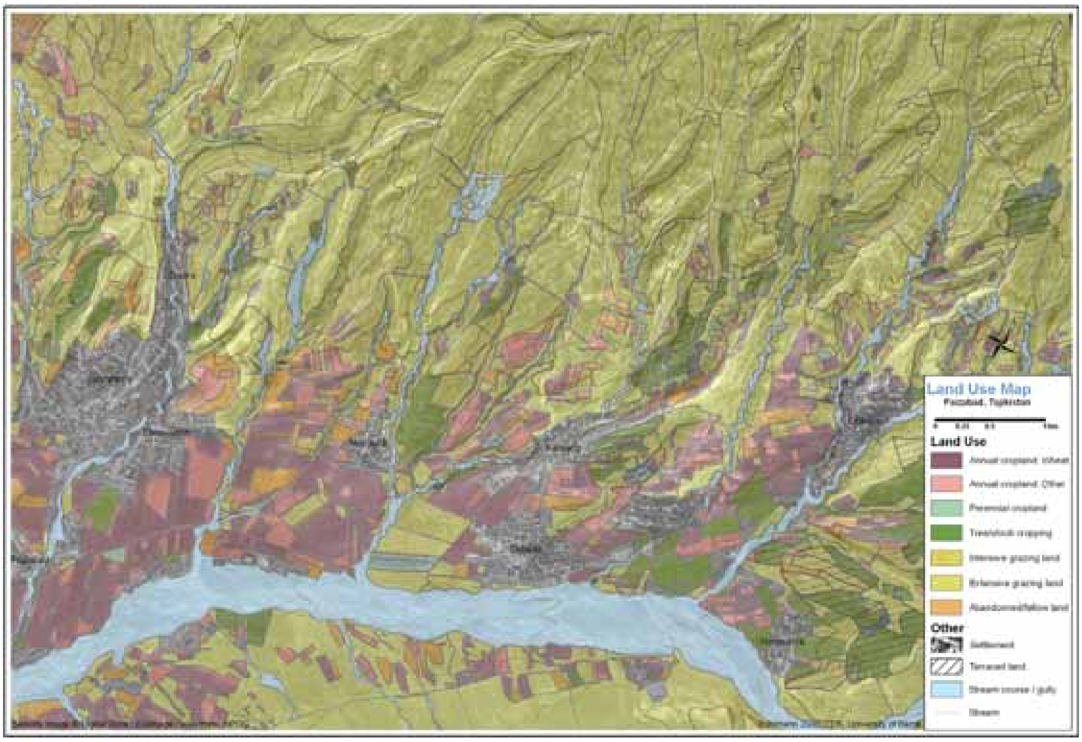


Figure 13: Land use map displaying main land use categories within the study area (for full extent and more detailed land use information consult the A0-format Land Use Map in Appendix 5) Contour lines: Russian Military Topographic Map, 1983 Map background: DigitalGlobe, 2005 (Quickbird satellite image, 0.6m resolution)

The study area comprises of 1202 crop fields covering 1581 ha (16% of the study area) and 534 polygons of grazing land, generated per homogeneous hill slope section, covering 70% of the study area. The remaining 14% of the study area is mainly covered by settlements and river beds. The main food crop in the study area is wheat (accounting for 60% of the annual cropland in the study area). Wheat serves as staple food in rural families and is usually cultivated on field plots considered the most fertile of the farm. Furthermore, peasants cultivate chickpeas, which can be found in many traditional dishes, and flax, which is used for oil production, comprising each between 6 and 7% of the total annual cropland. Most irrigated vegetable land, covering 17% of the total annual cropland, is cultivated by state farms.

3.2 Predicted Soil Loss under Current Conditions

3.2.1 Analysis of Model Outputs

The factors described above were determined for each polygon and saved as attributes in an ArcGIS Layer. Subsequently, the average (spatial and temporal) annual erosion *A* expected on these field slopes was computed by multiplying these factors plot-wise. An average soil loss rate of 79.2 t/ha*year was obtained for the study area. Average values for the main land use classes ranged from 27.3 t/ha*year (tree/shrub cropping) to 89 t/ha*year (grazing land). The predicted average annual soil loss for cropland was predicted at 33.3 t/ha. The spatial distribution of the model outputs is displayed in the Erosion Risk Map in Figure 14. The range of soil loss values for the erosion rate categories was: very low (1.4-5 t/ha*year), low (5-10 t/ha*year), moderate (10-30 t/ha*year), high (30-50 t/ha*year) and very high (>50 t/ha*year).

Figure 14: Map of predicted current annual soil loss within the study area (for full extent and higher spatial resolution consult the A0-format erosion risk and Erosion Risk Map in Appendix 5) Contour lines: Russian Military Topographic Map, 1983 Map background: DigitalGlobe, 2005 (Quickbird satellite image, 0.6m resolution)

Figure 14 shows that the spatial extent of *high* to *very high* erosion rate categories occupies about 35% of the cropland area and 82% of the total study area. Areas with *very high* erosion risk are mainly located in the steep hill slopes in the upper part of the study area, which are usually grazed. The rather great spatial extent of the *moderate*, *high* and *very high* erosion risk zones emphasises the urgent need for conservation in these areas.

Figure 15 focuses on the current soil erosion on cropland.

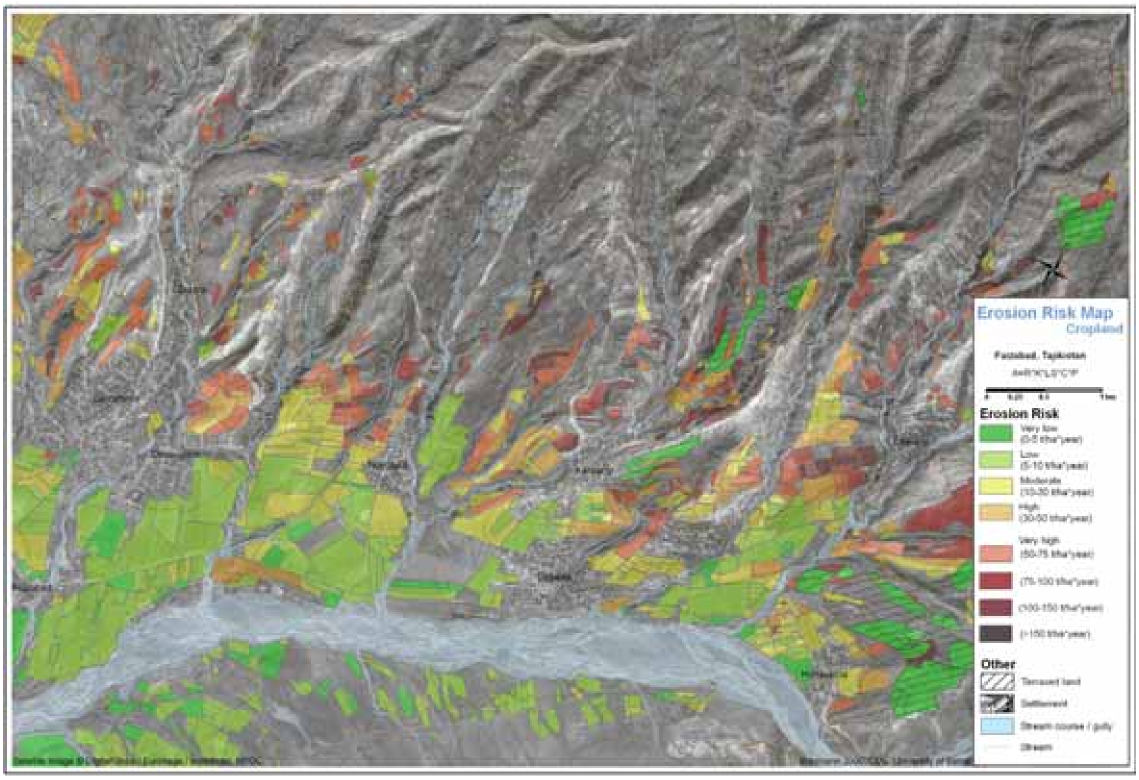


Figure 15: Map of predicted current annual soil loss on cropland
Contour lines: Russian Military Topographic Map, 1983
Map background: DigitalGlobe, 2005 (Quickbird satellite image, 0.6m resolution)

Cropland showing *low* to *moderate* erosion rates, is mainly located on the valley floor. Fields in the transition zone from the valley floor to the steep hill slopes are often exposed to *high* and *very high* erosion rates. Terraced land, for which *very low* erosion rates are predicted, and land on the valley floor are mainly cultivated by state farms, while sloping agricultural land is primarily rent to peasants. This indicates that land users in Faizabad do not share the burden of soil erosion equally. Hence, effective SWC technologies, which can be afforded and implemented by small-holders, need to be found.

Figure 16 indicates that current soil erosion rates are generally much higher on grazing land than on cropland (compare with Figure 15). However, the relatively large grassland area showing *very high* erosion rates is more likely a result of the extreme topography in which grazing land in Faizabad usually is located, rather than a purely land use related feature.

Figure 16: Map of predicted current annual soil loss on grazing land
Contour lines: Russian Military Topographic Map, 1983
Map background: DigitalGlobe, 2005 (Quickbird satellite image, 0.6m resolution)

In the area of Faizabad, extensive grazing land and haymaking plots (WOCAT classification: intensive grazing land) can often be found next to each other on the same hill slope. Analysis showed, furthermore, that average field slopes of these two land use types did not significantly differ from each other. Figure 16 indicates that grassland used for haymaking (dotted polygons) does show lower soil loss rates than extensive grazing land (grazed field plots). Pastures in Faizabad are often overgrazed and lack access control opportunities. Hence, the comparatively higher soil loss rates on grazed grassland in comparison to haymaking plots is most likely a consequence of poor canopy cover and braking of the soil surface by animal trampling. Particularly the fields along animal pathways (dashed lines) are in a bad condition, resulting in severe degradation of the soil resource.

Comparing intensive grazing land (haymaking plots) with close by cropland (see also Figure 15) reveals that a permanent and well managed grass cover is less vulnerable to erosion than cropland in a comparable physical environment. Hence it follows that for cropland, severely affected by soil erosion, a land use change to intensive grazing land may be an option. Land use related differences in erosion will be assessed in a more detailed way below.

Figure 17 illustrates the occurrence of soil erosion within different land use classes.

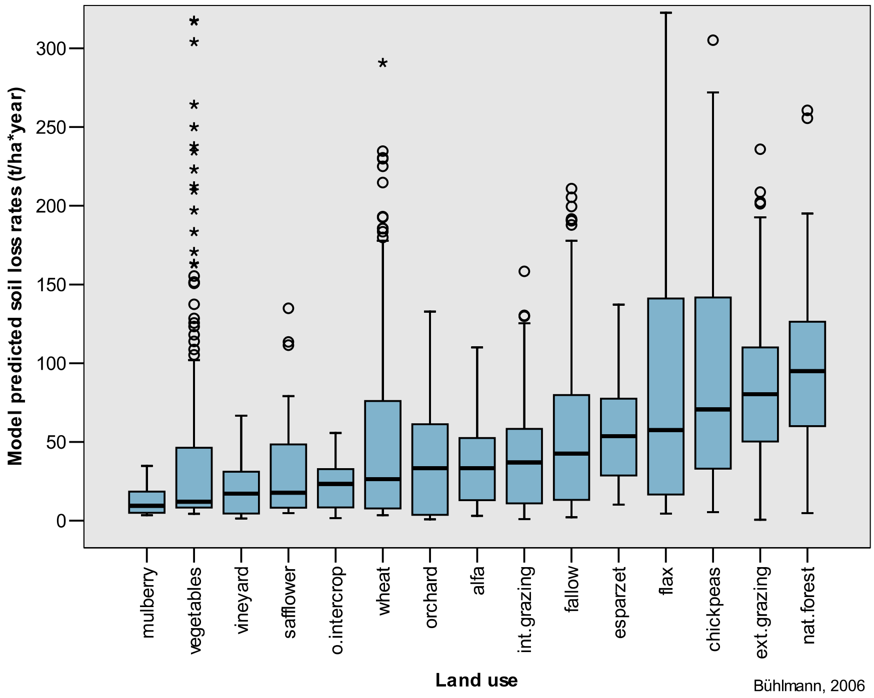


Figure 17: Boxplot showing annual soil loss per land use type, predicted by the RUSLE model

Ranking of the soil loss medians per land use category leads to rather unexpected results: the median for the land use class *vegetables,* which experienced the lowest canopy cover fractions and C factors (see Figure 12), shows the second smallest erosion rate. Moreover, wheat performs better than, for instance, perennial herbaceous fodder plants (alfa alfa and esparzet), grazing land and natural forest. These observations can be explained with the differences in location in which these land use classes are observed. While most vegetable fields are located on the plain valley floor, natural forests, for instance, are observed exclusively on very steep hill slopes where no other land use is possible. The incidence of soil erosion in relation to slope steepness is documented in the figures below.

Figure 18 shows study area wide erosion predictions per main land use category in relation to slope, while Figure 19 focuses on the occurrence of erosion on annual cropland.

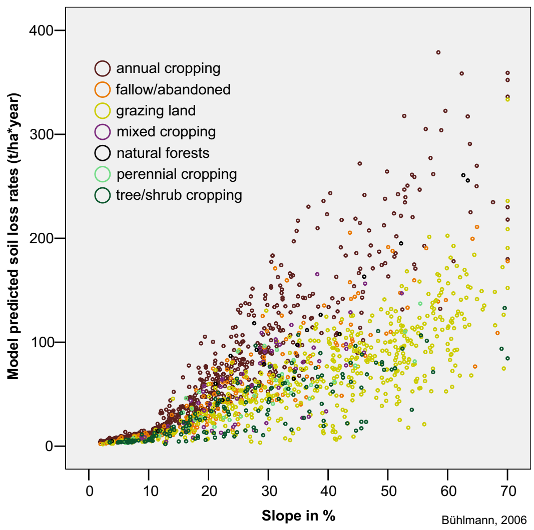


Figure 18: Predicted current soil loss within the study area in relation to slope steepness

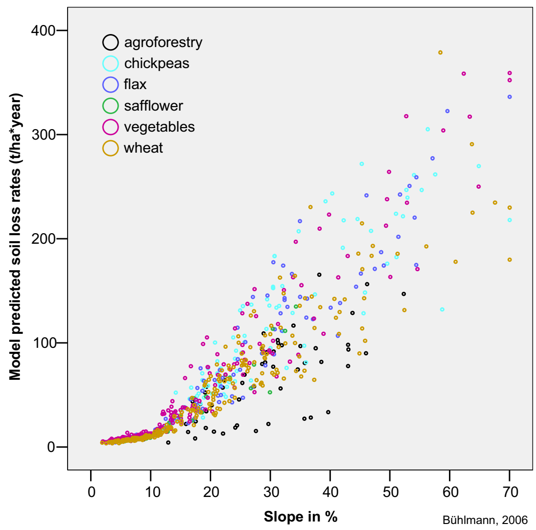


Figure 19: Predicted current soil loss rates for annual cropland in relation to slope steepness

The scatters in Figure 18 and Figure 19 represent the computed soil erosion rates per field in relation to slope. The scatter clouds (colours) mark the difference in soil loss between land use classes. Even though slope steepness is only one amongst many factors influencing soil erosion, its inclusion in the output figures helps to visualise disparities between crop and land use classes. Figure 18 demonstrates that soil loss on annual cropland is generally higher than on grazing land or perennial cropland. This phenomenon is found especially on slopes steeper than 12%. The distinct scatter-clouds observed with increasing slope steepness suggest that land use is a crucial factor especially on moderate to steep slopes. Even though fallow and abandoned land proved to have rather low canopy cover fractions at the stage of maximum vegetation height (see Figure 10), its permanent cover seems to be more effective reducing soil erosion than the temporally much higher cover fractions of wheat for instance. Tree and shrub cropping systems appear to be the best protection against erosion processes. However, since orchards coincide often with terraces, no definite conclusions can be drawn in this context. Figure 19 suggests that wheat protects the soil better from erosion in comparison to vegetables, chickpeas and flax. Intercropping of annual crops in orchard systems has the potential of reducing soil losses significantly. If the layout of intercropping systems is designed carefully, soil erosion may be virtually halted (black scatter cloud in Figure 19).

3.2.2 Reliability of the Model

Due to its modest data demands and transparent model structure, the (R)USLE remains the most popular tool for soil erosion risk assessment. However, the model has shortcomings which are likely to have prominent implication for the model's results. The mathematical form of the equation, the multiplication of six factors, easily leads to large errors whenever one of the input data is misspecified (Nearing, 1998; Sonneveld and Nearing, 2003). Hence, it should be stressed that absolute values provided by soil erosion models are merely estimations of soil loss and that conclusions drawn from soil erosion modelling should arise from relative comparison of estimations.

3.2.3 Comparison of Model Outputs with Rill Erosion Assessment Results

To assess the reliability of the absolute values predicted by the soil loss model applied in Faizabad, the model outputs were correlated with soil erosion rates derived from rill measurements. Although the number of samples, especially for fields with high soil erosion rates, is too small to allow definite interpretation, the scatter plot in Figure 20 indicates that the model may slightly over-predict erosion. However, since the measured rills may have replaced previous rill networks (see Figure 3), the ACED method may not account for the total annual linear erosion and, hence, may underestimate annual soil losses. In this light, the fairly good correlation observed, especially for erosion rates below 100 t/ha*year, implies that predicted soil erosion rates are reliable in most cases.

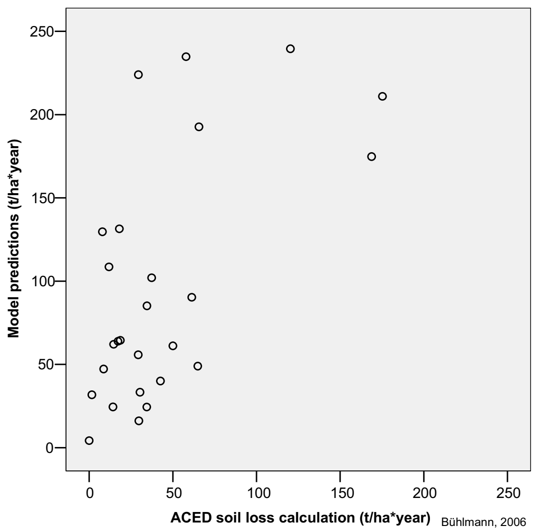


Figure 20: Erosion rates derived from the mapping method (ACED) versus model predictions of the RUSLE

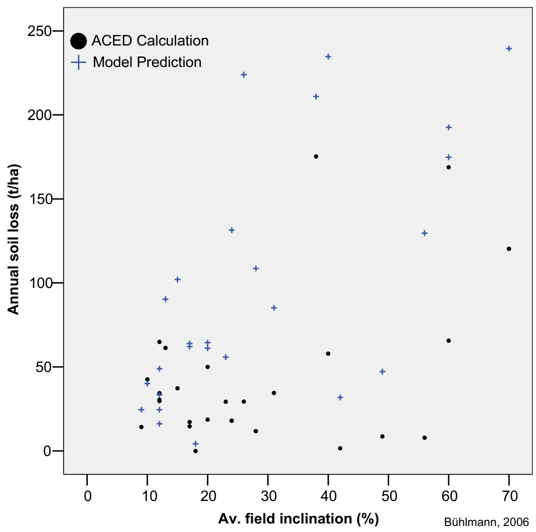


Figure 21: Erosion rates derived from the mapping method (ACED) versus model predictions of the RUSLE in relation to field slope

Figure 21 displays erosion rates obtained from rill mapping and model predictions in relation to average field inclination. Results from linear erosion assessment do not necessarily augment in accordance with increasing slope steepness as it is observed for the model predictions. This suggests that the model output relates much more to the slope than the mapped erosion does. However, since slope steepness is only one of many variables influencing soil erosion and the number of field samples is rather small, no definite conclusions can be drawn in this context.

3.3 Causes of Soil Erosion – an Evaluation of Field Sampling Data

This part of the study evaluates the information gathered from field sampling (method is described in section 2.4). Figure 22 provides an overview of field sampling sites within the study area.

Figure 22: Overview of SWC case studies and the fields assessed with the field protocol
Contour lines: Russian Military Topographic Map, 1983
Map background: DigitalGlobe, 2005 (Quickbird satellite image, 0.6m resolution)

Altogether 57 fields were mapped and evaluated and with the field protocol. The fields assessed are gathered around six case studies on SWC.

3.3.1 Categorising Primary Causes of Soil Erosion

Since soil erosion processes are highly complex, a broad range of features were included in the field protocol to be able to determine causes of soil erosion. These features are not always easy to distinguish from direct causes of erosion. However, the impact of a single feature or a combination of them can be so prominent that it can be called a cause (Herweg, 1996). Three categories of primary soil erosion causes were formed to which all gathered features could be assigned to: topographic, agricultural and off-site causes. For each of the 42 field plots experiencing linear erosion, the main reasons for soil erosion were determined and assigned to the according main categories. Thereby, three points were allocated to the most important cause; if applicable, two points and one point to the second and third cause respectively. The summed up scores, displayed in Figure 23, indicate the frequency and, hence, the importance of primary soil erosion causes.

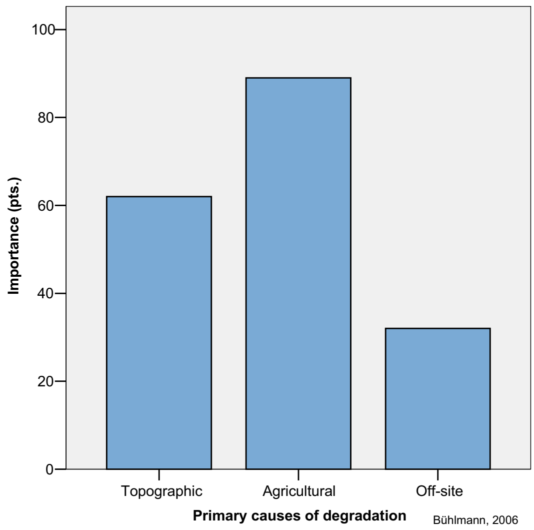


Figure 23: Primary causes of soil erosion and their importance based on qualitative assessment of field sampling data (assigning 3, 2 and 1 points according to the rank of importance)

Agricultural causes and topographic effects seem to be more often responsible for soil losses in the mapped fields than runon. This may be linked to the fact that on approximately two third of the mapped fields, SWC technologies were implemented, many of them preventing runon onto the field. Since far less SWC measures are observed elsewhere in the study area, off-site causes are expected to become more important if the study was extended to the entire study area. The rather high importance of agricultural causes suggests that the present situation may considerably improve by implementing cost extensive agronomic measures, such as cover cropping, mulching, contouring, contour cultivation, mixed cropping and annual establishment of drainage ditches. Where topographic effects or off-site causes dominate, often structural and vegetative measures are unavoidable to address the source of the problem.

3.3.2 Dependency of Field Sampling Variables and Soil Loss

The objective in this part of the study is to use multivariate statistics for partitioning the individual and joint variance contribution of soil loss rates derived from rill measurement data. All variables analysed are field measurements and were gathered with the field protocol. For analysis, six metric variables (field size, field length, inclination, slope length, canopy cover, topsoil compaction) and two nominal variables (presence of SWC technologies, presence of runon) were correlated with the dependent variable soil loss. The independent variables analysed for partial correlation were chosen using forward selection. The resulting individual percentage of contribution to the variance of soil erosion are shown in Table 1 below.

Table 1: Percent contribution of field protocol variables to soil loss (rill measurements) from multivariate statistical analysis

Independent variables	Contribution in %
Slope length	24.21
Inclination	7.78
Presence of runon	6.07
Canopy cover	6.03
Field position on slope	2.21
Field length (down slope)	1.85
Presence of SWC	0.99
Topsoil compaction	0.63
Field size	0.00005
Total	49.76

Individually, field size contributed the least (0.00005%), whereas slope length (24.21%), inclination (7.78%), presence of runon (6.07%) and canopy cover (6.03%) contributed the most to the soil loss rate variance. Examination of bivariate correlation coefficients between slope length and inclination with soil erosion (0.492 and 0.442) suggest that both variables contribute more or less equally to the soil loss rate variance (inclination alone would account for 19.54% of the total soil loss variance). The substantial difference in individual variance contribution can be explained with a high degree of observed multi-collinearity, i.e. the two variables correlate fairly well with each other. Since the Shapiro-Wilk test suggests normal distribution of the residues, one can conclude that solely the variables slope length and canopy cover significantly predict soil erosion. The relatively low effect of canopy cover on soil erosion seems surprising at first, however, it coincides with finding of Herweg and Stillhardt (1999) reporting high soil losses even on fields where the soil cover exceeded 70%. The explanation for the rather low contribution of SWC technologies can be found in the great heterogeneity of the applied measures and the strong dependency of their effectiveness on other variables. Altogether, the analysed variables contribute only to 49.76 percent of the total soil loss rate variance which indicates that soil erosion is an extremely complex process that cannot be expressed with the proposed variables alone. Furthermore, a sample of 26 examined fields may be too small to evaluate these relationships in appropriate depth.

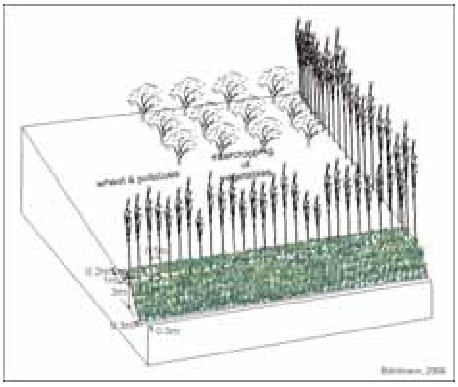
3.4 Case Studies on Local SWC Practices

Land degradation affects the livelihood of many farmers in the hill zone of western Tajikistan. Even though the severity of the problem is generally recognized among the land users, only a few farmers started implementing measures to overcome it. This section will focus on SWC technologies developed by local peasants which have the potential to be adopted by other land users in the area. Based on an analysis of the benefits, advantages and disadvantages, economic impacts, acceptance and adoption of the technology, propositions for amendments will be made. The impact of SWC technologies on soil erosion will be assessed in section 3.5.

3.4.1 Overview on SWC Case Studies

Each case study is documented by a short description containing information on layout, purpose, establishment and maintenance activities as well as a comparison of advantages and disadvantages. Design and technical specifications are illustrated with technical drawings, and are complemented with a picture giving an overview of the technology. Costs were calculated based on information given by the land user in interviews. The costs are expressed in US Dollar and incorporate virtual expenses for labour which were calculated on the basis of hired labour wages (3 USD per person per day). For more details on the conducted SWC case studies, see WOCAT four-page-summaries or browse the MS-Access-Database on the CD-ROM in Appendix 4 of this paper.

a) TERRACE WITH TREE BARRIER



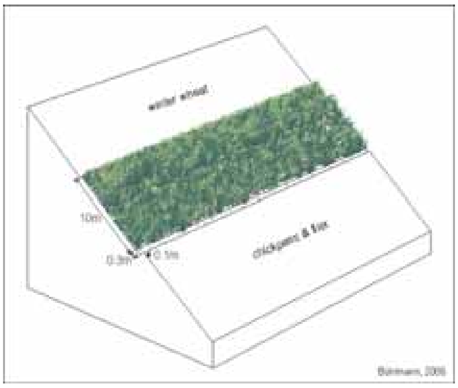
Forward sloping terrace stabilized with aligned trees and adjacent grass strip; cut-off drain diverts water at downslope field boundary

Forward sloping terrace stabilized with aligned poplar trees and adjacent grass strips; cut-off drain along tree barrier (Photo by: E. Bühlmann, April 2005)

Description. On steep and severely eroded cropland a forward sloping terrace (15% inclination) was established moving available earth with a bulldozer. At the downslope edge of the terraced field, a cut-off drain diverts excessive rain- and irrigation water to an existing gully. Terrace and cut-off drain are stabilized by an aligned tree barrier (poplar trees in 0.5 metre intervals) and by two parallel grass strips of 1-2 metre width. The terrace was established to diminish soil erosion and entailing fertility decline through reduction of slope angle. The tree barrier is planted because of the usefulness of poplar trees for construction purposes and to mark field boundaries; its capability of stabilizing terraced land is rather a welcomed side effect.
The terrace was built using a bulldozer. Digging of the cut-off drain and planting of poplar cuttings was done by hand. For initial establishment of the grass strips, clods were transferred from a neighbouring pasture. The poplar trees are pruned in early spring; the cut off-drain needs to be cleared of washed in soil after heavy storm events. The described terrace is established on steep cropland affected by soil erosion. The technology is relatively simple to implement. Establishment costs and the rather low maintenance costs are offset by benefits from harvested wood. Poplar trees can be gradually felled and used for construction purposes 15 years after initial planting. Through reduction of the slope angle, risk of soil erosion is lowered significantly. However, poplar trees can only be planted on land where sufficient water for irrigation is available, since they need to be watered on a weekly basis during summer. Furthermore, the technology covers land which cannot be used for cultivation of food crops.

Establishment costs. 165 USD Recurrent costs. 15 USD

a) Buffer Strip on Cropland in the Middle of Steep Slope



Buffer strip with adjacent drainage ditch in the middle of sloping cropland (overall slope length 110 metres)

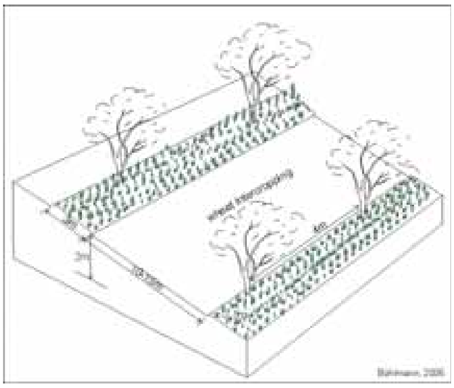
Buffer strip in the middle of sloping cropland (wheat, upslope; flax, downslope)(Photo by: E. Bühlmann, April 2005)

Description. An approximately 10 m large grass strip is left uncultivated across the upper part of the slope. The buffer strip is followed by an adjacent drainage ditch to enhance the technology's capability of reducing run-on onto the field further down slope. Neighbouring land users decided to implement the technology in order to reduce soil erosion on their cropland (wheat, chickpeas and flax) and to prevent disputes about land management practices. Upslope and downslope land user stated a significant reduction of observed rill development and fertility decline emphasizing that the benefits of the grass strip do offset the land losses associated with it. The farmers paid equally for the lost cropland area.

Apart from the annual digging of the drainage ditch no establishment activities are required, since the grass strip was simply left uncultivated when the former pasture was turned into cropland. The drainage ditch needs to be cleared from washed in soil on a regular basis; the grass strip is cut for haymaking once during a growing season. The technology is cost and labour extensive and is easy to implement. Farmers state the area losses as only disadvantage. However, the grass strip alone does only reduce (not prevent) soil erosion and should therefore be combined with other SWC technologies such as drainage ditches, terraces and/or agroforestry.

Establishment costs. 10 USD Recurrent costs. 4 USD

c) Orchard-based Agroforestry (intercropping)



Intercropping of wheat between tree rows of an apricot orchard (rows aligned on contour)

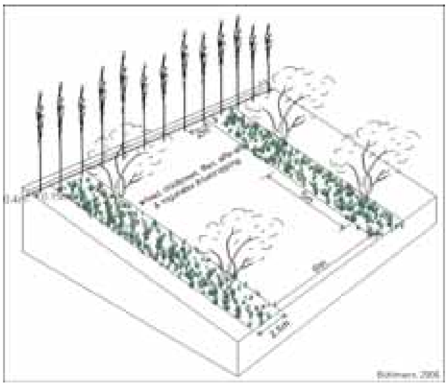
Intercropping of wheat in apricot orchard established during Soviet times (Photo by: E. Bühlmann, May 2005)

Description. Wheat is intercropped in an existing apricot orchard established during soviet times to increase farm production by integrating different resources in an environment protected from soil erosion. The intercropped area is ploughed by tractor. In general, farmers do not practice crop rotation since they usually allocate cereal production to the most fertile field plots of their farm. Along the trees aligned on contour a three meter large grass strip is left uncultivated to control runoff and to protect the ground from splash erosion. Spacing between rows is 13 metres, which allows unhindered farm operations.

Most orchards in Faizabad Rayon were established during Soviet times. Tree rows were planted rather close to each other in order to obtain maximum yields from the orchard monoculture systems. Every second tree row was removed, allowing more space for intercropping. The technology is applied in existing orchards which generally range between 10-25% of inclination. In existing orchards, intercropping alone is relatively cost extensive. Harvesting two crops at a time increases overall farm production and improves food security since harvests of intercropped food crops are found to be more reliable than those on exposed annual cropland. However, many orchards are still owned by state farms which usually do not practice intercropping. Since management of fruit trees require considerable labour and material inputs (e.g. chemicals for pest/disease control as well as fertilizers) which frequently cannot be met by peasants, yields of fruit trees are often declining after privatisation. Furthermore, farmers often lack knowledge for appropriate orchard management and miss the opportunity to gradually replace old trees by new seedlings.

Establishment costs. 31 USD Recurrent costs. 281 USD

d) IRRIGATED ORCHARD-BASED AGROFORESTRY (ESTABLISHMENT OF ORCHARD)



Irrigated orchard system with intercropping; irrigation channel (stabilized by aligned poplar trees) also acts as cut-off drain to prevent runon

Irrigated orchard system (here with intercropping of chickpeas) established on previously severely degraded cropland (Photo by: E. Bühlmann, May 2005)

Description. The fruit orchard (apple, apricot, cherry, pear and nut trees) is established on degraded cropland. Annual crops such as wheat, flax, chick peas and vegetables as well as perennial herbaceous fodder plants (alfa-alfa and esparzet) are intercropped since the first year after establishment of the orchard. Only the onion plot is rotated systematically since the farmer stated fertility decline due to heavy soil losses resulting from irrigation. Spacing between the tree rows varies between 8-10 m; the intercropping system is cultivated by tractor. Fruit trees are aligned in slope direction to facilitate irrigation. At the top of the field, an irrigation channel (40 cm wide, 15 cm deep) stabilized with aligned poplar trees directs water onto the orchard system. During the raining season the channel serves as cut-off drain, protecting the land from runon. Along the trees, a 2.5 m wide grass strip protects the ground from splash erosion.

The orchard system was established to increase farm production by integrating different resources while simultaneously conserving soil and water resources and preventing development of gullies. Prior to tree planting, the area had been levelled with a bulldozer to restore the severely degraded cropland. The bought seedlings were planted in hand-dug pits. During summer, the orchard system is watered three days per week (furrow irrigation); manure is applied around the fruit trees on an annual basis. Pruning of the trees is done in early spring. Due to irrigation, the grass strips can be harvested twice a year for haymaking.

Gross farm production could be considerably increased by cultivating multiple crops; the farmer considered the technology being successful. However, establishment and maintenance of the technology is cost intensive and, in this case study, was only affordable due to the farmer's off-farm income. Since the tree rows are aligned up and down slope, soil erosion is solely reduced by the capability of the irrigation channel (and aligned tree barrier) to prevent the system from runon. Planting tree rows on the gradient will substantially increase the technologies potential to reduce soil losses.

Establishment costs. 470 USD | Recurrent costs. 210 USD

e) Perennial Herbaceous Fodder Plants for Intact Canopy Cover

Cultivation of esparzet entails an intact canopy cover (>85%) and high yields for fodder production (plant height up to 80-100cm) (Photo by: E. Bühlmann, May 2005)

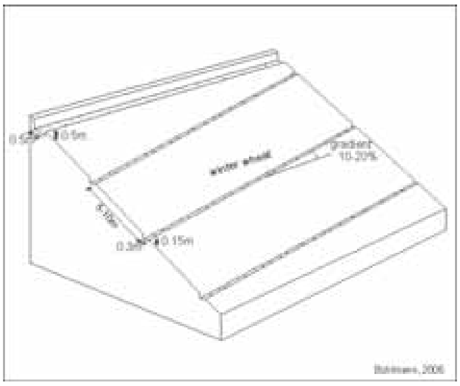
Cultivation of alfa alfa (left) and esparzet (right) on steep slope for fodder production (Photo by: E. Bühlmann, June 2005)

Description. Perennial herbaceous fodder plants such as alfa-alfa and esparzet are cultivated for fodder production and to fertilize unproductive cropland. Esparzet and alfa-alfa are often grown on steep slopes not suitable for annual cropping and on unproductive cropland as green manure. Through nitrogen fixation they fertilize soils so that farmers can plough or harrow the land after 5-10 years to grow annual crops again.

Alfa-alfa and esparzet can be harvested 6-10 years without tillage (depending on soil characteristics and slope steepness). As yield from perennial herbaceous fodder plant fields starts declining 4-6 years after initial cultivation, farmers make up for declining yields by applying additional seeds. Alfa-alfa and esparzet can be harvested twice a year (3-4 harvests if irrigated), which results in a significantly higher annual farm fodder production in comparison to ordinary haymaking fields. Some farmers stated problems in growing esparzet or alfa-alfa in slopes with an inclination of more than 30%. However, various examples have shown that perennial herbaceous fodder plants can be cultivated on steep slopes up to 60% of inclination. On steep slopes an increased amount of seeds has to be applied to offset downslope washing before germinating. Alfa alfa and esparzet are effective in reducing soil erosion since their cultivation leads to an intact ground cover throughout the year. Furthermore, zero tillage during up to ten years helps conserving the soil resource.

Establishment costs. 58 USD Recurrent costs. 12 USD

f) Drainage Ditches in Sloping Cropland



Graded drainage ditches in sloping cropland, cut-off drain at top of field to prevent runon

Left: Overview of field with graded drainage ditches and cut-off drain at top of field; Right: Clos-up of drainage ditch (Photos by: E. Bühlmann, April and May 2005)

Description. In steep wheat field drainage ditches are dug with a spate in 5-10 m intervals to reduce soil erosion. The ditches are in average 15 cm deep and 30 cm wide and are dug with a gradient of 10-20% to facilitate draining of excessive rain water. At the top of the field a 50x50 cm cut-off drain prevents run-on onto the field.

The small drainage ditches within the field are dug annually after tillage and sowing activities. The removed earth is heaped up below the ditch to decrease the risk of braking. Labour input for the annual establishment does not exceed three person days per hectare. The cut-off drain at the top was established 5 years ago and is cleared regularly from washed in soil. Most farmers in Faizabad establish 1-3 drainage ditches in their sloping cropland. Drainage ditches and cut-off drains are often not constructed deep enough and are not well maintained. Construction of the technology is not time consuming or costly, however, drainage ditches and cut-off drains are absolutely ineffective if not cleared from washed in soil on a regular basis.

Establishment costs. 8 USD Recurrent costs. 21 USD

From interviews with the land users emerged that farmers do ask relatives and neighbours for assistance whenever labour intensive farm activities, as for instance the establishment of SWC technologies, are to be carried out. The characteristics of voluntary labour assistance in Faizabad were analysed with WOCAT questionnaire *Approaches* (see WOCAT Approach TAJ05 on “Voluntary Labour Assistance” in Appendix 4 of this thesis). During informal land user gatherings and at the time the work is carried out, farmers share experiences and technical know-how on SWC and land management. Since all members of such labour exchange groups can request labour aid, labour shortages for extensive farm activities can be effectively circumvent. All farmers interviewed stated that fellow land users mainly do not implement SWC measures due to a lack of knowledge. Lacking awareness may again considerably influence the financial priorities set by the land user. Yet, many farmers face difficulties meeting the actual costs for SWC.

Farmers lease the land from the state and have to pay an annual rent. The farmers interviewed pay 20 to 40 USD per hectare a year for annual cropland, depending on its state, location and availability of irrigation water. Intensive grazing land for haymaking costs between 2-3 USD per hectare a year. To graze animals on state pastures, farmers pay approximately 1 USD per animal per year to the land committee. Farmers usually practice subsistence farming. Food crops are grown for self-supply and are rarely sold. Small-holders usually possess one or two cows and half a dozen goats or sheep which are held to provide the peasant family with milk and meat. Solely fruits and vegetables are sold at markets, whenever yields exceed family demands. Since the actual returns from farming are rather small, nearly all land users within the study area are highly dependent on off-farm income which is mostly generated in Russia, either by themselves or by their relatives (Winnig, 2005). Until now, only a few farmers have been willing to invest this money in SWC.

3.4.2 Comparative Analysis

Before analysing the SWC technologies, the criteria and desired impacts have to be defined. While soil loss has to be reduced, overall farm production should at least remain at the same level or increase in comparison to the situation before SWC implementation. Establishment and maintenance costs should not exceed these gains in a long term perspective. Generally, it can be expected that the lower the costs are to implement and maintain a SWC measure, the more likely will be its adoption by fellow farmers. Furthermore, the SWC technology should not hinder traditional farm operations and should allow changes in land use practices such as mechanisation. Lal and Pierce (1991) state that the objective of sustainable agriculture is to balance the soil resource and crop requirements in innovative soil and crop management systems which are not necessarily low-input systems. However, the emphasis is not on maximizing production but on optimising resource use and sustaining productivity over a long period. The need to keep conservation costs low and to increase production calls for intensified production, supported for example, by agronomic and vegetative SWC. Moreover, increase in soil cover is considered a highly efficient and cost extensive mean of controlling erosion, at least as effective as the runoff barrier approach (Herweg and Ludi, 1999). Nonetheless, intact plant cover alone may not be a sufficient protection, hence, it is necessary to combine structural, agronomic and vegetative SWC practices to achieve an adequate reduction of soil losses.

Effect on Soil Erosion. Based on field observations and farmer statements it can be concluded that reduction of slope angle through terracing (a) and tree rows in combination with grass strips and cut-off drains aligned on contour (c) are very effective measures against soil erosion. If a similar orchard system is aligned up and down the slope (d), soil losses cannot be significantly reduced but not halted. An intact ground cover during the periods of high rainfall erosivity (e) entailed a considerable reduction in rill development in comparison with surrounding fields, but was unable to prevent linear erosion entirely. The buffer strip across the slope (b) successfully trapped sediment but could not entirely prevent runon onto field below. If carefully constructed and maintained, cut-off drains at the top of the field (b,c,d,f) successfully prevent runon, but should be combined with other measures in order to accomplish adequate soil loss reduction. Graded drainage ditches (f) reduce slope length and divert excessive rainwater which prevents deepening of rills. After severe rain storms, the transport of excess rainfall caused headcutting and undercutting of the ditch bank by hydraulic shear. The force of concentrated water is documented in Figure 24 showing a drainage ditch after a heavy rainstorm event with high rainfall intensities.

Figure 24: Drainage ditch diverting water from wheat field (top right) after rainstorm event with high rainfall intensity (Photo by: E. Bühlmann, May 2005)

Figure 24 underlines the importance of drainage ditches: these water masses would flow over the field causing severe rill erosion if not diverted from the field to a water carrier.

Economical Characteristics. All farmers stated that overall farm production remained at the same level or increased three years after implementation of the technology. However, significant differences in establishment and recurrent costs are stated between the technologies. While implementation and maintenance costs of case study *b*, *e* and *f* were rather low, establishment of SWC measures in case study *a* and *d* was costly and could only be met due to significant off-farm income contributions. Case study *c* is in this way a special case since the orchard already existed and did not have to be established. The difference in price to acquire an existing orchard land in comparison to ordinary cropland prices could not be evaluated.

However, the costs for maintaining orchard systems *c* and *d* are equally high and are difficult to meet without off-farm income.

Geographical Characteristics. Some SWC measures are site-specific and can only be applied where certain criteria are met. For instance, stabilizing a cut-off drain with an aligned poplar tree barrier (a, e) is only possible where sufficient water for irrigation is available. Poplar trees need frequent watering during dry summer months. Furthermore, where water is to be diverted from the field (a,b,c,d,f) a water carrier or a gully needs to be nearby leading the excessive water to a river or reservoir. Water when concentrated is likely to cause severe damage if it is not carefully diverted. Occasionally geographical limitations can be circumvent: while some farmers stated problems growing perennial fodder crops (f) on slopes with and inclination of more than 30%, other land users successfully circumvented this problem in applying additional seeds. Farmers stated that, in this way, cultivation of esparzet and alfa-alfa is possible on slopes with an inclination of up to 60%.

Concluding Statements. Establishment of intercropped orchard systems (d) is an effective but costly way of reducing soil erosion. Orchard systems can only be established in Faizabad with considerable financial contribution of off-farm activities, which explains the rather moderate adoption of the technology in the area so far. Not only establishment costs are high; management of integrated orchard systems is very input intensive as well. Lack of fertilizers and chemicals for pest and disease control can lead to heavily declining yields from fruit trees. Figure 25 shows apple trees infested by caterpillars.

Figure 25: Apple trees infested by pest (caterpillars) since farmer lacks chemicals for pest control; the orchard is practically unproductive at present (Photo by: E. Bühlmann, May 2005)

Virtually no fruit yields could be obtained from this orchard since the second year after infestation. Hence, it only makes sense to invest in the establishment of orchards if recurrent costs can be met too. The same can be accounted for case study *c*.

Slope length, inclination and runon situation determine whether a SWC technology is successful in reducing soil erosion or not. To ensure a technology's effectiveness in a challenging environment, it needs to be adjusted or combined with other measures. For instance, the steeper the slope is, the shorter the intervals between buffer strips, cut-off drains and drainage ditches should be. If a field plot experiences runon, a cut-off drain should be established at the field top which is an effective but low cost and labour extensive measure. Soil detachment in channels can be reduced by introducing channels that are non-erodible (e.g. stones or grass cover). Finally, it can be concluded that easy-to-implement and cost-extensive technologies (e.g. buffer strips, cut-off drains, drainage ditches and cultivation of perennial fodder plants) have the potential reduce soil erosion considerably. Where these measures do not achieve adequate reduction of soil erosion, orchard intercropping systems terraces and should be established which are much more costly and labour intensive to implement and to maintain. However, the financial and ecologic returns from terraces and orchard intercropping systems are proved to be considerably higher in the long run in comparison to the returns of the assessed low-input measures.

3.5 Scenarios for Soil Loss Reduction

The aim of this section is to incorporate all findings of previous sections to develop a conservation map proposing SWC innovations for field plots currently affected by soil erosion. The current land use pattern is considered to be emerged more in consequence of food shortages and the present and past legal situation rather than being a result of free choice. Hence, the three scenarios, elaborated to predict the impact of a sustainable land use on soil erosion, are set up in a way that they do not demand changes in crop type. The SWC technologies considered, do all originate from conservation initiatives of local farmers. Amendments are proposed if necessary. Defining criteria and calculation procedures for the conservation technologies is of particular importance previous to scenario calculation (see section 3.5.1.). The predicted soil loss reduction of these SWC technologies is analysed in section 3.5.2 for SWC on grazing land and in section 3.5.3 for SWC on cropland. The outcomes from scenario calculation are presented and discussed in section 3.5.4.

3.5.1 SWC Considered

Analysis of current erosion risk predictions suggested that especially land farmed by smallholders is at high risk of soil erosion. This indicates that land users in Faizabad do not share the burden of soil erosion equally and that SWC measures will need to be implemented mainly by peasant farmers. Hence, exclusively farmer innovations for SWC were contemplated for scenario calculation, ensuring that the suggestions made are feasible, economic and acceptable to smallholders. For some SWC technologies, combinations and amendments were proposed, to increase the effectiveness in reducing soil erosion. The technologies considered are described below: Table 2 gives an overview including a brief general description as well as criteria, costs and the proposed calculation procedure for each measure. For more information on the proposed SWC technologies see SWC case studies above.

Table 2: Overview of local SWC technologies considered for scenario calculation on cropland (Group 1: area-wide application; Group 2: proposed if Group 1 SWC do not bring satisfying results) and on extensive grazing (technology Z); E = Establishment costs and R = Recurrent costs

	Code	Brief Description	Application area	Changes in RUSLE calc.	USD/ha
SWC Group 1	**C**	Contouring: ploughing by tractor on annual cropland, along contour	Annual and perennial cropland, agroforestry, field slope < 15%	*P* factor (RUSLE) for contouring with av. tillage rill depth 6 cm	No direct costs
	P	Perennial herbaceous fodder crops: to improve canopy cover on fallow/abandoned fields by cultivating esparzet or alfa	Fallow or abandoned field plots, field inclination > 60%	Assign av. *C* factor of perennial cropland	E: 58 R: 12
	W	Zero Weeding: to improve canopy cover of chickpea fields by leaving more weeds between the crops	Chickpea field, canopy cover < 75%-quantil	Assign *C* factor of chickpea field with canopy cover 75%-quantil	No direct costs
SWC Group 2	**D**	Drainage ditches & cut-off drain: to divert excessive rainwater after heavy rain storms, cut-off drain on field top	Annual and perennial cropland, agroforestry, fallow/abandoned land	Set slope length to 5 m (if slope > 25%) and to 10 m (if slope ≤ 25%)	E: 11 R: 21
	I	Intercropped orchard systems: Establishment of fruit orchard, trees aligned on contour, intercropping between tree rows	Annual and perennial cropland, fallow/abandoned land	Set slope length to 10 m, assign av. *C* factor of intercropped orchards	E: 470 R: 210
	T	Terraces & intercropped orchard systems: Land is terraced by machinery, then orchard with intercropping is established	Annual and perennial cropland, fallow/abandoned land	*P* factor (RUSLE) for terracing, av. *C* factor of intercropped orchards	E: 635 R: 225
SWC Grazing	**Z**	Change in management on grazing land: to improve canopy cover on overgrazed land through access control	Extensive grazing land, canopy cover < median	Assign *C* factor of ext. grazing land median	No direct costs

Categorisation of main erosion causes suggested that immediate reduction of soil losses can be achieved through implementation of the generally cost extensive agronomic measures. Even though they do merely reduce, not prevent, soil erosion, agronomic measures are proposed first separately before combined with the much more costly vegetative and structural measures. Therefore, the considered SWC technologies for cropland were grouped into two categories: (i) *SWC Group 1* consists of two agronomic measures (contouring, zero weeding) and one management measure (cultivation of perennial fodder crops); (ii) *SWC Group 2* includes vegetative and structural measures and combinations of these (diversion of excessive rainwater, establishment of orchard intercropping systems, terracing in combination with intercropped orchards). The category *SWC Grazing* is treated independently and considers changes in management of extensive grazing land.

(C) Contouring. In the study area only few land users till their land along contour. Farmers stated that ever since tractors are used for tillage operations, they cultivated their land up and down the slope. On relatively smooth soil surfaces, the flow pattern is determined by random natural microtopography. When tillage is oriented along the contour, the ridges or oriented roughness will partially or completely redirect the runoff, thereby modifying the flow pattern. Hence, contour tillage reduces erosion by reducing both, the runoff and the grade along the flow path. The effect of contouring on soil erosion is dependent on slope and tillage rill height. If accumulated water overtops the ridges, rill and concentrated flow erosion may occur (Renard et al., 1997). The effect of contouring on soil erosion is described in the *P* factor of the RUSLE and is expressed as

$$P_b = a(s_m - s_c)^b + P_{mb} \qquad s_c < s_m$$

$$P_b = c(s_c - s_m)^d + P_{mb} \qquad s_c \geq s_m$$

$$P_b = 1 \qquad s_c \geq s_e$$

where P_b = base values of the P factor for contouring, s_m = slope (expressed as sine of the slope angle) at which contouring has its greatest effectiveness, s_c = slope (expressed as sine of the slope angle) for which a value of P_b is desired, s_e = slope steepness (expressed as sine of the slope angle) for which contouring is ineffective and P_{mb} = the minimum *P* value for a given ridge height with base conditions. The coefficients a, b, c and d also vary with ridge height and were obtained from a table in Renard et al. (1997). Field protocol measurements suggested that average tillage rill height in Faizabad valley is 6 cm, which coincides with category *low* as defined in the RUSLE. The obtained *P* values for contouring are corresponding with figures suggested by Renard et al. (1997) which are displayed in Figure 26.

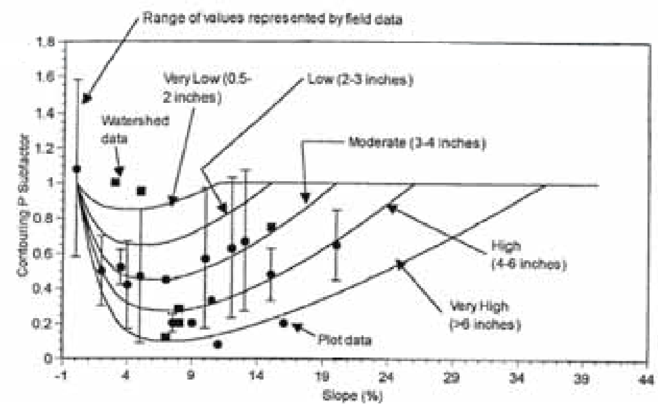


Figure 26: P values for contouring in relation to tillage rill height and slope gradient: observed average tillage rill height in Faizabad is 6 cm (2.36 inches or category "low") (Renard et al., 1997)

Figure 26 illustrates that *low* tillage rills on contour reach the greatest soil reducing effect at 6%-slopes with a *P* factor value of 0.65. The *P* value for contouring rises towards 1 for flat areas, furthermore contouring is assumed to lose effect at slopes steeper than 15%. For scenario calculation, contouring was applied exclusively to annual cropland, perennial cropland and agroforestry field plots.

(P) Perennial herbaceous fodder plants. (See case study *e* in section 3.4.1) Perennial crops herbaceous fodder plants, such as esparzet and alfa alfa, enjoy great popularity among farmers in Faizabad because of their high yield potential. Farmers stated that abandoned fields are usually rather sparsely vegetated, even in cases in which the field plots had been given up more than five years ago. Analysis of the canopy cover fractions derived from satellite imagery proved that esparzet and alfa alfa field plots show much better canopy covers than the rather sparsely vegetated fallow and abandoned fields. Hence, sowing perennial herbaceous fodder crops just before a field is given up or left uncultivated may improve canopy cover significantly. It is now suggested, to cultivate perennial herbaceous fodder plants on field plots left uncultivated. To simulate cultivation of perennial herbaceous fodder plants on fallow and abandoned fields, the *C* factors are replaced with the average annual *C* factors of esparzet and alfa alfa.

(W) Zero weeding. Field observations revealed that chickpeas alone account only for a small share of a field's overall canopy cover, while the contribution of weeds is far higher. Hence, weeded chickpea fields generally have low canopy cover fractions even at stage of maximum vegetation height. Regarding the expected increase in soil erosion risk on weeded chickpea fields, it is questionable whether a complete weeding is advisable. Some farmers were aware of this problem and stopped weeding their chickpea fields to increase canopy cover. Farmers stated that, in the long-term, yield losses due to increased plant competition are generally smaller in comparison to yield declines due to fertility loss. For scenario calculation it was assumed that the average *C* factor for zero-weeded chickpea fields is represented best by the canopy cover 75%-quantil. *C* value of chickpea fields below this threshold were replaced by the *C* value of the canopy cover 75%-quantil.

(D) Drainage ditches & cut-off drain. (See case study *f* in section 3.4.1) Assessment of SWC measures showed that drainage ditches are effective in diverting excessive rainwater, especially during rainstorm events with high rainfall intensities. Case studies suggested that intervals between the ditches should be smaller with increasing slope in order to achieve the desired effect. It was observed that on fields up to 25% of inclination, intervals of 10 metres may be adequate. 5 metre intervals are proposed for fields with an inclination above this threshold. The promising effects of properly implemented and maintained drainage ditches on soil erosion are further underlined by the results from the conducted multivariate statistical analysis in section 3.3.2. Variance contributions suggested that slope length is the most important factor influencing soil erosion which can be effectively reduced by the proposed technology. Additionally, a cut-off drain should be implemented to prevent runon onto the field. Stones or grass cover will reduce soil detachment by shear in the channel. Drainage ditches and cut-off drains are only effective in reducing soil erosion if carefully implemented and adequately maintained.

(I) Orchard systems with intercropping. (See case studies *c* and *d* in section 3.4.1) Plants intercropped in orchard systems are much better protected from soil erosion in comparison to those cultivated in ordinary monoculture systems. The soil conserving effects of tree rows aligned on contour in combination with runon-protection is believed to outperform benefits from agronomic measures. For scenario calculation, slope length was reduced to the average row interval of 10 metres while replacing the *C* factor with the median of intercropped orchards. The establishment and recurrent costs of orchard systems are high, however, payback from harvesting two crops at a time may, at least partially, compensate these expenditures. Since no productivity analysis was conducted, the effect of yield changes on costs could not be included in this study.

(T) Terraces & orchards systems with intercropping. (See case studies *a* and *d* in section 3.4.1) Field observation have shown that cultivation of annual crops on very steep hill slopes is only sustainable, if terraces are established. Terracing is only proposed in combination with orchard based intercropping systems, a combination which is frequently observed within the study area. Tree rows and grass strips closely aligned to the edge of the terrace considerably decrease the risk of braking and reduce soil erosion in the interterrace interval. This technology is a complex and costly measure, however, it is only proposed where other technologies do not bring about satisfying results.

(Z) Change in management on extensive grazing land. This technology is the only measure proposed for grazing land. Observations in the field implied that some pastures were less overgrazed than others. Overgrazing damages the canopy cover, entailing greater bare ground fractions. Controlled access led to a considerable increase in canopy cover and to much lower soil loss rates on some pastures. Since no SWC case studies were conducted on pastures, this study lacks detailed information on pasture management in Faizabad. In this study, solely the potential soil loss reduction of management changes on grazing land was assessed, without explicitly defining these changes. It was assumed that the average *C* factor for well managed pastures is represented best by the canopy cover 75%-quantil of extensive grazing land. The *C* values of pastures below this threshold were replaced by the *C* value of the canopy cover 75%-quantil.

3.5.2 Predicted SWC effects on grazing land

A change in management (Z) was proposed for all pastures showing canopy covers below the 75%-quantile. The expected soil loss reducing effect is displayed in Figure 27.

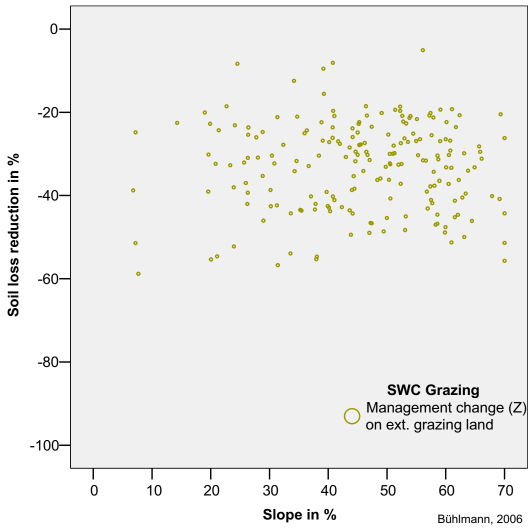


Figure 27: Predicted soil loss reduction for access control on extensive grazing land

Figure 27 suggests considerable soil loss reductions on grazing land which are independent from slope. The average soil loss rate for extensive grazing land is predicted to decrease from 95.1 to 72.3 t/ha*year which equals an overall reduction of nearly 24%.

3.5.3 Predicted SWC effects on cropland

The technologies of *SWC Group 1* and *SWC Group 2* were applied case by case to all annual, perennial, fallow and mixed cropping fields within the study area. The predicted reduction of soil loss rates obtained through these calculations is displayed in Figure 28 and Figure 29 in relation to field slope.

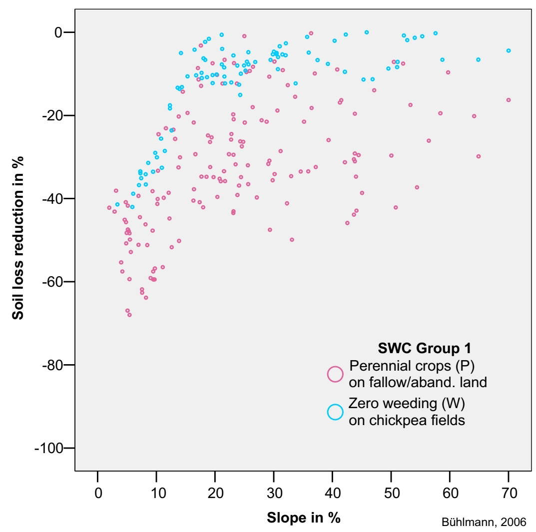


Figure 28: Predicted soil loss reduction under SWC Group 1 on cropland (where slope < 15%, combined with contouring C)

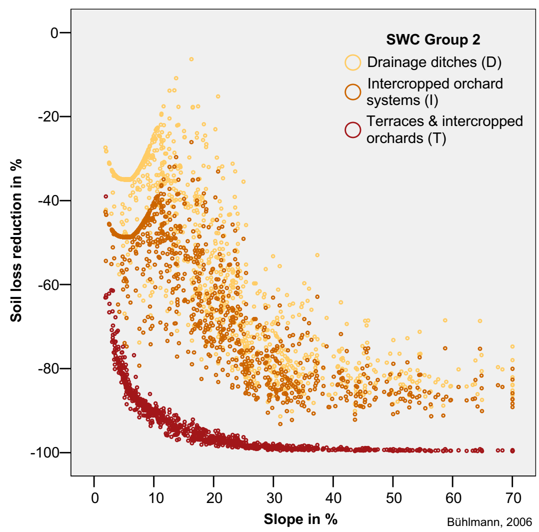


Figure 29: Predicted soil loss reduction under SWC Group 2 on cropland (where slope < 15%, combined with contouring C)

As Figure 28 shows, SWC Group 1 technologies are slope independent. Soil loss rates can be more efficiently reduced where technology P and W are combined with Contouring (C). Contouring solely has an effect on soil erosion on slopes up to 15% of inclination, reaching an average soil loss reduction of 11% per field. Furthermore, the figure suggests that rather modest benefits can be expected from zero weeding on chickpea fields. Cultivation of perennial herbaceous fodder crops on abandoned and fallow field plots is expected to entail more significant erosion reductions. The soil loss reduction achieved through Group 1 measures ranges from no effect to a decrease of almost 70% at low slope angles while averaging at 16%. It can be expected that on moderate to severely eroded fields a combination with Group 2 measures is unavoidable to achieve sufficient reduction.

Figure 29 illustrates the predicted effect of SWC Group 2 technologies on soil erosion in relation to slope steepness. In contrast to measures of SWC Group 1, the soil reducing potential of Group 2 technologies is slope dependent. A great difference in effectiveness can be observed especially for flat to moderate slopes. Again, fields with slope gradients below 15% are contoured; its effect is expressed by the curves for technologies D and I at low slope angles. As expected, terracing in combination with intercropped orchard systems (T) shows the most promising effects on soil erosion (average soil loss reduction of 93%). The soil loss reducing effect of intercropped orchard systems alone (I) and drainage ditches combined with cut-off drains (D) are predicted to perform equally well. Whereby intercropped orchard systems (average soil loss reduction of 63%) performed slightly better than drainage ditches (average soil loss reduction of 53%). Comparing predicted soil loss reduction of SWC Group 1 measures with Technology D & I suggests that much better results can be expected from the more expensive Group 2 technologies especially for fields on slopes steeper than 15-20%. Even though technology (T) performs best at all slope angles, the expected soil loss reduction decreases from almost 100% to 60% at slope gradients below 15%. Hence, it is not sensible to establish cost and labour intensive terraces on fields with slopes below 15% of inclination.

In general, the predicted soil loss reducing effects of local SWC innovations correspond well with field observations and farmer statements discussed in section 3.4.2. In contrast to the computations made above, field observations suggested that intercropped orchard systems with tree alignment on contour (I) have a considerably higher potential to reduce soil erosion than ditches (D). Since soil loss reduction for technology I is computed by reducing slope length and by increasing canopy cover only, the effect of grass strips along the tree rows may not be fully accounted for. However, introducing a P factor for buffer strips in addition to the suggested computation method was likely to overestimate the benefiting effect of technology I on soil erosion.

3.5.4 Scenario Calculation

Since the assessed SWC case studies are implemented on cropland only, this part of the study will focus on this land use. The main objective of the conservation scenarios is to propose SWC technologies for each field to reduce erosion rates below a certain threshold value. To achieve the required reduction in soil loss, the SWC technology entailing the least establishment and recurrent costs was chosen. The used thresholds can be considered as *soil loss tolerance* values: the maximum rate of soil erosion that can occur and still permit crop productivity to be sustained economically over a longer-term. It was concluded in section 1.3.1 that the value of soil loss tolerance can be interpreted in different ways. The soil loss tolerance value may range from the almost immeasurable rate of soil formation to soil loss rates of 20 t/ha*year ensuring sustained crop productivity over two to three centuries if inputs (e.g. fertilizers) are increased. Authors in literature (e.g. Bakker et al., 2004; Renschler et al., 1998; Schwertmann, 1987) consent on a soil loss tolerance value of 10 t/ha*year for deep brown-soils from loess formation as observed in Faizabad. Hence, the current average annual erosion rate of 33.3 t/ha*year predicted for cropland is far away from being sustainable. Three scenarios were developed through which (i) an realistic soil loss reduction in a short-term perspective (Scenario 30), (ii) a reduction desirable in a long-term perspective (Scenario 20) and (iii) an ambitious soil loss reduction shall be achieved (Scenario 10).

Calculation Procedure. The procedure for scenario calculation consists of two main steps: (i) the least expensive SWC Group I measures were assigned to all fields meeting the criteria defined earlier in Table 2. Where soil losses nevertheless exceeded the scenario specific soil loss tolerance values, the cost extensive technology D of SWC Group II was chosen and, where applicable, combined with a Group 1 measure. If erosion rates were still greater than the set soil loss tolerance value, the next more expensive technology I and, finally, technology T was proposed to control erosion rates. Technologies of SWC Group II were not combined with each other in the assignment procedure since they already involve a combination of measures.

Firstly, a scenario was computed setting the soil loss tolerance value to 30 t/ha*year (Scenario 30). After applying Group 1 SWC measures, for every field showing a higher annual soil loss than 30 t/ha the next cost extensive SWC of Group 2 was proposed. This process continues until annual soil loss is below the desired value on every field. The same was done for Scenario 20, with a soil loss tolerance value set at 20 t/ha*year, and for Scenario 10, with a soil loss tolerance value set at 10t/ha*year which coincides with the soil loss tolerance value proposed in the literature.

Calculation Results. The obtained average soil erosion rates and the resulting soil loss reduction predicted for each scenario are displayed in Table 3. Figures for cropland are considered individually.

Table 3: Predicted average soil loss rates for each scenario in comparison to current conditions

	Current condition	**Scenario 30**	**Scenario 20**	**Scenario 10**
Av. soil loss rate (total study area)	79 t/ha*year	60 t/ha*year	59 t/ha*year	58 t/ha*year
Soil loss reduction (total study area)		- 24%	- 25%	- 27%
Av. soil loss rate (cropland)	33 t/ha*year	16 t/ha*year	13 t/ha*year	10 t/ha*year
Soil loss reduction (cropland)		- 53%	- 61%	- 71%

Table 3 shows that soil erosion rates in the study area may be reduced by 24% if Scenario 30 is applied. As expected, the more ambitious Scenario 20 and Scenario 10 cannot further decrease overall annual soil loss since grazing land accounts for the greatest share of the total study area and no radical measures could be proposed for these areas. Looking at cropland only, Scenario 30 more than halves annual soil loss, while Scenario 20 and Scenario 10 reduce erosion by another 8-10% each. Soil loss on cropland may be reduced by as much as 71% under Scenario 10. Distribution of soil loss classes are examined in Figure 30.

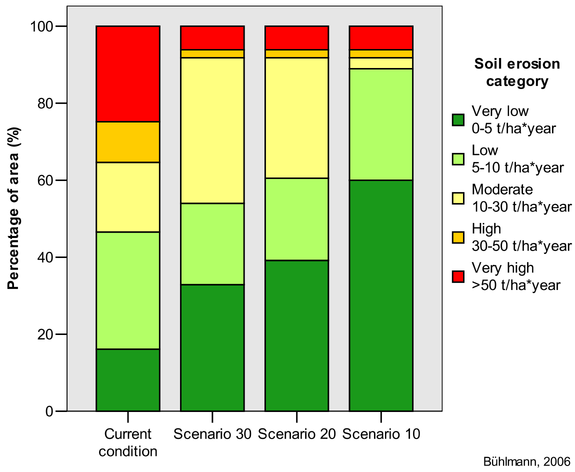


*Figure 30: Distribution of predicted soil loss rates on cropland in each scenario (Scenarios with soil loss tolerance values set at 30 t/ha*year, 20 t/ha*year and 10 t/ha*year respectively)*

Figure 30 shows that the erosion rates under current conditions were *low* and *very low* in 46.5% of the cropland area. While this area percentage is predicted to increase modestly in Scenario 30 and Scenario 20, a rather abrupt increase is predicted for Scenario 10. This “jump” constitutes mainly of a shift from area facing *moderate* soil loss rates to area within the *very low* erosion category. This phenomenon may be due to an increase of proposed terracing and will be further examined below. An other prominent incident constitutes the rapid decline of area experiencing *high* to *very high* soil loss rates in Scenario 30 dropping from 35.4% under the current land use situation to 8.1%. Soil erosion in theses areas cannot be further decreased with the assessed SWC technologies. It can be concluded that promising soil loss reduction can be expected from all scenarios in comparison to the present condition. While rather great differences can be observed between Scenario 20 and Scenario 10, the spatial extent of erosion is expected to be similar in Scenario 30 and Scenario 20.

To get a better impression of how this soil loss reduction on cropland was achieved, details on the frequency and distribution of proposed SWC technologies have to be consulted. Figure 31, Figure 32 and Figure 33 give an impression of the frequency of the technologies proposed for each scenario, displaying the predicted soil loss reduction per field plot and SWC technology. To assess the validity of the SWC propositions made, slope gradient was included as second variable on the x-axis. Although slope steepness is one among many factors influencing soil erosion, it may help to imagine the situation in the field. The scatters are marked by SWC measure: green dots represent fields for which solely Group 1 measures are proposed; brown coloured dots stand for fields for which the more radical Group 2 technologies are recommended. Group 2 technologies can include combinations with Group 1 measures.

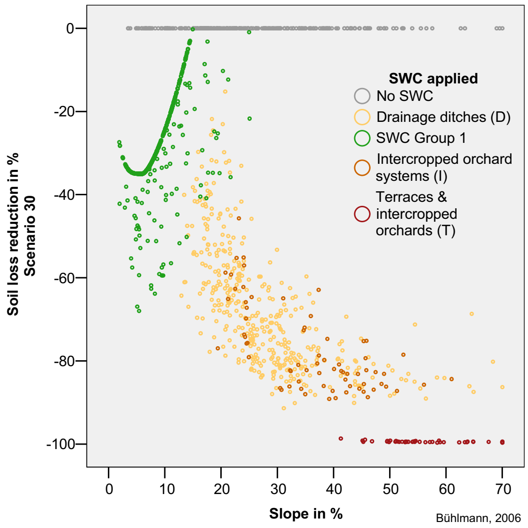


Figure 31: Soil loss reduction per field plot and SWC measure under Scenario 30 for cropland

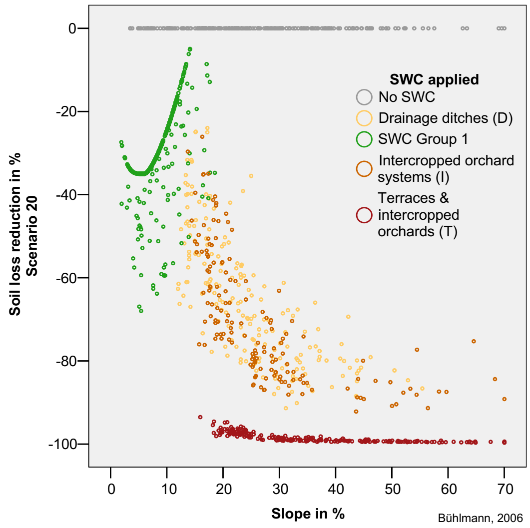


Figure 32: Soil loss reduction per field plot and SWC measure under Scenario 20 for cropland

Scenario 30 (soil loss tolerance value 30 t/ha*year) in Figure 31 suggests that Group 1 measures alone can sufficiently reduce soil loss up to slope gradients of 15%, up to which contouring (C) remains effective. For slopes with between 18-30% establishment of drainage ditches (D) will bring about the required reduction in most cases. For slopes between 30-50%, it is recommended to establish orchard systems in which the desired plant can be intercropped (I). Technology (T) is proposed only where slope gradients exceed 45%. In Scenario 20 (see Figure 32), similar to the previous scenario, Group 1 measures or combination of these are likely to reduce soil erosion below the set soil loss tolerance value of 20 t/ha*year on slopes up to 15%. In comparison to the previous scenario, a shift from drainage ditches (D) to intercropped orchard systems (I) can be observed: for many field plots with slopes between 15% and 35% technology D is not capable in reducing soil loss below the tolerance value. Increasingly, intercropped orchard systems (I) and terraces (T) are proposed for these slope gradients. On fields with high canopy covers fractions and, hence, lower soil loss rates, drainage ditches still bring about the desired effect. Terraces (T) are proposed solely for fields with slopes steeper than 18% and only if high to very high erosion rates are currently observed.

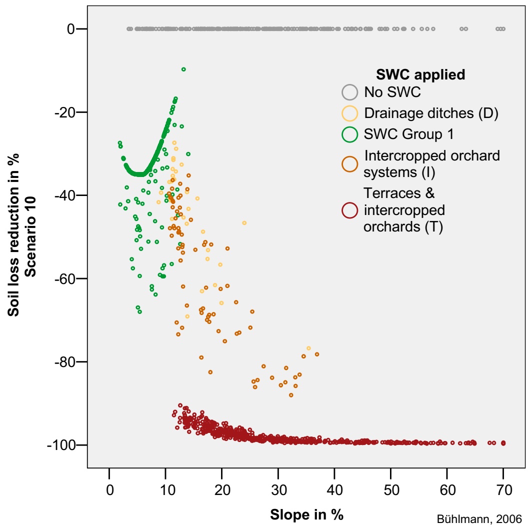


Figure 33: Soil loss reduction per field plot and SWC measure under Scenario 10 for cropland

As illustrated in Figure 33, to reach the goals set by Scenario 10 (reducing soil loss below 10t/ha*year), for most fields with an inclination above 12% terracing (T) is proposed. This means that the much cheaper Group 1 measures and Technology D are not expected to be able to decrease soil erosion below the soil tolerance value often quoted in the literature for soils in Faizabad.

Looking at the frequency of SWC propositions rises questions about the area distribution of proposed measures which may be crucial to evaluate the labour and financial inputs needed to implement a scenario. Figure 34 compares the area percentages of the SWC technologies proposed in different scenarios.

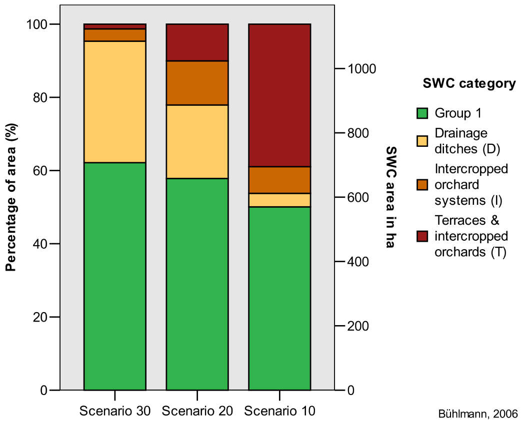


Figure 34: SWC area distribution on cropland for each scenario

Figure 34 underlines the earlier findings that intercropped orchard systems (I) and terraces (T) are only proposed in very few cases in Scenario 30 while wide-spread drainage ditches are thought to bring about the required soil loss reduction. Furthermore, it proves, that the abrupt increase of erosion classes *low* and *very low* from Scenario 20 to Scenario 10, observed in Figure 30, is mainly due to a rise of proposed terracing in Scenario 10: terracing is proposed for nearly 40% of the total cropland area. To reduce soil loss below 20 t/ha*year (Scenario 20) it is suggested to implement drainage ditches (D) on 20%, intercropped orchard systems (I) on 12% and terraces on 10% of the treated cropland area. The fact that on almost half of the cropland area sustainable soil loss rates (Scenario 10) can only be achieved by implementing the complex technologies I and T implies that the present land use type in these areas is not appropriate for such conditions. Hence, present land use in these areas should be reconsidered.

Validity of the SWC propositions was further scrutinised by comparing each scenario's conservation map (see A0-format Erosion Risk Map and Conservation Map for propositions made in Scenario 20 and the map documents on the DVD-Rom in Appendix 5 for prepositions made in Scenario 30 and Scenario 10). Figure 35 compares the technologies proposed on a sample hill slope for different scenarios. The colours represent the soil loss classes under current conditions (red = very high, orange = high, yellow = moderate, light green = low) while letters symbolise the SWC measure proposed for each field plot. Slope steepness increases from the bottom of the picture (average field slope 8%) towards the top section (average field slope 27%).

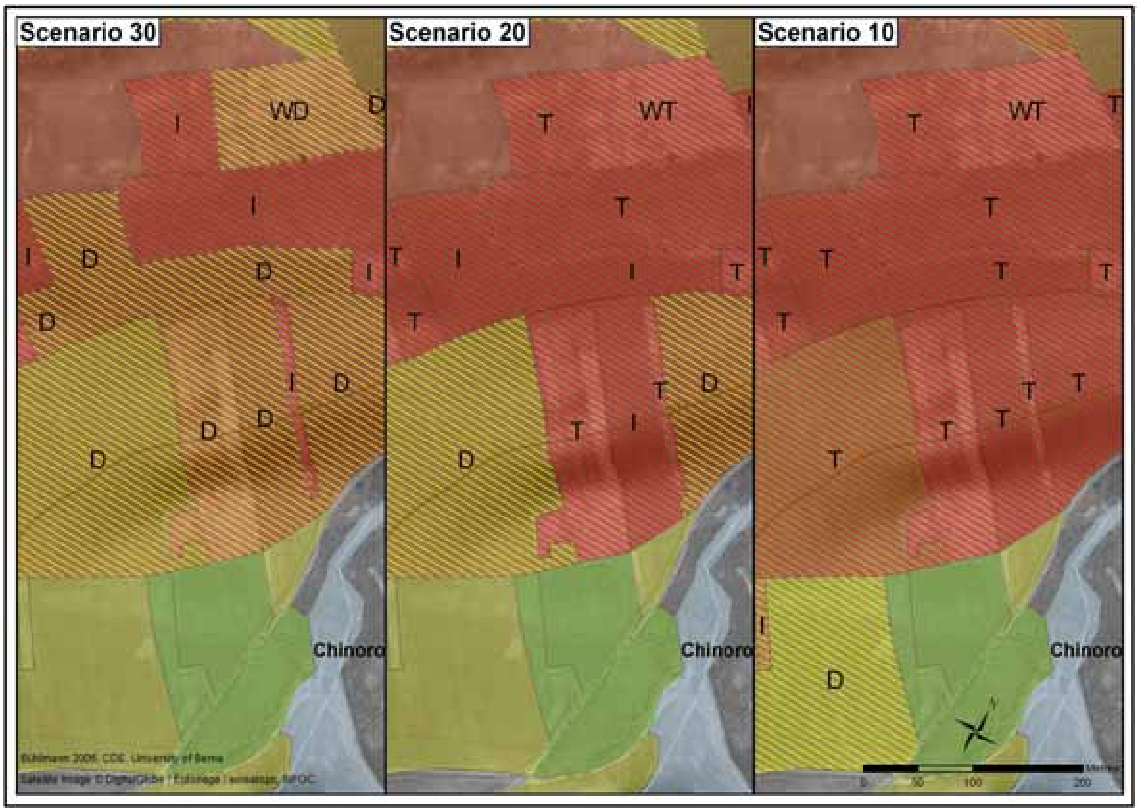


Figure 35: SWC propositions made in different scenarios on a hill slope increasing from lower part (8%) towards the upper part of the picture (28%); colours represent soil loss classes under current conditions, D=Drainage ditches, I=Intercropped orchard systems, T=Terracing (yellow hatches: SWC establishment costs 10-100 USD/ha, red hatches: SWC establishment costs >100 USD/ha)
Contour lines: Russian Military Topographic Map, 1983
Map background: DigitalGlobe, 2005 (Quickbird satellite image, 0.6m resolution)

Figure 35 shows that soil erosion can be reduced to 30 t/ha*year by implementing drainage ditches (D) and intercropped orchard systems (I). To be able to meet the requirements of Scenario 20, intercropped orchard systems (I) and terraces (T) had to be proposed for most fields on the slope. Scenario 10 proposes terracing (T) for almost the entire hill slope. An interesting feature is that in Scenario 20 terracing (T) had to be proposed for sparsely vegetated vegetable plots (bright, inhomogeneous polygons in the slope middle) while on neighbouring fields the required soil loss reduction can be achieved by drainage ditches and intercropping. This again implies that instead of terracing, a change in land use together with implementation of low input technologies may bring about the desired soil loss reduction. However, land use changes are not considered in this study. In general, it can be concluded that Scenario 30 is relatively easy to achieve while efforts need to be considerably increased to be able to reduce soil erosion to the levels required in Scenario 20 and Scenario 10.

This rises questions about the costs of a scenario. As we know from SWC case studies in section 3.4.1., establishment and maintenance of SWC technologies can be very cost intensive. Although the benefits evolving in the longer-term, e.g. yield increases and rise in overall farm production, could not be evaluated in this study in adequate profundity, the actual costs of a technology may serve as an indicator. The actual implementation costs of a technology may influence a farmer's decision whether to invest in SWC or not. If recurrent costs to maintain the technology cannot be met, the expected extra returns may not be generated and the technology may loose effectiveness. It can be concluded that a scenario may only be achievable, if the costs are bearable to the land users. Table 4 lists average expenses to implement and maintain SWC technologies under a scenario. The costs are calculated per hectare, according to the figures presented in section 3.5.1.

Table 4: Estimated average SWC costs on cropland for each scenario

	Scenario 30	**Scenario 20**	**Scenario 10**
Av. establishments costs for SWC on cropland	125 USD/ha	342 USD/ha	546 USD/ha
Av. recurrent costs for SWC on cropland	58 USD/ha*year	135 USD/ha*year	197 USD/ha*year

Table 4 shows that for Scenario 30 and Scenario 10 a great difference in establishment and recurrent costs has to be expected. The costs to implement and maintain SWC technologies for Scenario 20 lie somewhere in the middle. The rather high costs per hectare predicted for Scenario 10 are mainly due to the large area to be terraced. It remains doubtful whether the recurrent costs of nearly 200 USD, required for management in Scenario 10, can be offset by the additional returns resulting from SWC. If Scenario 20 or Scenario 10 are to be implemented and maintained, contribution from off-farm income are in the present economic situation in Faizabad, at least in the short-term, unavoidable.

Altogether it can be concluded that annual soil erosion on cropland can be halved to merely 16 t/ha with relatively little effort. Implementation of mainly cost and labour extensive technologies, as proposed in Scenario 30, will allow rapid soil loss reduction. However, drainage ditches (D) and Group 1 technologies often have to be annually implemented or reconstructed, entailing the risk that an achieved reduction may be reversed in an other year. Scenario 10 reduces average soil erosion on cropland below the ideal soil loss tolerance value of 10 t/ha*year proposed in the literature. Though desirable, the propositions made in this scenario seem not to be practicable under the current economic situation. Scenario 10 suggests terracing (T) for virtually all fields with an inclination of more than 12%. Since terracing (T) is a labour and cost intensive measure, it is unlikely that land users will follow such recommendations at a voluntary basis. Scenario 20, with an average soil loss rate of 13 t/ha*year, strikes a balance between these two extremes: on many fields, soil erosion can be reduced below 20 t/ha*year by cost and labour extensive measures; intercropped orchard systems (I) and terraces (T) are only proposed where slope steepness exceeds 18% and other measures do not bring about required reduction. Comparing Scenario 20 with Scenario 10, the area for which terracing is proposed is reduced by 330 hectares through which the costs for scenario implementation and maintenance can be considerably reduced. In Scenario 20 annual soil loss for these fields lies between 10 t/ha*year and 20 t/ha*year. If feasible these fields still can be terraced at a later point. Hence, a Conservation Map was produced showing present land use and conservation costs per field under Scenario 20 (see Figure 36), besides the SWC prepositions made in this scenario can be reviewed in the A0-format Conservation Map.

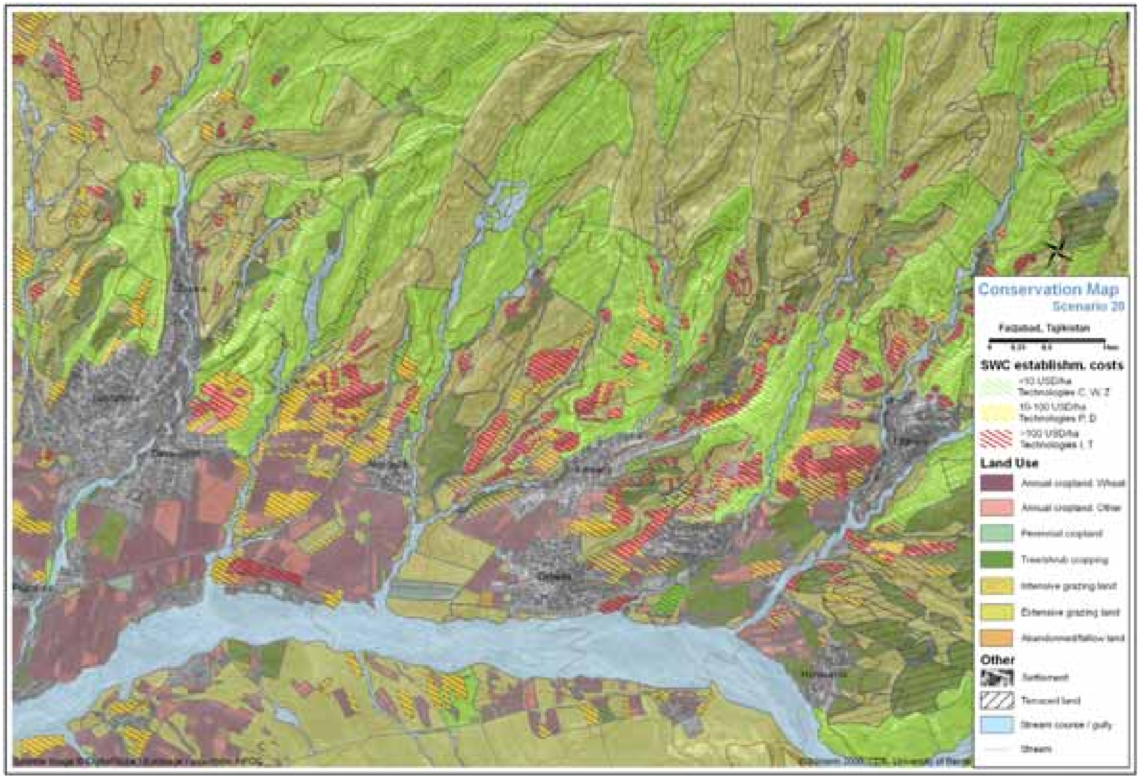


Figure 36: SWC establishment costs under Scenario 20 and land use. (for SWC propositions, consult the A0-format Erosion Risk Map or the Conservation Map in Appendix 5)
Contour lines: Russian Military Topographic Map, 1983
Map background: DigitalGlobe, 2005 (Quickbird satellite image, 0.6m resolution)

The hatch patterns represent the establishment costs of proposed SWC measures. Farmers are likely to be able to meet implementation costs for green and yellow areas, while off-farm income contributions or public investment may be needed to control soil erosion on red areas.

4 CONCLUSIONS

Soil erosion is a major threat to sustainable agriculture in all hilly areas of Tajikistan. Excessive erosion degrades the landscape, reduces soil productivity, increases the difficulty of establishing and maintaining vegetation, inconveniences farm operations and produces sediment that can cause downstream damage. Carefully selected conservation systems can reduce or prevent these negative effects and have the potential to sustain the land for much-needed agricultural production.

This study provides methodologies for collecting representative data needed as input data in the RUSLE and demonstrates its usefulness for predicting current soil loss and for proposing conservation priorities. Comparison of erosion predictions with rill measurement data showed fairly good correlation, which implied that the model outputs are reliable. In the GIS environment, the RUSLE can be easily applied to predict potential erosion hazards over large areas and is simply to adapt in order to assess the potential benefits of implementing different combinations of SWC practices. Furthermore, SWC scenarios can be evaluated easily through changes in the input files. Conducting SWC case studies using WOCAT methods helped to increase knowledge on SWC, through documenting and evaluating all relevant aspects of local conservation technologies and approaches. A deeper understanding of erosion processes and their agents was obtained through mapping of 60 field plots with a field protocol which included a broad range of features.

The multispectral and panchromatic Quickbird high resolution satellite images provided the basis for accurate land use mapping and canopy cover assessment. The high resolution of data allowed to consider the great spatial heterogeneity and variability of land use and crop management observed in Faizabad. Analysis of high resolution remote sensing data, combined with further spatial information in a GIS, provided an integrated and effective tool for resource management within the scope of sustainable development in developing countries. A limiting factor in this context was the rather low accuracy of available topographic data. It is uncertain whether the DEM accuracy was sufficient for orthorectification of high resolution satellite images.

The soil loss model was applied to a study area of 100 km^2 in Faizabad, western Tajikistan, comprising 15% cropland area (1202 field plots) and 70% grazing land. The average predicted soil loss rate ranged from 0.8 to 378 t/ha*year, averaging 79 t/ha*year. High to very high erosion rates (> 30 t/ha*year) were predicted for 35% of the cropland area. The distribution map of soil erosion risk showed the fields where conservation measures should be taken. Furthermore, the erosion map indicated that the marginal cropland farmed by peasants shows generally higher erosion rates than the relatively flat land cultivated by state farms. Hence, effective local SWC innovations was looked at, which can be afforded and implemented by small-holders.

Evaluation of field sampling data revealed that agricultural causes and topographic effects are more often responsible for soil loss than runon. Multivariate statistical analysis of field protocol variables and rill measurements implied that topographic variables correlated best with soil erosion: slope length and slope steepness contributed more to the soil loss variance than runon-situation and canopy cover. WOCAT case studies on local SWC innovations as well as erosion/conservation modelling showed that following local SWC technologies have a promising potential to control soil erosion: tilling and planting on contour (average soil loss reduction predicted at -11%), zero weeding of chickpea fields and cultivation of perennial fodder plants (-16%), graded drainage ditches (-53%), intercropping in orchard systems (-63%) and terraces (-93%). The potential effect of these technologies on current soil loss rates were found to be consistent with field observations and farmer statements from case studies.

Modelling of conservation scenarios revealed that soil erosion on cropland may be more than halved (Scenario 30) if land users start implementing cost-extensive agricultural measures. To reduce soil erosion below 10 t/ha*year (Scenario 10), the assumed sustainable soil loss tolerance value for deep loess brown-soils, virtually all fields steeper than 12% of inclination would have to be terraced. Striking a balance between these extremes, Scenario 20 was introduced which aims at reducing soil loss on cropland below 20 t/ha*year. The average soil erosion predicted for this scenario lies only 3 t/ha*year above the sustainable soil loss rate. Cost-extensive agricultural measures were thought to have the potential to reduce soil erosion below the set threshold value on fields with gentle to moderate slopes. Since these technologies often did not bring about desired soil loss reduction on hilly slopes, the more complex and costly technologies, intercropped orchard systems and terraces, had to be increasingly proposed for these slope gradients. On fields with high canopy cover fractions and, hence, lower soil loss rates, drainage ditches still did produce the desired effect. No terracing was proposed for fields sloping less than 18%, which reduced the costs for scenario implementation and maintenance considerably in comparison to Scenario 10.

Following recommendations can be made: (i) Land users should be encouraged to implement cost-extensive agricultural measures such as contouring, zero weeding, drainage ditches and cut-off drains, according to the prepositions made in Scenario 30. (ii) Implementing Scenario 20 is thought to reduce soil loss rates on cropland to a virtually sustainable level in the long term. Hence, ways and means of support should be found that help to introduce, implement and apply SWC technologies proposed in Scenario 20. Before complex and costly SWC measures are implemented on severely eroded land, one should consider to alternatively cultivate the desired plant on a nearby plot of land which is better protected from soil erosion. Privatisation of state farms may increase the availability of land for food crop production. This may entail an increase in food security so that crop cultivation on severely eroded field plots is not a need any longer and may be substituted by a more sustainable land use. (iii) As a long-term goal, soil loss rates should be reduced to sustainable levels which in some cases may have to be achieved through additional terracing.

Presently, many farmers lack knowledge on necessity and opportunities for sustainable land use. Information on appropriate land management should be made available to land users in the area. Until now, only a small range of SWC technologies emerged in the area of Faizabad, more efforts need to be made to identify effective SWC measures appropriate for local farming conditions. A special focus should be put on SWC for grazing land, for which many questions remain unanswered in this study. Even though the discussed SWC measures are in the long run financially attractive to farmers in Faizabad, the majority of them have often limited capital to invest in SWC measures. Considerable public investments in SWC practices are required to advance their implementation in areas with steep slopes and low yields such as Faizabad.

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List of Tables and Figures

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APPENDICES

The Appendices of this paper are stored on the DVD-ROM below.

Appendix 1 (Literature). More than 120 papers reviewed in this thesis are filed in eight thematic folders. The file names are consistent with the citations used in this thesis and comprise of the first author's surname and the year of publication.

Appendix 2 (Figures). All figures displayed in this thesis are stored in various file formats and can be viewed with any picture viewer software.

Appendix 3 (Empty Field Protocol & WOCAT-Questionnaires): The empty protocol and questionnaires used to gather data in the field can be viewed or printed as pdf-file (questionnaires) and as xls-file (field protocol).

Appendix 4 (SWC Case Studies & Field Sampling Data). Full information on the SWC case studies can be obtained by exploring the full records in the WOCAT database. Four-page summaries provide an overview of the assessed SWC technologies. Furthermore, the collected field sampling data can be browsed.

Appendix 5 (Map Documents & Spatial Data). Maps are saved in ArcGIS map documents (mxd) allowing quick and easy exploration of spatial data presented in this study. The data is stored in shapefiles (shp) and in a MS-Access database files (mdb). The orthorectified panchromatic and multispectral Quickbird satellite images can be browsed as image files (img). For detailed information on the contents of the files, see metadata.

Appendix 6 (Pdf-File of Thesis). The complete thesis can be electronically viewed as Acrobat Reader file.