A multi-scale approach for erosion assessment in the Andes

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Chapter 1

Introduction

1. Introduction

1.1 Erosion in the Andes

Hillside agroecosystems in the tropical South American Andes experience high rates of soil degradation. Reported data show great variation in the erosion rate. For the Colombian Andes, Suarez de Castro and Rodríguez (1962) reported 1-800 Mg ha^{-1} y^{-1} for the same soil and Ruppenthal et al. (1966) mention a maximum of 222 Mg ha^{-1} y^{-1}. Based on sediment measurements in rivers, the average for five watersheds in Ecuador was 7.3 Mg ha^{-1} y^{-1} and erosion was found to depend more on land use than on soil type. However, it has been pointed out that the conditions under which measurements were taken are generally not properly reported (Stroosnijder, 1997).

Peru is one of the Andean countries exhibiting different states of the erosion problem (Amezquita et al., 1998). The first attempt to assess soil erosion rates in Peru was made by Felipe-Morales et al. (1977). Using runoff plots, they found erosion rates of between 2.8 and 20 Mg ha^{-1} for central Peru. Since then, there have been very few erosion investigations, and reference to Andean soil erosion has often been criticized because of a lack of quantitative data. The causes of the erosion are the intensive land use, overgrazing of pastures, cultivation of annual crops on steep slopes, deforestation, built-up areas, roads and abandoned land (Stroosnijder, 1997). Insufficient attention has been given to elucidating the factors that affect the soil erosion processes.

Evidence of concern about soil erosion in Peru is provided by the Peruvian government´s National Program of Soil and Water Conservation (PRONAMACHCS), which has been in operation since 1981. Its aim is the promotion of sustainable land use at the highland watershed scale, through the execution of conservation strategies intended to prevent soil erosion and to generate economic development for residents (Ministerio de Agricultura, 2000). However, in spite of the effort invested and the relative success achieved, this institution is based on textbook technical proposals and lacks a scientific scientific basis.

1.2 Multiscale approach

Lack of understanding of the causes and effects of erosion hampers the development of appropriate conservation strategies. Obviously, there is a need for a better quantitative understanding of erosion processes at the hillslope scale for on-site impact assessment and at the watershed scale for off-site impact assessment. Soil erosion studies should be described at different scales, e.g. plot scale and catchment scale. Small plots are used to study basic erosion processes that are difficult to study in detail on larger plots (e. g. surface sealing, aggregate stability, splash, etc.) and experimental results at this level should complement those obtained at bigger scales (Mutchler et al., 1994). Studies at the plot scale (e.g. USLE plots) provide the opportunity to evaluate quantitatively the effectiveness of alternative land management treatments in terms of soil loss, water retention and possible loss of the productive value of parcels of land (Stroosnijder, 1997). Studies at the catchment scale indicate the integrated consequences of the complex combination of land characteristics and land management in the 3-D landscape (Briquet and Claude, 1998) that does not necessarily reflect what happens at plot scale.

For a better assessment of erosion, the relations between the information obtained at each scale must be examined. The information generated at plot and land parcel scales is useful if a continuous monitoring system and well-distributed network of plots have been installed in the watershed. Hotspots can be detected this way, although the high cost that the set-up requires must be considered as a disadvantage. On the other hand, the analysis of sediments in the river provides us with rough estimates of what is happening in the catchment but does not allow us to identify the susceptible area(s) that are being eroded.

1.3 Soil erosion modeling

Simulation models are modern tools for understanding erosion processes and their interactions and for setting research priorities. They can predict erosion risk under various land management practices and best practices can be determined (Visser, 2004). One well-validated erosion prediction model that is widely used is the Water Erosion Prediction Project (WEPP) model (Bhuyan et al., 2002). It will help to identify which part of the system is the most important to the overall erosion process and should be given attention in research and development of erosion control technology (Nearing et al., 1994). WEPP constitutes a powerful and modern tool to achieve such understanding and is intended to replace older empirical approaches such as the USLE (Wischmeier and Smith, 1978).

WEPP (Flanagan and Nearing, 1995) is a distributed parameter, process-based, continuous simulation, erosion prediction model designed for personal computers that is based on fundamental hydrologic and erosion science. The hillslope version estimates soil detachment and deposition along a hillslope profile (sheet and rill erosion) and the net total soil loss at the end of the slope. The model can also simulate the hydrologic and erosion processes of small watersheds.

1.4 Study area

The area where fieldwork was done for this thesis is in La Encañada watershed in the Andean highlands of Peru, 40 km east of Cajamarca. It is located between 7°0’21’’S and 7°8’2’’S, 78°11’22’’W and 78°21’31’’W. The altitude in the watershed ranges from 2950 masl to 4100 masl (Figure 1).

The average precipitation for the whole La Encañada is 576 mm per year, distributed in the months of September to March. The main meteorological information is presented in Table 1, using three weather stations within the watershed: La Toma (3590 m), Usnio (3260 m), and Las Manzanas (3020 m) during 1995-2000. In general, the area is under the effect of low intensity rainfall events (< 10 mm h^{-1}). However, an increased number of high intensity rainfall events were related to the anomalous year of “El Niño” in 1997, where the highest intensity reached 130 mm h^{-1} in La Toma in 1997.

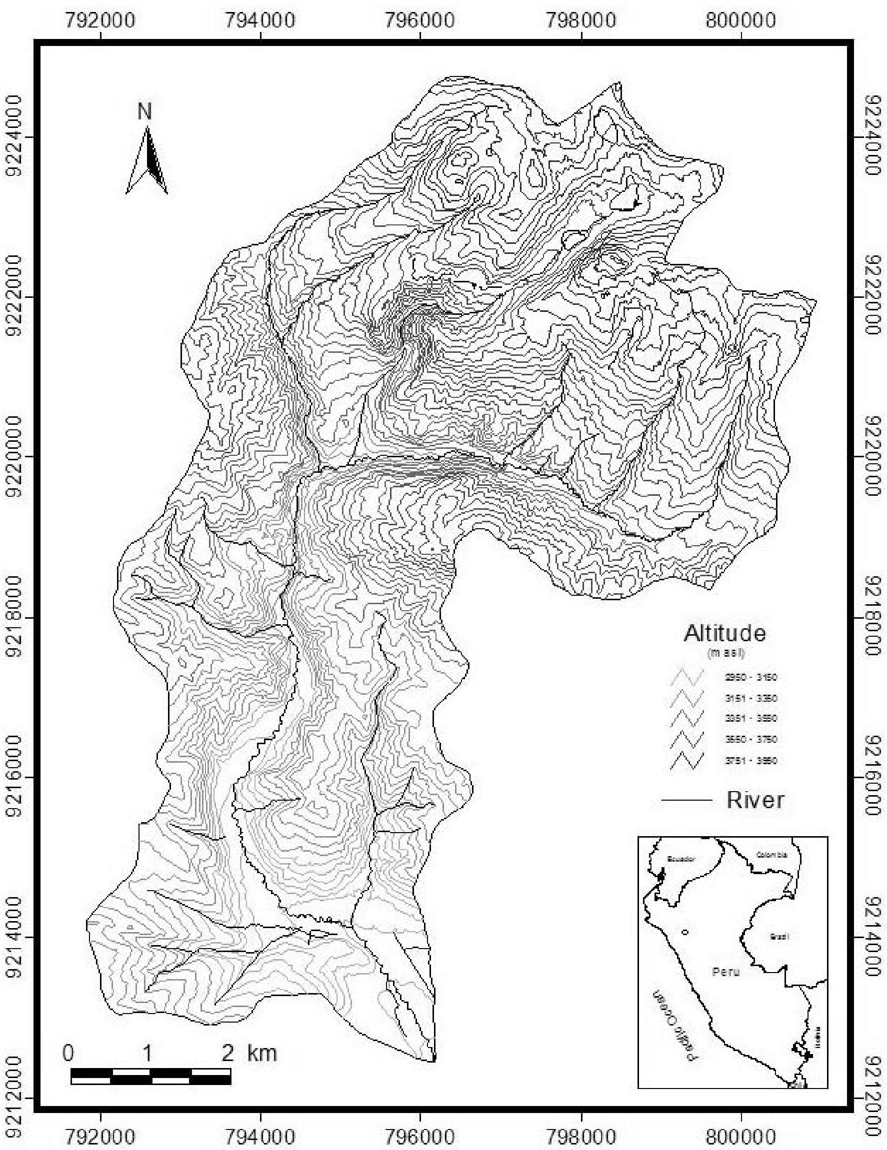

Figure 1.1. *Location map of La Encañada watershed, northern Peru.*

The soil parent materials are limestone, sandstone, siltstone, shale and quartzite whereas the dominant soils in La Encañada are classified as Entisols (Fluvents), Inceptisols (Ochrepts and Umbrepts) and Mollisols (Aquolls and Ustolls) in the U.S. Taxonomic Classification System (INRENA, 1998). Most of the watershed area presents sandy loam soils and the dominant organic matter level in the soil is medium to high (over 2%). Deep soils with high organic matter content are cultivated, with the most important crops being cereals, potato, maize and legumes. Crop yields are variable, depending on soil fertility and climatic conditions. Shallow soils of poor fertility are sometimes also cropped, in spite of being associated with steep slopes showing erosion characteristics. However, most shallow soils are only suitable for natural pasture (Overmars, 1999; Proyecto PIDAE, 1995). Near sixty five percent of the area has a slope gradient less than 15 %, so the topography is gentle for erosion processes. However, there are also areas with very steep slopes (exceeding 70 %), where there is increased risk of erosion. The aim of the study described in this thesis was to analyze the erosion process at different scales in the La Encanada watershed, using the

WEPP model. For this, a special three-stage methodology was developed for data collection and model validation. Step one consisted of a broad investigation of all WEPP input parameters at the watershed scale, followed by an uncertainty analysis. This analysis provided the decision support for the second step that consists of the validation of the hillslope version of WEPP. Finally, in a third step the hillslope version of WEPP was upscaled to obtain erosion maps at watershed scale to determine erosion hotspots in the area.

Table 1.1. *General climatic conditions (1995-2000) in La Encañada watershed, north Peru.*

Weather stations	Solar radiation (MJ m^{-2} d^{-1})	Maximum temperature (°C)	Minimum temperature (°C)	Rainfall (mm)	Number of days with rainfall
La Toma	19.9	10.8	2.8	832	193
Usnio	19.2	14.2	6.1	720	152
Manzanas	18.3	16.2	5.9	633	177
Average La Encañada	19.1	13.7	4.9	767	174

1.5 Thesis outline

This thesis has eight chapters. A general introduction to La Encañada area and the development of the methodology are given in Chapter 1. Chapter 2 presents a detailed study of the rainfall characteristics; the aggressiveness of rainfall to produce erosion, also called erosivity of rainfall, is highlighted. The susceptibility of soils to be lost both by rainsplash and by concentrated flow is described in Chapter 3. The uncertainty analysis performed using the WEPP model on the input parameters collected is described in Chapter 4. Chapter 5 presents the validation of the hillslope version of WEPP, whereas Chapter 6 introduces a new tool, the GEMSE interface, which permits the visualization of the erosion process at the watershed scale. The methodologies applied during the execution of the fieldwork for this thesis are presented in Chapter 7 and conclusions are drawn in the final chapter.

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Chapter 2

Rainfall erosivity in the northern Andean Highlands of Peru: The case of La Encañada watershed

2. Rainfall erosivity in the northern Andean Highlands of Peru: The case of La Encañada watershed

Abstract

Information related to rainfall erosivity in Peru is scarce. This study was carried out to determine the erosive potential of rainfall in La Encañada watershed (in the northern Andean Highlands of Peru) using daily rainfall data from 1995 to 2000. We analysed the total amount, duration, intensity, kinetic energy and probability of return of the daily rainfall. Almost 80 % of rainfall events had an average rainfall intensity less than 2.5 mm h^{-1} and only 4 % had an average intensity larger than 7.5 mm h^{-1}. A relationship was found between the El Niño phenomenon and the total amount of rainfall as well as the probability of high intensity events. During a La Niña phenomenon the rainfall intensities were low but the total rainfall was higher than in an El Niño year. The spatial rainfall distribution and the optimal density of weather stations within the watershed were also analysed.

Keywords: Rainfall, erosivity, Andes, El Niño.

2.1 Introduction

Rainfall data are of interest for land use planning. (Whiteman, 2000; Schwab, et al., 1993) because rainfall characteristics such as duration, frequency and intensity affect the soil erosion process. The energy of raindrops helps detach soil particles, and by generating runoff the rain contributes to the transport of these particles (Morgan, 1995). Rainfall can be characterised in many ways, varying from total precipitation in a year, season or other period, to daily rainfall or totals per rainfall event (Hoogmoed, 1999). However, often a shortage of water for farming is not the consequence of low annual rainfall but of poor seasonal distribution (Sivakumar & Wallace, 1991). Furthermore, the response of soil to rainfall in terms of soil loss can be variable: dramatic erosion processes can be observed during the rainy season, when heavy but not extreme precipitation intensities coincide with infrequent high soil moisture conditions in the watershed.

The study area, La Encañada watershed in the northern Peruvian Andes, receives between 500 and 1000 mm per year, so the zone could be considered as relatively wet for the Andes. It is characterised by its hilly topography, with steep slopes constantly at risk of land degradation processes.Therefore, this research set out to characterise the rainfall in this watershed. The characteristics analysed were total amount, duration and intensity per rainfall event, kinetic energy and return period. This information is relevant since rainfall analyses are scarce in Peru due to the lack of data. The high variability of the mountain climate makes it difficult to analyse the area's rainfall, especially in relation to the El Niño and La Niña phenomena.

2.2 Materials and methods

The study area

The research was carried out in La Encañada watershed (approximately 160 km^2) in the northern Peruvian highlands (Cajamarca-Peru), between 7°00' and 7°08' S, 78°11' and 78°21' W longitude, at 2950 to 4000 m altitude. There are three base weather stations in the area: La Toma (3590 masl), Usnio (3260 masl) and Manzanas (3020 masl). The oldest, Usnio, was set up in 1983; the other two were set up in 1995. For this research, six additional automatic weather stations with rainfall, temperature and humidity sensors were installed in the study area to verify the spatial variation of rainfall. The general climatic conditions are presented in Table 2.1; Figure 2.1 shows the location of all weather stations.

Table 2.1. *General climatic conditions (1995-2000) in La Encañada watershed, north Peru.*

Weather stations	Solar radiation ($MJ\ m^{-2}\ d^{-1}$)	Maximum temperature (°C)	Minimum temperature (°C)	Rainfall (mm)	Number of days with rainfall
La Toma	19.9	10.8	2.8	832	193
Usnio	19.2	14.2	6.1	720	152
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Average La Encañada	19.1	13.7	4.9	767	174

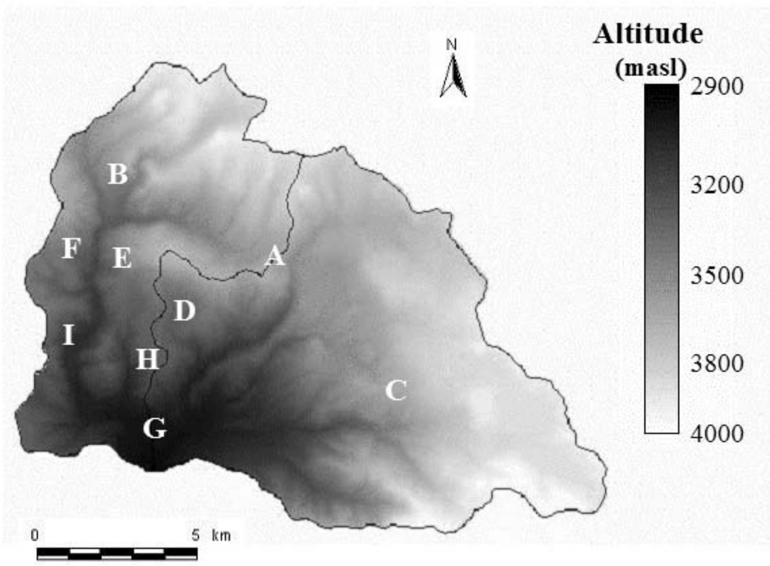

Figure 2.1. *Spatial distribution of weather stations of La Encañada watershed north Peru.*
A= La Toma, B= Quinuamayo, C= San Jose, D= Usnio, E= Paulino, F= Sogoron, G= Manzanas, H= Chagmapampa, I= Calvario.

The soils in La Encañada watershed are Entisols, Vertisols and Molisols. The rainy season is from September to March. The cropping season is determined more by the actual rainfall pattern than by the average rainfall, since farmers do not use weather data but instead rely on collective indigenous knowledge.

The rain events were divided into 4 size classes: very small (<1mm), small (1-10 mm), medium (10-20) and large (>20 mm) (Hoogmoed and Stroosnijder, 1984). Using the rainfall charts of the three base weather stations for 1995 to 1998, we analysed rainfall amount, duration and intensity. Though there were no charts for 1999 onwards, data for 1998 to 2000 were available from the automatic raingages.

The most suitable expression of the erosivity of rainfall is an index based on the kinetic energy of the rain (Morgan, 1995). To calculate kinetic energy we used the Wischmeier and Smith (1958) equation:

$$KE = 11.87 + 8.73 \log I \qquad (1)$$

Where I is the rainfall intensity (mm h^{-1}) and KE is the kinetic energy (J m^{-2} mm^{-1}).

We constructed the intensity-duration-frequency relationship curves for different return periods. They were constructed to facilitate the description of the geographical variability of rainfall in an specific location (Linsley, 1977). This type of analysis reveals the probability of a rainfall event of a given magnitude happening. This is important, since some events could be so heavy or so intense that they are likely to produce 'exceptional' floods (streams overflowing), increasing the risk of erosion downstream in the catchment. Consequently, we did this analysis for several reasons:

- in order to predict the likelihood of an exceptionally heavy rainfall event reoccurring. For this estimate return periods (Oklahoma Climatological Survey, 1996) are used. A return period is an estimate of the period between rainfall events of a given magnitude and is based on statistics.
- to improve the information that prevails in areas like this. The information gained will make it easier to predict flooding.

2.3 Results and discussion

Table 2.1 shows the average (1995-2000) annual rainfall at the three base weather stations. The average for the whole watershed was calculated as 767 mm; on this basis, the area can be classified as Tropical Summer Rain High Mountain climate (HAw) according to Köppen's reformed classification (Rudloff, 1981). However, an analysis per year shows oscillating values (Table 2.2), with large variations: at La Toma, from 298 mm in 1996 to 1122 mm in 1997; at Usnio, from 363 mm in 1996 to 1054 mm in 1997; and at Manzanas, from 526 mm in 1997 to 858 mm in 1998.

The temporal variability observed during these years can be related to the information given by the Climate Prediction Center (CPC) (National Oceanic and Atmospheric Administration (NOAA), 2001), which has compiled the cold (La Niña) and the warm (El Niño) episodes to provide a season-by-season breakdown of conditions in the Tropical Pacific. The neutral years corresponded to 1995 to 1996, with a weak incidence of La Niña at the end of 1995. From the end of 1997 to the beginning of 1998 a strong El Niño phenomenon occurred, characterised by a major increase in the rainfall at La Toma and Usnio weather stations, resulting in the totals exceeding 1000 mm. At the Manzanas weather station, however, the rainfall was similar to that of neutral years: 526 mm (Table 2.2). Weak and strong episodes of La Niña occurred during 1998 to 2000 (CPC-NOAA, 2001). At all three weather stations, total rainfall during the La Niña years was higher compared to neutral years.

Thanks to the network of weather stations in the study area it was possible to study the spatial variability of rainfall with the altitude. Figure 2.1 shows the spatial variation of the stations and Table 2.3 the total rainfall recorded from 4 December 1998 to 4 January 1999. For example, point "I" (Calvario weather station) recorded 166 mm and point "E" (Paulino weather station) recorded 29 mm; these stations are only 1.5 km apart and both are at 3250 m altitude. Point "G"(Manzanas weather station), at a lower altitude (2900 m) recorded 107 mm, whereas point "A" (La Toma weather station), at 3800 m altitude, recorded 203 mm of rainfall. From these data, no relationship could be established between the rainfall and altitude, because of the complexity of the mountainous terrain. Rainfall is not only affected by the altitude of the terrain but also by the proximity to moisture sources, the relief and the aspect relative to the direction of the approaching wind (Whiteman, 2000). Storms may occur randomly over complex terrain depending on local stability.

In the five years from 1995 to 2000, rainfall events varied from 0.1 to 56 mm, with the average being 3 mm. During a neutral year (e.g. 1995) most (90%) events were less than 10 mm and only 1.2% had more than 20 mm (Table 2.4). In the El Niño year (1997-1998), there was an increase in the number of events in the higher part of the watershed (La Toma and Usnio): here, there was a 15% increase in the events of 10-20 mm rainfall. Events of more than 20 mm increased by up to 3.8%. However, in the Manzanas area there were fewer events than in a neutral year, despite events of 10-20 mm increasing from 51% to 69%. During the La Niña years, events in all size classes increased at Manzanas. Here, the percentual distribution was similar to that of an El Niño year at La Toma and Usnio, but at Manzanas there were more events <1 mm and 10-20 mm than in an El Niño/neutral year. Because of this, the rainfall totals recorded at Manzanas were higher during La Niña years.

Table 2.2. Total amount of rainfall, maximum rainfall intensity and number of events with >25 mm h^{-1} per rainy season (1995-2000)

	La Toma			Usnio			Manzanas			
Rainy season	Total rainfall mm	Max. avg. intensity mm h^{-1}	Number of events	Total rainfall mm	Max. avg. intensity mm h^{-1}	Number of events	Total rainfall mm	Max.avg. intensity mm h^{-1}	Number of events	Weather anomalies
1995 (9/95-3/96)	408	40.0	2	629	156.3	5	531	70.0	1	Neutral
1996 (9/96-3/97)	298	55.0	2	363	11.0	0	512	147.3	3	Neutral
1997 (9/97-3/98)	1122	130.0	3	1054	17.7	0	526	82.5	11	El Niño
1998 (9/98-3/99)	1252	7.4	0	826	16.8	0	858	82.4	1	La Niña
1999 (9/99-3/00)	1081	5.0	-	728	4.5	-	736	4.4	-	La Niña

Table 2.3. *Rainfall between 04.12.1998 and 04.01.1999 at 9 different locations in La Encañada watershed, north Peru.*

Code in Figure 2.1	Name of station	Altitude (masl)	Rainfall (mm) 04.12.98 – 04.01.99
A	LA TOMA	3590	203
B	Quinuamayo	3500	298
C	San Jose	3550	27
D	USNIO	3260	117
E	Paulino	3250	29
F	Sogoron	3400	99
G	MANZANAS	3020	107
H	Chagmapampa	3300	99
I	Calvario	3250	166

Table 2.4. *Frequency analysis of rainfall size classes for different altitudes and El Niño/La Niña years at La Encañada, north Peru.*

Neutral years (1995 and 1996)

	< 1 mm	1-10 mm	10-20 mm	>20 mm
LA TOMA				
No. of events	112	133	3	0
% of total	45.2	53.6	1.2	0
USNIO				
No. of events	72	121	26	4
% of total	32.3	54.3	11.7	1.8
MANZANAS				
No. of events	101	134	22	5
% of total	38.5	51.1	8.4	1.9

El Niño year (1997)

	< 1 mm	1-10 mm	10-20 mm	>20 mm
LA TOMA				
No. of events	69	104	32	8
% of total	32.4	48.8	15	3.8
USNIO				
No. of events	40	84	26	10
% of total	25	52.5	16.3	6.3
MANZANAS				
No. of events	23	77	8	3
% of total	20.7	69.4	7.2	2.7

La Niña years (1998 and 1999)

	< 1 mm	1-10 mm	10-20 mm	>20 mm
LA TOMA				
No. of events	147	216	64	15
% of total	33.3	48.9	14.5	3.4
USNIO				
No. of events	109	158	43	8
% of total	34.3	49.7	13.5	2.5
MANZANAS				
No. of events	93	178	49	7
% of total	28.4	54.4	14.9	2.1

From the frequency analysis of rainfall size classes (Table 2.5) it can be seen that during the five years (1995-2000) the distribution of the four size classes at the three weather stations is similar. Approximately 85% of the events were < 10 mm. Though small events, they represented 51% of total rainfall. Though only 14% were bigger than 10 mm, this percentage was responsible for 49% of the total rainfall. By contrast, events > 20 mm were extremely rare, representing only the 3% of the total events but up to 18 % of total rainfall. Most of these bigger events were reported during the El Niño year (1998).

Table 2.5. *Frequency analysis of rainfall size classes in north Peru (1995-2000).*

	< 1 mm	**1-10 mm**	**10-20 mm**	**>20 mm**	**Total**	**Per year**
LA TOMA (3590)						
No. of events	328	454	96	23	901	180
% of total	36	50	11	3	100	
mm in class	137	2035	1365	622	4159	832
% of total	3	49	33	15	100	
USNIO (3260)						
No. of events	221	363	93	22	699	140
% of total	32	52	13	3	100	
mm in class	91	1542	1300	668	3601	720
% of total	3	43	36	18	100	
MANZANAS (3020)						
No. of events	217	389	79	15	700	140
% of total	31	56	11	2	100	
mm in class	91	1566	1099	408	3164	633
% of total	3	50	35	13	100	

According to the NWS (1995) there are three categories of rainfall intensity: light (up to 2.5 mm h^{-1}), moderate (2.6 to 7.5 mm h^{-1}) and heavy (more than 7.5 mm h^{-1}). Our analysis of the average intensity of all rainfall events during 1995-2000 revealed that 71% of the events at the three weather stations were < 2.5 mm h^{-1}, approximately 16% of events were between moderate and only a 4% of events were heavy. See Figure 2.2. The data given in Table 2.6 refer to the average intensities of rainfall. In this table the data are given per year, showing that during El Niño year there were 18% of events > 7.5 mm h^{-1} recorded at the Manzanas weather station, in the lower part of the watershed. On the other hand, more low intensity events were recorded during La Niña year: 91% of events were < 2.5 mm h^{-1}. In the entire area, only 0.6% were > 7.5 mm h^{-1}.

The difference between neutral years and abnormal years with El Niño/ La Niña is remarkable, especially in relation to the spatial distribution of the number of heavy rainfall events. The maximum value for a neutral year was 156 mm h^{-1}, recorded at Usnio weather station, whereas during the El Niño year the highest value was 130 mm h^{-1} (Table 2.2). What makes an El Niño year really different from a neutral year is the total amount of rainfall and the high number (14) of events

> 25 mm h^{-1}. During La Niña years there was only one heavy event of 82.4 mm h^{-1}; most events were light (< 2.5 mm h^{-1}).

The intensity analysis was done to ascertain the kinetic energy of rainfalls. If, in accordance with Hudson (1981), 25 mm h^{-1} is considered to be the minimum intensity that will induce significant erosion, 28 of the events in our data set meet this criterion (Table 2.2). Fourteen of them were in the El Niño year. During this rainy season there was a big landslide in the watershed. From this we conclude that the risk of erosion might be higher during an El Niño year than in neutral or La Niña years.

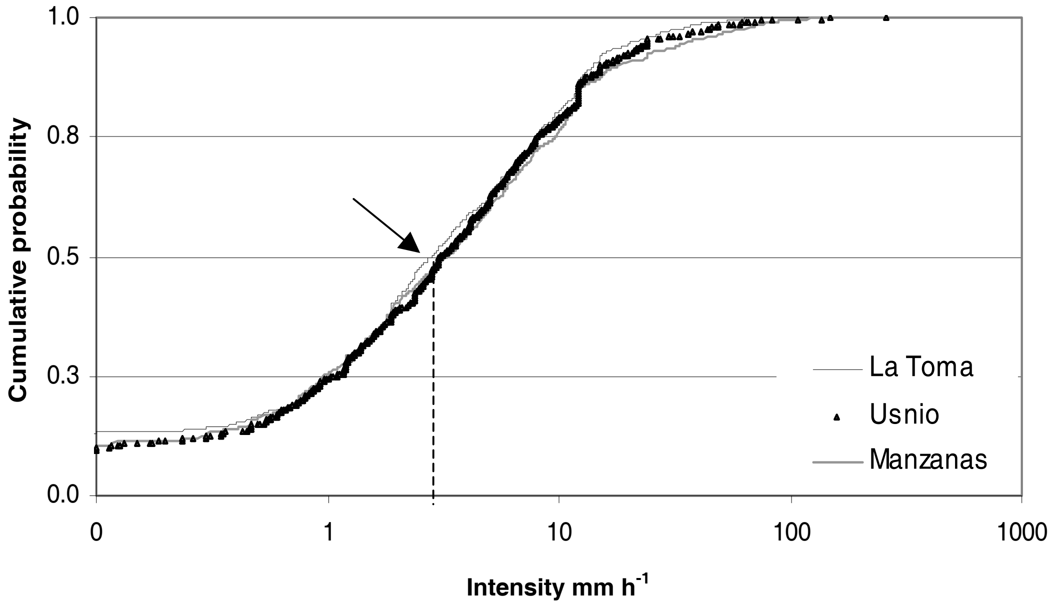

Figure 2.2. *Rainfall intensity probability of occurrence at three weather stations in north Peru.*

In runoff and soil erosion research it is crucial to determine the kinetic energy of rainfall, since this energy is what drives these processes. We determined this parameter from data from the three base weather stations. The probability curves constructed are shown in Figure 2.3. At least 50% of rain had kinetic energy values below 17 J m^{-2} mm^{-1} ; most of the remaining 50% did not surpass values of 29 J m^{-2} mm^{-1}. Once again it can be observed that the more erosive rainfalls were in the lower part of the watershed at Manzanas (3020 masl). Fortunately, this area is flatter than the higher areas and there is therefore less risk of erosion. The upper parts of the watershed have lower values of kinetic energy but the topography is more complex and the erosion and runoff processes can still be important.

So far, the analysis has been based on the average intensities of the rain event. Yet within a rain event there are short periods when the intensity can be very high, and therefore very erosive. In order to determine this, the Wischmeier index (EI30) (Lal and Elliot, 1994) was calculated from three random rain charts based on the principle that the erosivity of the chosen rainfalls is equal to that of all erosive rainfalls (Xie et al., 2001). Three examples of two-hour duration rainfalls were chosen (Table 2.7).

Table 2.6. *Frequency analysis of rainfall intensity classes for different altitudes and Neutral/El Niño/La Niña years at La Encañada watershed, north Peru.*

Neutral years (1995 and 1996)

	< 2.5 mm h^{-1}	2.5 – 7.5 mm h^{-1}	> 7.5 mm h^{-1}
LA TOMA			
No. of events	163	63	23
% of total	65.5	25.3	9.2
USNIO			
No. of events	130	78	16
% of total	58.1	34.8	7.1
MANZANAS			
No. of events	179	63	15
% of total	69.6	24.5	5.8

El Niño year (1997)

	< 2.5 mm h^{-1}	2.5 – 7.5 mm h^{-1}	> 7.5 mm h^{-1}
LA TOMA			
No. of events	151	55	7
% of total	70.9	25.8	3.3
USNIO			
No. of events	99	42	2
% of total	69.2	29.4	1.4
MANZANAS			
No. of events	72	19	20
% of total	64.8	17.1	18.0

La Niña years (1998 and 1999)

	< 2.5 mm h^{-1}	2.5 – 7.5 mm h^{-1}	> 7.5 mm h^{-1}
LA TOMA			
No. of events	355	37	0
% of total	90.6	9.4	0
USNIO			
No. of events	289	21	2
% of total	92.6	6.7	0.6
MANZANAS			
No. of events	370	27	5
% of total	92.0	6.7	1.2

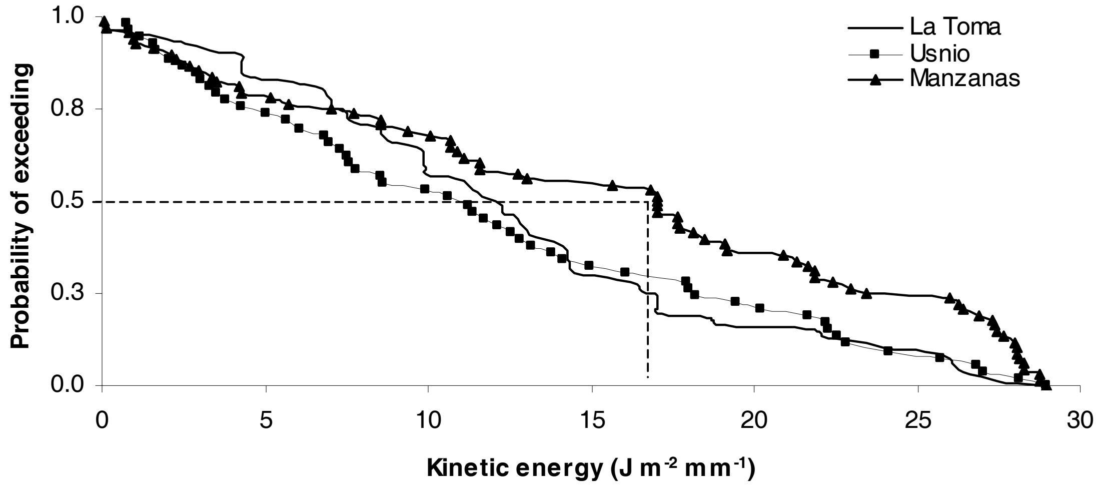

Figure 2.3. *Kinetic energy analysis at three weather stations at La Encañada watershed, north Peru.*

According to the duration analysis, 50% of the total rainfall events in the watershed were shorter than 2 hours. Like most of the events recorded in the area, these events were of light intensity and the amount of rainfall was small (<10 mm), In general terms, the values of EI30 were low. The maximum was at Manzanas weather station, at the bottom of the watershed: 295.1 J mm m^{-2} h^{-1}. The minimum was at La Toma weather station, in the highest part of the watershed: 20.3 J mm m^{-2} h^{-1}. Using the same equation, Hudson (1995) reported a value of EI30 equal to 262,668.98 J mm m^{-2} h^{-1}, for a tropical rainfall event. The comparison confirms that most of the rainfall events in this part of the Andes are light, but some are heavy enough to inflict real damage to the soil surface.

Table 2.7. *Three typical examples of two-hour rainfall events, showing the total kinetic energy and EI30 indexes.*

Location Altitude	**La Toma 3590 masl**		**Usnio 3260 masl**		**Manzanas 3020 masl**	
Interval (min)	Intensity (mm h^{-1})	Δ E J m^{-2}	Intensity (mm h^{-1})	Δ E J m^{-2}	Intensity (mm h^{-1})	Δ E J m^{-2}
30	1.2	7.5	2.0	14.5	0.2	0.6
30	0.6	2.9	0.5	2.3	2.8	22.1
30	1.4	9.2	0.3	1.1	1.0	5.9
30	0.2	0.6	0.8	4.4	4.4	38.5
Total E (J m^{-2})		20.3		22.31		67.1
Max.30-min rainfall		1.4		2.0		4.4
EI30 (J mm $m^{-2}h^{-1}$)		20.3 x 1.4		22.3 x 2		67.1 x 4.4
		= 29.13		= 44.6		= 295.1

The curves for 25, 10 and 5-year return periods are shown in Figure 2.4 for the three weather stations. The more intense events could be expected in the lower part of the watershed (Manzanas weather station) and the less intense events in the top of the watershed (La Toma weather station). At each location, the most intense events have a long period of return (e.g. 25 years). For example, the return period for a 10-min rainfall of 75 mm h^{-1} intensity in La Encañada is 25 years, at Manzanas weather station. For the same period of time (25 years) a 10-min rainfall of 38 mm h^{-1} intensity could be expected at the top of the watershed (La Toma weather station). Within a 5-year period of time, the maximum expected intensities for a 10-min rainfall event are between 12 and 28 mm h^{-1} . However, longer events with slightly lower intensities could also be expected (e.g. 100-min duration): these events also increase the risk of erosion in the area.

The intensity analysis revealed that during the El Niño year more events with high intensities were recorded at the bottom of the catchment. This is attributable to the marked warming of plane surfaces inducing convective rainfall (Barry and Chorley, 1980), since the lower part of La Encañada watershed is next to a plateau of approximately 60 km^2 called “Pampa de la Culebra”, which is a large convective area. The areas more susceptible to erosive events can be determined and although the response of soils depends not only on rainfall but also on factors like soil type and slope, knowing the return periods of rainfall events allows us to evaluate the erosion risk over time.

Importance of the number of weather stations for monitoring rainfall

For hydrometeorological monitoring in tropical mountain regions, the World Meteorological Organization (1970) recommends one weather station for an area of 100 to 250 km^2. In our study we found great differences in the measured parameters (e.g. rainfall amount), even across distances as short as 1.5 km. The density of weather stations recommended by the WMO is too extensive to reveal the great spatial variation hidden in this complex terrain. Even though we did not set out to recommend a new number of weather stations per unit of area, we wish to note that in order to understand the climate variability in mountainous areas, there must be a higher density of weather stations. In our study the density was 1: 20 km^2. The density of weather stations has repercussions on research on other topics, such as soil erosion modelling (Nearing et al., 1989) and crop production modelling (Tsuji et al., 1998), since the spatial and temporal distribution of rainfall and other related parameters are used as model input. The output generated by models depends on the accuracy of rainfall data and the representativeness of the weather station network. One example of the importance of having more detailed climatic data in order to be able to model the real rainfall distribution in mountain areas more closely is the new process-based model that generates rainfall data (Baigorria et al., 2000).

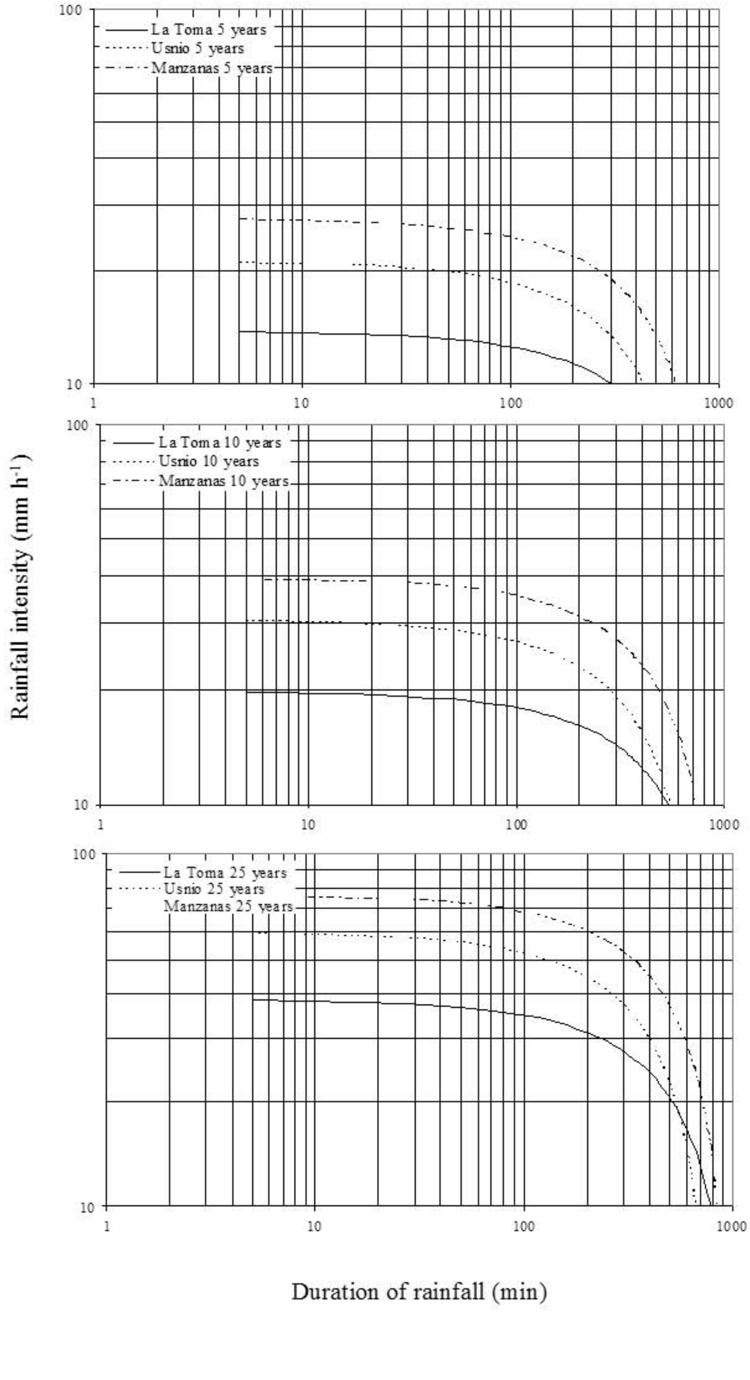

Figure 2.4. *Rainfall intensity-duration-frequency curves at three weather stations at La Encañada watershed, north Peru.*

2.4 Conclusions

This study of the spatial and temporal distribution of rainfall characteristics in La Encañada watershed in north Peru from 1995 to 2000 revealed that in the neutral years (9/95-3/96 and 9/96-3/97) mean annual rainfall was < 600 mm. However, during El Niño (9/97-3/98) and La Niña (9/98-3/99 and 9/99-3/00) years the annual amount increased, with the maximum being 1200 mm. In general, rainfall intensities were very low, with 96 % of events < 7.5 mm h^{-1}. But during El Niño year, the number of high intensity events increased in the lower part of the watershed (18%) where normally only 4 % of events were high intensity. The La Niña year was characterised by a large rainfall total, but lower intensities.

Our analysis showed that in the lower part of the watershed, rain events are more erosive, especially during abnormal years such as El Niño. Being near to a big plateau of approximately 60 km^2, the lower part of of La Encañada is a large convective area. This area is most likely to experience the highest intensity rainfall events in subsequent years, whereas the lowest intensity events are more likely to be in the upper part of the watershed. However, in the latter area the total annual rainfall is higher.

Depending on the year, some spatial variation can be observed in the amount of rainfall falling at different altitudes. This variation seems to be related to the topography and to phenomena like El Niño/La Niña that affect wind circulation and the convective movement of air masses. Areas at risk of erosive events can be determined within the watershed, although the response of soils depends not only on rainfall erosivity but on many other factors such as soil type, slope and vegetation.

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Chapter 3

Soil erodibility in the northern Andean Highlands of Peru: The case of La Encañada watershed

3. Soil erodibility in the northern Andean Highlands of Peru: The case of La Encañada watershed

Abstract

There is little information about erodibility in La Encañada watershed (northern Peru), even though this one of the most important factors affecting soil erosion. Therefore, to ascertain how susceptible the soils in this area are to erosion, and to relate erodibility to their physical characteristics, the interrill (Ki) and rill (Kr) erodibility factors of the soils were determined. The erodibility factor of the Universal Soil Loss Equation was also determined. At each point of the evaluation, the percentages of sand, clay, silt, very fine sand and organic matter were determined. A stepwise analysis was applied to ascertain the influence of the independent variables on the measured Ki and Kr values. Equations were chosen in accordance with the lowest standard deviation and the highest correlation indexes of these variables. The observed interrill erodibility ranged from 1.9 to 56 10^5 kg s m^{-4}. Rill erodibility ranged from 0.3 to 14 10^{-3} s m^{-1}. Most of the evaluated soils had low erodibility values. The most erodible were those with higher contents of silt and very fine sand. On the basis of the findings, the following refined equations are proposed: Ki = -756916+1801775 silt + 15852646 vfs and Kr = -0.00778 + 0.00840 clay + 0.0341 vfs + 0.139 orgmat, where silt, clay, vfs (very fine sand) and orgmat (organic matter) are expressed as fractions. It was also found that Ki and K (USLE) had a polynomial relationship whereas Kr and K (USLE) had an exponential relationship. The results suggest that in La Encañada watershed the erodibility is generally low and the risk of erosion is low. However, silty soils can still be a source of sediments in the area.

3.1 Introduction

La Encañada is a 160 km^2 watershed located in the northern Andes of Peru, between 3000 and 4000 masl with around 800 mm precipitation during the rainy season (October-March). In this area the soil properties such as texture, organic matter content and chemical constituents have been well studied but there is little information about soil erosion in the area.

A soil's inherent susceptibility to erosion by water is quantitatively expressed by its erodibility (El-Swaify and Dangler, 1977). This susceptibility depends on soil properties like texture, structural stability, organic matter content, type of clay and chemical properties. The risk of erosion increases if a soil contains a greater amount of silt and very fine sand. These are the most erodible particles, since they are more easily detached and transported than sand and clay particles. Sandy soils can easily be detached but is less easily transported; clay soils can form stable aggregates with organic matter, which protect them from detachment and transport. The soils in La Encañada are predominantly sandy, but in some areas have a silty texture.

With the development of the Universal Soil Loss Equation – USLE (Wischmeier and Smith, 1978) – the identification of the soil erodibility "K" factor became a central issue in erosion studies (Bryan et al., 1989). However, erosion can be divided into two components: rill and interrill erosion. Interrill erosion is caused by soil particles being detached by raindrops and transported by overland flow. Rill erosion, however, is the detachment and transport of soil particles by concentrated flow: it is a function of the shear of the water flowing in the rill (Lal and Elliot, 1994). Recent computer simulation models like the Water Erosion Prediction Project – WEPP (Nearing et al., 1989) – developed by the United States Department of Agriculture (USDA) require the input of two erodibility values for each soil type: interrill (Ki) and rill (Kr) erodibility.

Erodibility factors should be measured in the field, particularly in areas where no determinations have previously been made. The erodibility can be determined using different kind of rainfall simulators. These are research tools designed to apply water in a form similar to a natural rain. The drawbacks of rainfall simulator research are the cost and time required to construct a suitable simulator and the logistics (equipment and personnel) entailed (Meyer, 1994).

The USLE empirical technology, which is still applied all over the world, provides a practical alternative: the K factor is estimated from certain physical properties of the soil (Wischmeier and Smith, 1978). WEPP technology also includes two regression equations to calculate interrill (Ki) and rill (Kr) erodibility, also based on soil properties (Flanagan and Nearing, 1995). However, Vanelslande *et al.* (1984) have reported that the Wischmeier nomograph is unsuitable for estimating the erodibility of soils in the tropics. Though its climate is temperate due to its altitude (3000 to 4000 masl), La Encañada is in the tropics. Therefore, in this area, it is inadvisable to use the Wischmeier equations.

The main approach of the study reported here was to determine the interrill and rill erodibility factors on different plots within the watershed using field experiments. These data were then used to construct regression equations for soils of La Encañada. In this paper we will also estimate the K factor for every plot using the Wischmeier's nomograph. Finally, we will compare all these values and try to establish a relationship between the quantitative (Ki and Kr) and the qualitative (K) erodibility factors.

3.2 Material and methods

The study area

La Encañada watershed is in the Andean highlands of Peru, 40 km east of Cajamarca. It is located between 7°0'21''S and 7°8'2''S, 78°11'22''W and 78°21'31''W. The altitude in the watershed ranges from 2950 masl to 4100 masl. The main meteorological information is presented in Table 3.1, using three weather stations within the watershed: La Toma (3590 m), Usnio (3260 m), and Las Manzanas (3020 m).

The soil parent materials are limestone, sandstone, siltstone, shale and quartzite. In addition, there are unconsolidated soil parent materials: alluvium and fine and coarse fluvio-glacial, glacial, alluvio-colluvial or colluvial materials. The dominant soils in La Encañada are classified as Entisols (Fluvents), Inceptisols (Ochrepts and Umbrepts) and Mollisols (Aquolls and Ustolls) in the U.S. Taxonomic Classification System (INRENA, 1998). Figure 3.1 shows a soil map based on another soil survey made by Jimenez, 1996 (Overmars, 1999). Most of the watershed area presents sandy loam soils. The dominant organic matter level in the soil is medium to high (over 2%).

Deep soils with high organic matter content are cultivated, with the most important crops being cereals, potato, maize and legumes. Crop yields are variable, depending on soil fertility and on climatic conditions. Shallow soils of poor fertility which display soil erosion characteristics because they occur on steep slopes, are sometimes also cropped. However, most of them are only suitable for natural pasture (Overmars, 1999; Proyecto PIDAE, 1995).

Most of the area (65%) has a slope gradient less than 15 %. However, there are also some very steep slopes exceeding 70 %: Figure 3.2.

Table 3.1. *General climatic conditions (1995-2000) in La Encañada watershed, north Peru.*

Weather stations (masl)	Solar radiation (MJ m^{-2} d^{-1})	Maximum temperature (°C)	Minimum temperature (°C)	Rainfall (mm)	Number of days with rainfall
La Toma (3590)	19.9	10.8	2.8	832	193
Usnio (3260)	19.2	14.2	6.1	720	152
Manzanas (3020)	18.3	16.2	5.9	633	177
Average La Encañada	19.1	13.7	4.9	767	174

Interrill detachment was measured using a portable rainfall simulator (Kamphorst, 1987) at 21 points within the watershed, trying to cover most of the soils. Table 3.2 shows the minimum and maximum values of the main physical properties. Before the simulator was set up, stones and loose organic materials were carefully removed from each plot, taking care not to disturb the soil surface. After the simulator had been set up, a standard rain shower of 105 mm h^{-1} intensity was applied for 5 minutes. Runoff was sampled every minute. Sediment that splashed off the front of the tray was collected; only down slope splash erosion was measured. Splash and runoff samples were oven-dried at 105°C to obtain soil loss expressed in kg m^{-2}. Only bare-soil conditions were tested.

The Ki values were calculated using the formula (Elliot et al., 1989):

$$D_i = Ki\ i^2\ S_f, \qquad (1)$$

Where D_i = interrill erosion rate (kg m^{-2} s^{-1}); Ki = interrill erodibility (kg s m^{-4}); I = rainfall intensity (m s^{-1}) and S_f = slope factor (dimensionless =1.05 – 0.85 exp $^{(-0.85\ \sin[\theta])}$ where theta is expressed in degrees).

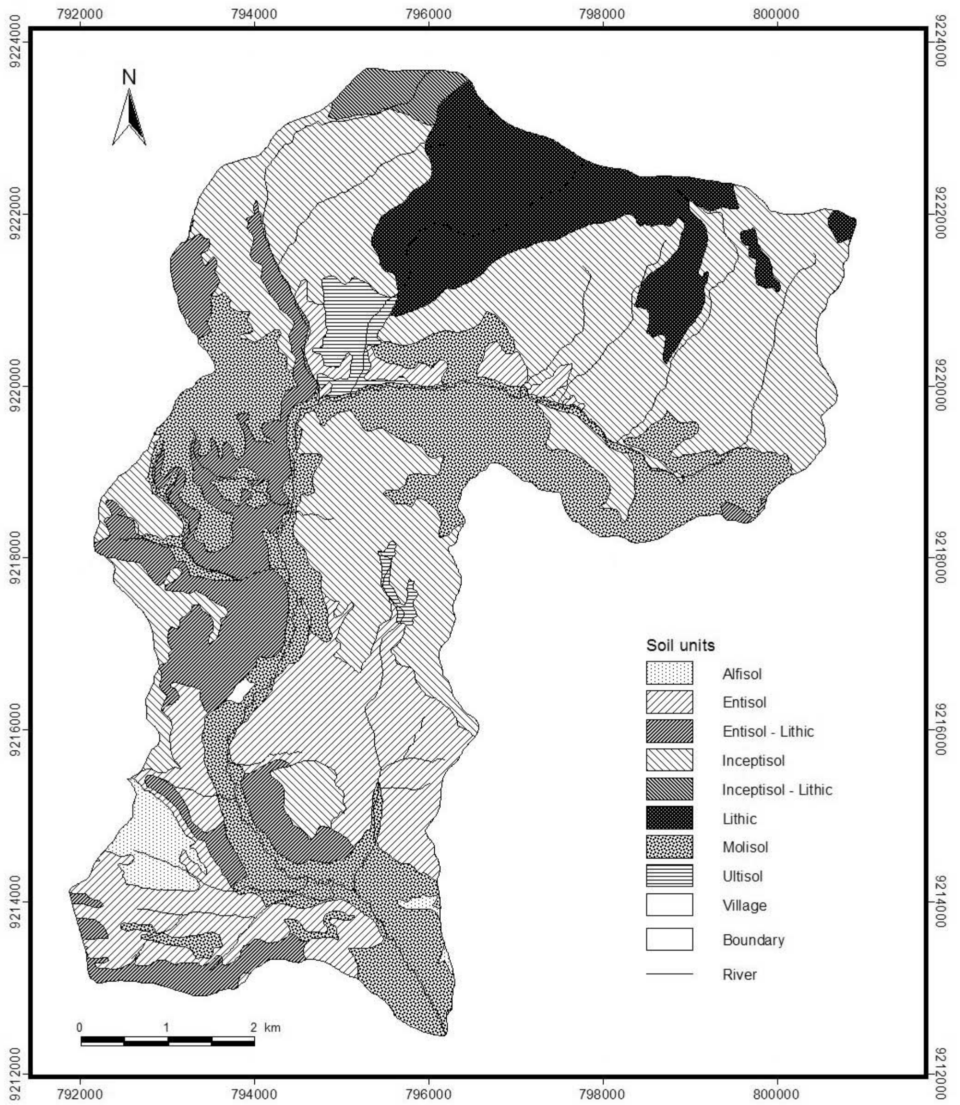

Figure 3.1. *Soil map of La Encañada watershed, Peru, based on Jimenez (1996).*

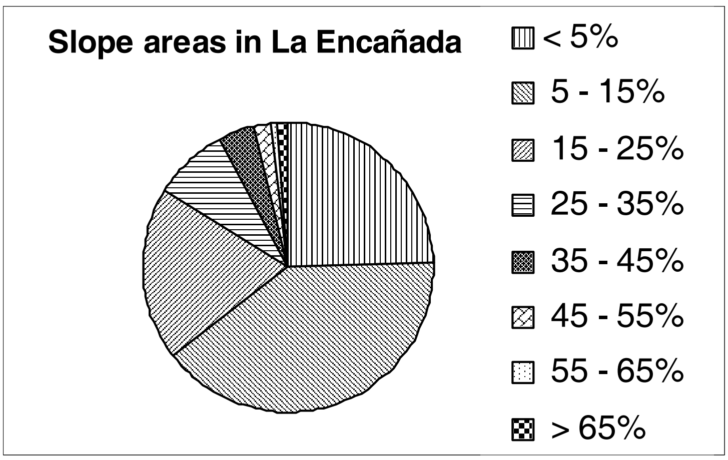

Figure 3.2. *Distribution of slopes in La Encañada watershed, Peru.*

At each of the 21 points Ki was also estimated using the formula of Flanagan and Nearing (1995) used in the WEPP model:

$$Ki = 2728000 + 19210000 \text{ vfs}, \qquad (2)$$

where vfs = very fine sand fraction.

Table 3.2. *Maximum and minimum physical soil properties at 21 points where Ki was measured in La Encañada watershed, Peru.*

	% Clay	% Silt	% Sand	% Very fine sand	% Organic matter
Minimum	2	16	22	4	2.3
Maximum	36	44	78	27	7.2

Rill erodibility (Kr) was measured using a procedure recommended by Lal and Elliot (1994). Seventeen points in the watershed were chosen. These points, which did not necessarily overlap with those used for the Ki determination, were sited where tap water was available. It was attempted to cover most soil types. Table 3.3 shows the minimum and maximum values of the main physical properties of the soil at these 17 points.

Using a shovel, artificial rills 0.1m wide and 3 m, 6 m, and 9 m long were created up and down the slope. Approximately 10 minutes of artificial rain was applied on each rill using a hosepipe, until an equilibrium outflow from the rill was observed. Then, while continuing the rain, tap water was added at the top of the plot, at 8, 10, 12 and 14 l min^{-1}. After reaching equilibrium outflow, the flow velocity and the concentration of sediment in the outflow were measured. For each combination of rill length and inflow sampling was done five times. The cross-sectional area (A) and wetted perimeter (P) were measured to determine the hydraulic radius (r) in each rill (r = A/P). Between each test, the rill was kept humid.

Using these measured data, the following rill detachment equation was applied to calculate Kr values (Elliot et al., 1989):

$$D_c = Kr\,(\tau - \tau_c), \qquad (3)$$

where D_c = rill detachment capacity for clean water (kg m^{-2} s^{-1}); Kr = rill erodibility (s m^{-1}); τ_c = critical shear stress (Pa); τ = hydraulic shear stress of flowing water (Pa; $\tau = \gamma$ r s, where γ = specific weight of water = 9810 N m^{-3}; r = hydraulic radius of rill, m; and s = hydraulic gradient of rill flow).

Measured rill detachment values (kg m^{-2} s^{-1}) were plotted against the hydraulic shear (Pa) values. The slope of the regression line is Kr, and the intercept with the horizontal axis is the critical shear, τ_c. Note that for each Kr value there were 60 data points plotted (5 samples * 3 rill lengths * 4 inflows). It was planned to use the information on τ_c for the construction of a regression equation so that in the future the critical shear of these soils could be calculated based on physical parameters.

At each of the 17 points Kr and τ_c were also estimated with the formulas of Flanagan and Nearing (1995) used in the WEPP model:

$$Kr = 0.00197 + 0.030\ vfs + 0.03863\ e^{-184 orgmat} \text{ and} \quad (4)$$
$$\tau_c = 2.65 + 6.5\ clay - 5.8\ vfs \quad (5)$$

where, vfs = very fine sand fraction and orgmat = organic matter fraction and clay = clay fraction.

Table 3.3. *Maximum and minimum physical soil properties at 17 points where Kr was measured in La Encañada watershed, Peru.*

	% Clay	% Silt	% Sand	% Very fine sand	% Organic matter
Minimum	5	20	20	3.5	0.6
Maximum	48	52	72	21.9	10.6

At each point where interrill and rill erodibility were measured, soil samples were taken from the top 30 cm of the soil. The percentages of sand, silt and clay were determined in the laboratory, by the hydrometer method (Day, 1965). Very fine sand was determined by wet sieving. Soil organic matter was determined by the chromic acid digestion method (Walkley and Black, 1947). Permeability and structure classes were qualitatively determined in the field. Soil erodibility according to Wischmeier (K) values was determined using the Wischmeier nomograph (1978)[1].

A stepwise analysis was applied to determine the influence of the independent variables (sand, silt, clay, very fine sand and organic matter) on the dependent variables, Ki and Kr. Suitable regression equations were chosen according to the lower standard deviation, the higher correlation index and the less number of independent variables (see Tables 4, 5 and 6).

To visualise and determine the Ki-K and Kr-K relationships, the measured Ki and Kr values were plotted against their corresponding K values.

3.3 Results and discussion

The measured interrill erodibility (Ki) values ranged from 1.9 to 56 10^5 kg s m^{-4}. This range is quite different from the range calculated using Eq. (2): from 20 to 110 10^5 kg s m^{-4}. Figure 3.3 shows the result of comparing the measured values with the values estimated using Eq. (2). From this Figure it seems that Eq. (2) overestimated the Ki values. The implication is that the soils are more resistant to detachment and transport by raindrop impact and therefore that the soils of La Encañada are less erodible than expected.

Figure 3.4 shows the distribution of the measured Ki values. The maximum Ki value (57 10^5 kg s m^{-4}) was measured in a soil with the largest amount of very fine sand (27 %) and almost the largest amount of silt (42 %). This maximum observed Ki value coincided with the highest value predicted by the Flanagan and Nearing (1985) equation (80 10^5 kg s m^{-4}). The minimum measured

[1] K values are in US customary units [tons /(ac (hundreds of ft tons in)/(ac hr^-))]. Metric units for K in the SI system are [(t h)/(MJ mm)]. Divide K in US units by 7.62 to get K in SI units.

Ki value (1.9 10^5 kg s m^{-4}) was observed in a soil with the lowest percentage of very fine sand (4 %) although the soil was quite sandy (70 %) and contained a smaller amount of silt (12%). The lowest observed Ki value also coincided with the lowest value predicted using Eq. (2) (35 10^5 kg s m^{-4}). As expected, soils with high percentages of very fine sand and silt appear to be the most erodible (Lal and Elliot, 1994).

The multistep regression analysis showed that the highest coefficient of determination was found between Ki and the very fine sand fraction (r^2 = 0.56). For other parameters like clay, silt, sand and organic matter, r^2 < 0.04. The r^2 values for the combination of parameters are also shown (Table 3.4).

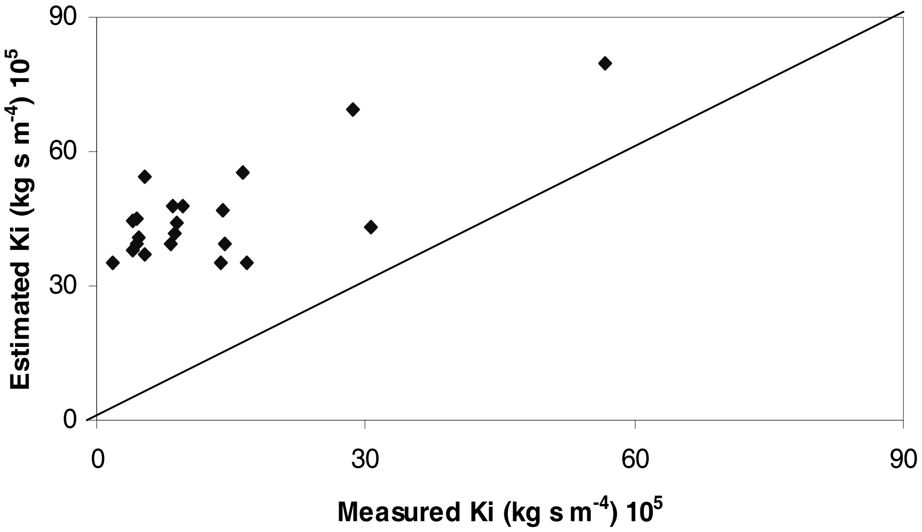

Figure 3.3. *Measured vs. WEPP estimated values of interill erodibility Ki for soils in La Encañada watershed, Peru.*

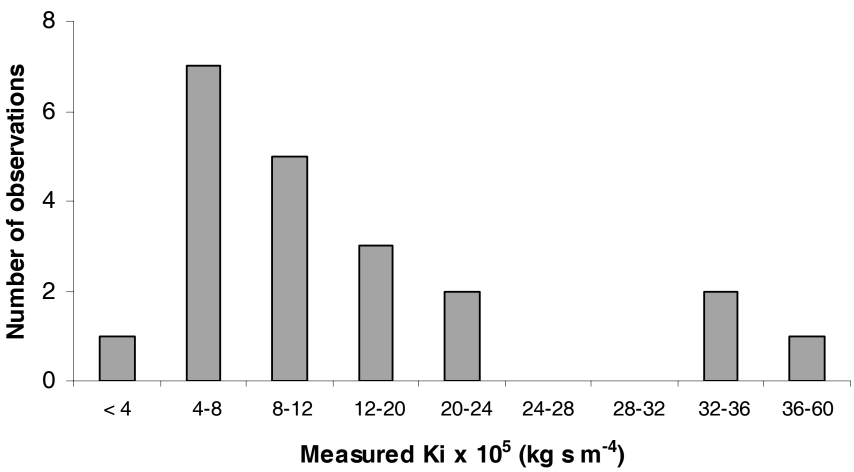

Figure 3.4. *Distribution of measured interrill erodibility values Ki in La Encañada watershed, Peru.*

Table 3.4. *Coefficient of determination (r^2) and standard deviation between interrill (Ki) & rill (Kr) erodibility and soil parameters, according to the multistep regression analyses. La Encañada, Peru.*

Soil parameters	**Ki**		**Kr**	
	St. dev.	r^2	St. dev.	r^2
Clay	1281498	0.024	0.00389	0.078
Sand	1271814	0.039	0.00399	0.030
Silt	1279035	0.028	0.00404	0.04
Very fine sand (VFS)	865131	0.56	0.00388	0.083
Organic matter	1289053	0.013	0.00366	0.182
Clay + Sand	1306278	0.039	0.00400	0.086
Clay + Silt	1306278	0.039	0.00400	0.086
Clay + VFS	888549	0.556	0.00381	0.171
Clay + OM	1315838	0.025	0.00379	0.183
Sand + Silt	1306278	0.039	0.00400	0.086
Sand + VFS	881303	0.563	0.00371	0.217
Sand + OM	1305259	0.041	0.00357	0.275
Silt + VFS	870534	0.573	0.00386	0.149
Silt + OM	1311101	0.032	0.00353	0.289
VFS + OM	886857	0.557	0.00316	0.432
Clay + Sand + Silt	1306278	0.039	0.00400	0.086
Clay + Sand + VFS	894978	0.574	0.00383	0.224
Clay + Sand + OM	134308	0.041	0.00359	0.316
Clay + Silt + VFS	894978	0.574	0.00383	0.224
Clay + Silt + OM	1343081	0.041	0.00359	0.316
Clay + VFS + OM	902574	0.567	0.00317	0.469
Sand + Silt + VFS	894978	0.574	0.00383	0.224
Sand + Silt + OM	1343081	0.041	0.00359	0.316
Silt + VFS + OM	887758	0.581	0.00327	0.435
Clay + Sand + Silt + VFS	894978	0.574	0.00383	0.224
Clay + Sand + Silt + OM	1343081	0.041	0.00359	0.316
Sand + Silt + VFS + OM	908719	0.587	0.00329	0.469
Clay + Sand + Silt + VFS+ OM	908719	0.587	0.00329	0.469

The measured rill erodibility (Kr) values ranged from 0.3 - 14 10^{-3} s m^{-1}; for most of the soils the values were around 0.5 – 2 10^{-3} s m^{-1} (Figure 3.6). These observations are lower than the range proposed by Eq. (3), i.e. from 2 to 45 10^{-3} s m^{-1} (Figure 3.5). The observed values showed that soils in La Encañada are resistant to detachment by concentrated flow. The minimum Kr value was observed in a soil with high clay content (36%), whereas the maximum Kr value was observed in a soil with low clay content (10%) but high sand content (70%). The cohesiveness of clay particles makes soils more resistant to detachment by water flow. Conversely, sand grains can easily be detached due to the lack of cohesion between them.

The multistep regression analysis showed low r^2 values between Kr and the individual soil parameters. However, when two or more parameters were considered jointly, the correlations improved, especially for the very fine sand, the organic matter and clay fractions (Table 3.4). However, the r^2 values were lower than 0.5.

The measured τ_c values ranged from 0.64 to 19.96 Pa. The values estimated by the WEPP equation varied between 2.1 and 4.9 Pa. The very high values measured indicate that the soils are resistant to detachment and transport by flow in rills. Multistep regression analysis showed very low values of r^2 (< 0.22) between τ_c and soil characteristics. We have not proposed an equation for the critical shear stress because it seems that the clay, sand, silt, very fine sand and organic matter fractions are not enough to explain τ_c.

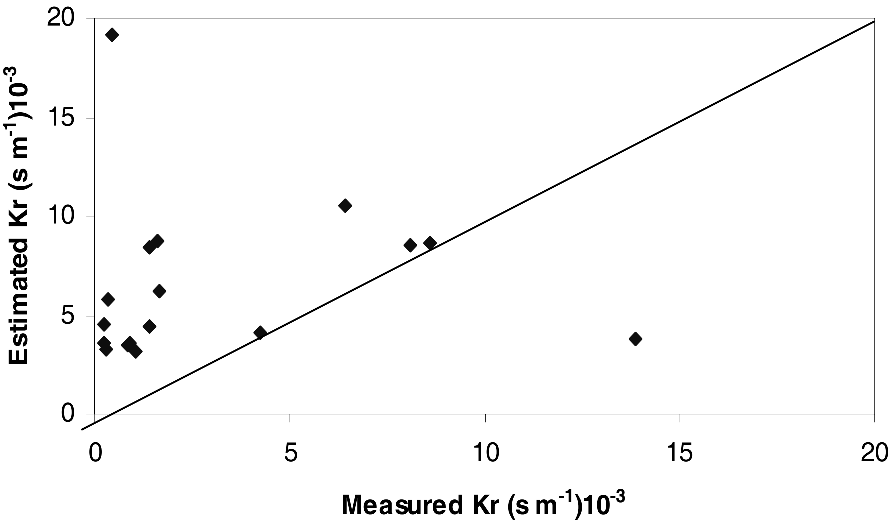

Figure 3.5. *Measured vs. WEPP estimated values of rill erodibility Kr for soils in La Encañada watershed, Peru.*

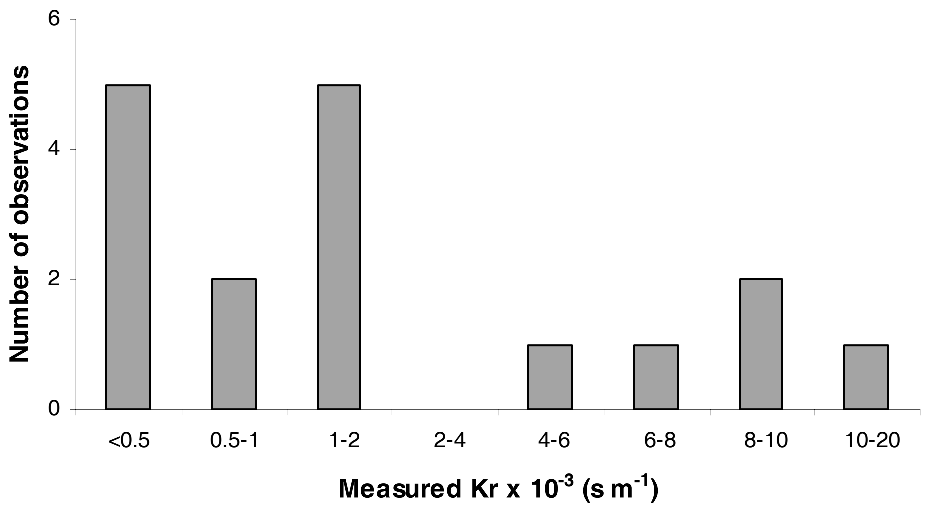

Figure 3.6. *Distribution of observed Kr erodibility values in La Encañada watershed, Peru.*

The K erodibility was estimated for all the locations where both interrill and rill erosion had been measured. This value was then used to estimate the K factor for the soils containing more than 4 % of organic matter, since the Wischmeier nomograph cannot be used for soils with such high organic matter content. The results are shown in Figure 3.7. Most plots showed K values lower than 0.4. According to the nomograph, the range is 0 to 0.7. This implies that most of the La Encañada soils are poorly erodible, which is in accordance with the values measured for both Ki and Kr. The highest estimated K values were for soils with a high content of silt and very fine sand and low content of organic matter.

Wischmeier's approach is the simplest approach to estimate soil erodibility, especially in areas like Peru where few data are available. Other works describe the applicability of this nomograph (El-Swaify and Dangler, 1977; Kidanu, 2004). However, other factors greatly influence the erodibility value during experimental tests in the field, and can vary much more than their USLE soil erodibility K-values (Meyer and Harmon, 1984).

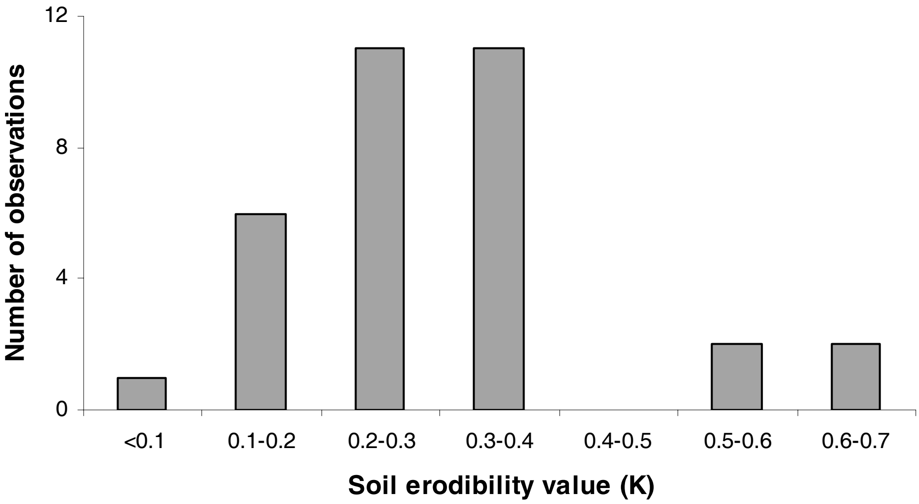

Figure 3.7. *Distribution of Wischmeier's K erodibility values in La Encañada watershed, Peru.*

Tables 3.5 and 3.6 show the WEPP proposed equations for estimating Ki and Kr and the newly proposed equations for the La Encañada watershed. The new equations were chosen according to the lowest standard deviation, the highest coefficient of determination (r^2) and the least number of variables (see Table 3.4). These equations do not show very good correlations. Flanagan and Nearing's equations (Eq. 2 and 4), were designed for estimating the erodibility parameters in cropland soils containing more than 30% sand. This was done because most experiments had been carried out on such soils.

In our study, silt + very fine sands had a better r^2 with observed Ki values (Table 4). Our proposed equation can explain about 57 % of the erosion process. On the other hand, clay + very fine sands + organic matter had better r^2 values for Kr values and our proposed equation can explain about 47 % of the processes involving Kr. Clearly, our first attempt to improve the estimation of soil erodibility in Peru needs to be improved: further investigation must be done to get a higher coefficient of determination between Ki and Kr and soil parameters.

Table 3.5. *Equation to estimate interrill erodibility proposed by Flanagan and Nearing (1995) and newly proposed equation for determining Ki of soils in La Encañada watershed, Peru.*

Ki equation (Flanagan and Nearing, 1995)	Ki = 2728000 + 19210000 vfs
Proposed equation	Ki = - 756916 + 1801775 silt + 15852646 vfs
	s = 870534; $r^2 = 0.573$

vfs: fraction of very fine sand; silt : fraction of silt.

Table 3.6. *Equation to estimate rill erodibility, proposed by Flanagan and Nearing (1989) and newly proposed equation for determining Kr in soils of La Encañada watershed, Peru.*

Kr equation (Flanagan and Nearing, 1995)	Kr = 0.00197 + 0.03 vfs + 0.03863 $e^{-184orgmat}$
Proposed equation	Kr = - 0.00778 + 0.00840 clay + 0.0341 vfs + 0.139 org mat
	s = 0.003168; $r^2 = 0.469$

vfs = fraction of very fine sand; orgmat = fraction of organic matter; clay = fraction of clay.

Despite all the measurements we obtained in the watershed, Ki and Kr coincided at only 5 points. Using these points we were able to establish a relationship between Ki, Kr and K. Figure 3.8a shows a polynomial relationship between Ki and K. Higher values of K relate to lower values of observed Ki, which is contrary to expectations. The three points in question represent soils with medium to high clay contents and with a medium percentage of silt. Clay gives cohesiveness to soils, and therefore this characteristic was an important cause of their reduced erodibility. Wischmeier’s nomograph assumes that a soil becomes less erodible as the silt fraction decreases, regardless of the corresponding increase in the sand fraction or the clay fraction (Wischmeier, 1978). However, the erodibility of soils is a function of complex interactions between physical and chemical properties and can vary within a standard texture. It seems to be an oversimplification that erodibility can be related to a few physical properties only (Bryan et al., 1989).

Figure 3.8b shows the relation between Kr and K that corresponds to a logarithmic relationship. Though nonlinear, this relationship between Kr and K is more in line with expectations. Figure 3.9 shows a response surface indicating the relationship between Ki, Kr and K for the soils of La Encañada.

3.4 Conclusions

Measurements of interrill and rill erodibility taken at 37 points within La Encañada watershed, northern Peru showed that in this area the soil erodibility is low. The most erodible soils were those with the greatest amount of silt + very fine sands. The most resistant were clay soils. Erodibility values estimated according to Wischmeier (1978) confirmed that most soil in the area has low erodibility values. The high critical shear stress values measured confirmed the low erodibility of soils. We have proposed two new regression equations that relate physical soil properties to both interrill and rill erodibility.

We found that silt and very fine sand are strongly correlated with the interrill erodibility values, whereas clay, very fine sand and organic matter are strongly correlated with rill erodibility. More soil parameters may need to be included in the estimates to get more accurate results, and therefore further investigation is encouraged.

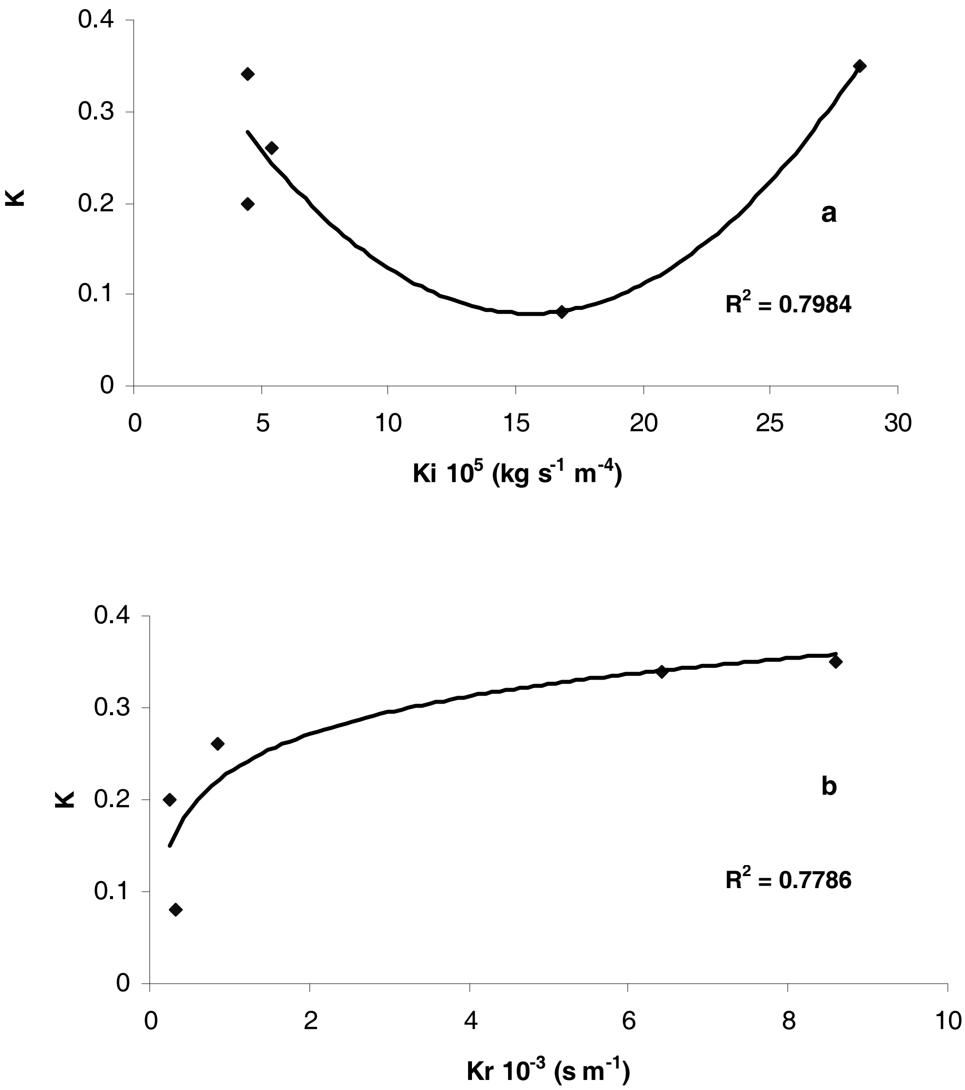

Figure 3.8 *Relationship between measured erodibility and Wischmeier's K for interrill erodibility (Ki in a) and rill erodibility (Kr in b).*

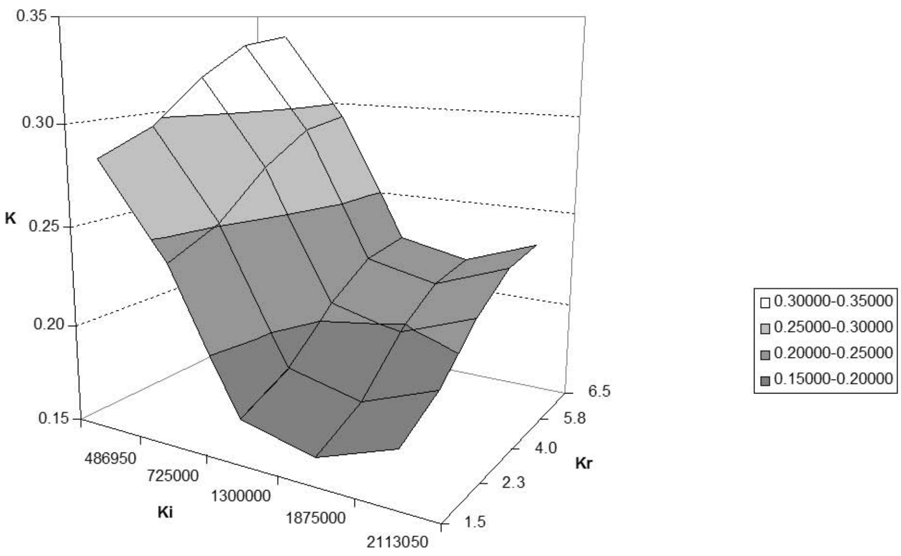

Figure 3.9. *Surface response showing the relationship between interrill erodibility (Ki), rill erodibility (Kr) and Wischmeier's K for soils of La Encañada watershed, Peru.*

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Chapter 4

Uncertainty analysis of WEPP for La Encañada, Peru

4. Uncertainty analysis of WEPP for La Encañada, Peru

Abstract

Erosion processes and their impact are driven by a multitude of bio-physical factors in the Andean highlands that are not well understood. The first attempt to assess soil erosion rates in Peru was made by Felipe-Morales et al. (1977) using runoff plots. Since then, there have been very few erosion investigations, and reference to Andean soil erosion has often been criticised because of the lack of quantitative data. Lack of understanding of the causes and effects of erosion also hampers the development of appropriate conservation strategies. There is a need for a better quantitative understanding of erosion processes at the hillslope scale for on-site impact assessment and at the watershed scale for off-site impact assessment. A modern tool to achieve such understanding is the physically based WEPP- model that has replaced older empirical approaches such as the USLE. However, the high data demand of this model in combination with the lack of local data hampers the application of WEPP. A methodology for data collection was proposed and was tested in La Encañada watershed (Cajamarca - Peru). It consisted of a broad investigation of all WEPP input parameters at the watershed scale followed by an uncertainty analysis of the WEPP model.

The estimated runoff values ranged between 15 % and 1.2% of the total annual rainfall. Under the most erosive rainfall regime and when potato is cropped, the estimated loss of very erodible soil (containing nearly 40 % silt) could be as high as 122 Mg ha^{-1} y^{-1}. Growing potato produced more erosion than growing barley or fallow. The most suitable planting time was June for potato and December for barley, since lower erosion and runoff were estimated for these months. The results presented in this chapter are only the preliminary findings of an evaluation of runoff and soil loss using WEPP. Since we do not yet have measured values of soil loss and runoff we cannot conclude that WEPP estimates are in the right order of magnitude. But since all input data used to run the model and to perform this analysis were measured *in situ*, the model predictions have given a range of values in which real data should fit. Finally, the uncertainty analysis has revealed the high sensitivity of parameters like climate, slope angle, erodibility, soil management and planting date in the model.

4.1 Introduction

In many countries soil erosion is the most serious form of soil degradation, with water its major driving force. In Peru, it is considered common knowledge that water erosion is a problem in agricultural production and has reduced the amount of cultivable land (Felipe-Morales et al., 1977). However, it is remarkable that little quantitative data on erosion are available and that there is little understanding of the processes and causes underlying the erosion in the Andean highlands (Stroosnijder, 1997).

The type and quality of available erosion data differ strongly per country. In Peru, data from Felipe-Morales collected in the 1970s are almost the only available data, reporting 2.8 to 20 Mg ha^{-1} y^{-1} from runoff plots, as a maximum loss at Huancayo, in the central Andes. La Torre (1985) studied the effect of crop rotation at San Ramon, in the eastern Peruvian Andes, measuring soil loss ranges from 3.8 to 45.3 for maize/peas and 12.1 to 70.4 Mg ha^{-1} y^{-1}, for the peas/cassava rotation. Rainfall was around 2000 mm y^{-1} and slope angle 20 %. Working in the same region, Pastor (1992), reported values of 0.69 Mg ha^{-1} y^{-1} for natural vegetation, 0.92 Mg ha^{-1} y^{-1} under sweet potato crop and a maximum value of 9.7 Mg ha^{-1} y^{-1} under fallow. Rainfall was around 1050 mm y^{-1} and the slope gradient ranged from 30 to 60 %. Sources from other Andean countries report higher rates of soil loss. For example, in the Colombian Andes extreme values of soil loss, fluctuating between 860 Mg ha^{-1} y^{-1} for bare soil and 0.21 Mg ha^{-1} y^{-1} for the same soil under coffee trees grown under shade, were reported in the early 1960s by Suarez de Castro and Rodríguez (1962). Rainfall was 2550 mm y^{-1} and the slope 22 %. In a case study at Quilichao, Colombia, Ruppenthal et al. (1996), reported values with a maximum of 222 Mg ha^{-1} y^{-1} under permanent bare fallow conditions, with a slope range from 7.7 to 17 % and a mean rainfall of 1450 mm. From these studies, it seems that the erosion rate depends on land use more than on soil type. Because of their sparse vegetation cover, crust formation and compacted soils, the risk of runoff and erosion is greater in fallow pastures and abandoned fields than in tilled fields (Stroosnijder, 1997).

It is known that soil loss is related to rainfall partly through the detaching power of raindrops striking the soil surface and partly through the contribution of rain to runoff. Intensity is generally considered the most important rainfall characteristic that influences particle detachment and splash (Hillel, 1998; Morgan, 1995), but as this is one of the rainfall characteristics less studied in detail in Peru, it is difficult to understand erosion in that country (Proyecto PIDAE, 1995). And as the necessary data analysis is not carried out routinely, the rainfall erosivity in Peru is unknown.

So, in order to be able to perform impact assessment in Peru, there is a need for a quantitative understanding of erosion processes. A powerful modern tool to achieve such understanding is the physically based Water Erosion Prediction Project (WEPP) model developed by the US Department of Agriculture for the quantitative prediction of erosion from hillslopes and small to medium-sized basins (Flanagan and Nearing, 1995). The WEPP model is starting to replace the empirical models previously used by the USDA, such as the USLE (Nearing et al. 1994). However, it is still in the testing and evaluation phase and it should be used with caution until the types of environment for which it gives reliable results have been clearly identified (Soto and Diaz-Fierros, 1998). The WEPP model describes the processes of soil particle detachment, transport and deposition due to hydrologic and mechanical forces acting on a hillslope or in a basin. However, its application is hampered by its high data demand in combination with the lack or inaccessibility of local data.

We have developed a three-stage methodology specifically for data collection and WEPP model validation in La Encañada watershed in Cajamarca, Peru. Step one consists of a broad investigation of all WEPP input parameters at the watershed scale, followed by an uncertainty analysis. This analysis provides the decision support for the second step that consists of the validation of the hillslope version of WEPP. Finally, in a third step the watershed version is validated using the knowledge and experience gained in the previous steps.

In this paper, we describe the first step of our multi-scale approach. We performed a reconnaissance inventory of all WEPP input parameters in La Encañada watershed. The uncertainty of the model was tested for the observed domain of the input variables. An uncertainty analysis differs from a sensitivity analysis in the fact that only the local variation of the input variables is used. Therefore, our uncertainty analysis is location-specific whereas a sensitivity analysis would have been independent of the site application. An uncertainty analysis enables the effect of an input parameter on the predicted soil loss estimates provided by the model to be realistically assessed.

4.2 Materials, methods and results for the data collection

Description of the study area

Data were collected from the La Encañada watershed. Located 40 km east of Cajamarca in Northern Peru (7°0' and 7°8'S, 78°11' and 78°21'W), the watershed has an area of 6000 ha and is 2950 to 4100 masl (Figure 4.1).

Climate

Daily meteorological data were obtained for four years (1995-1998) from two weather stations located in La Encañada, belonging to Asociacion Civil Para El Desarrollo Forestal De Cajamarca (ADEFOR) and the International Potato Center (CIP). Main meteorological data of La Toma (3590 m) and Las Manzanas (3020 m) weather stations are presented in Table 4.1.

Table 4.1. *Summary of meteorological data for two weather stations in La Encañada.*

Weather Station (altitude)	Mean daily solar radiation ($MJ\ m^{-2}$)	Mean daily maximum temperature (°C)	Mean daily minimum temperature (°C)	Mean annual precipitation (mm)
Las Manzanas (3590)	18.3	16.2	5.9	510
La Toma (3020)	19.9	10.8	2.8	642

In the four-year period the mean annual rainfall was 832 mm at La Toma and 633 mm at Las Manzanas (Table 4.1). More detailed information can be found in Chapter 2 of this thesis. The average for the whole of La Encañada is 767 mm per year. This indicates that the area can be classified as Tropical Summer Rain High Mountain Climate (Rudloff, 1981). The annual amount is distributed over more than 100 events per year (Table 4.2). However, average shower size is very small. In fact, 34 % of the recorded events are smaller than 1 mm. All these small showers together represent only 3% of the annual rainfall. There is an almost 90% probability that a rainfall shower does not exceed 10 mm (Table 4.2). Important for erosion is the fact that 12% of the events (about 13 showers per year) are > 10 mm. This class represents 46% of annual rainfall.

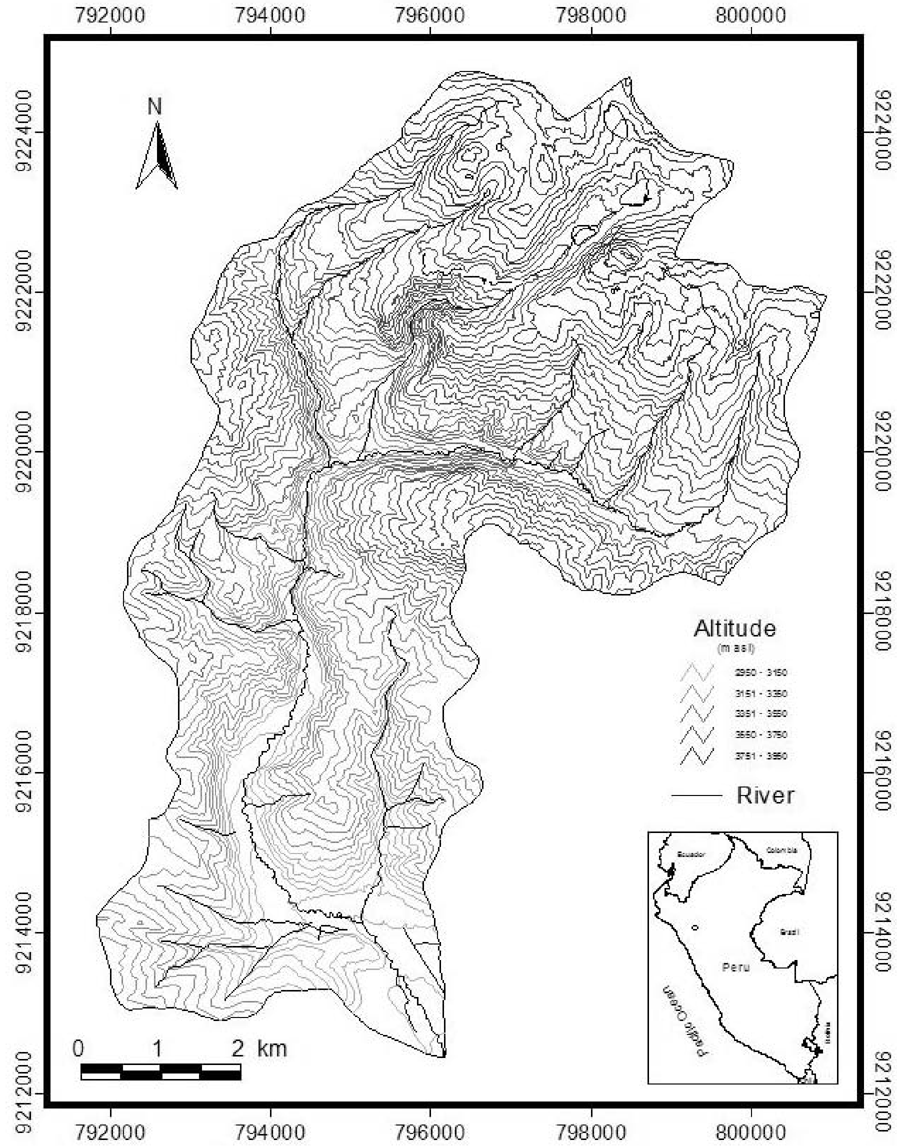

Figure 4.1. *Location map of La Encañada watershed, northern Peru.*

Table 4.3 shows the number of high intensity rainfall events prevailing at Manzanas and La Toma weather stations during 1995-1998. During these years there were 16 rainfall events with intensities greater than 25 mm h^{-1} in the area surrounding Manzanas weather station. La Toma weather station recorded only 8 events of this class. We considered 25 mm h^{-1} to be the threshold intensity for erosion to occur (Morgan, 1995). The difference in the number of high intensity rainfall events was related to the anomalous "El Niño" year that occurred during 1997 rainy season. That year was characterised by increased rainfall intensities, principally in the lower part of La Encañada watershed. The maximum intensity was 147 mm h^{-1} in Manzanas (in 1996) and 130 mm h^{-1} in La Toma, (in 1997).

Table 4.2. *Frequency analysis of rainfall events (30/6/95 – 30/11/98)*

	< 1 mm	1-10 mm	10-20 mm	>20 mm	Total	Per year
LA TOMA						
No. of events	205	265	44	11	527	132
% of total	39	50	8	2	100	
mm in class	91	1201	603	287	2183	642
% of total	4	55	28	13	100	
MANZANAS						
No. of events	134	236	35	8	413	103
% of total	32	57	8	2	100	
mm in class	54	969	484	231	1737	510
% of total	3	56	28	13	100	

Slopes

A Digital Elevation Model (De la Cruz et al., 1999) was used to determine the slope classes in La Encañada. Approximately sixty five percent of the area has a slope gradient less than 15%. However, very steep slopes (up to 65%) are also present (Figure 4.2), increasing the risk of erosion in this mountainous area. Steep slopes often occur adjacent to the river, so water erosion will contribute directly to the river sediment load.

Table 4.3. *Total amount of rainfall, maximum average rainfall intensity and number of events with >25 mm h^{-1} per rainy season (1995-1998).*

	La Toma			Manzanas			
Rainy season	Total rainfall mm	Max. avg. intensity mm h^{-1}	Number of events >25 mm h^{-1}	Total rainfall mm	Max.avg. intensity mm h^{-1}	Number of events > 25 mm h^{-1}	Weather anomalies
1995 (9/95-3/96)	408	40	2	531	70	1	Neutral
1996 (9/96-3/97)	298	55	2	512	147	3	Neutral
1997 (9/97-3/98)	1122	130	3	526	83	11	El Niño
1998 (6/98-11/98)	354	7	0	166	82	1	La Niña

Soils

Soils from La Encañada are classified as Entisols (Fluvents), Inceptisols (Ochrepts and Umbrepts) and Mollisols (Aquolls and Ustolls) in the U.S. Taxonomic Classification System (INRENA, 1998). On the basis of the soil map shown in Figure 4.3, 37 pits were dug to determine the physical properties of the topsoil and subsoil and the hydraulic properties of the topsoil (Table 4.4). Three soil samples were collected from each soil horizon and were bulked to make a composite sample. All samples were air dried and passed through a 2 mm sieve. In the laboratory, we determined the percentage of sand, silt and clay by the hydrometer method (Day, 1965); very fine sand was determined by the wet sieve method. Organic matter content was analysed using the method of Walkley and Black (1947).

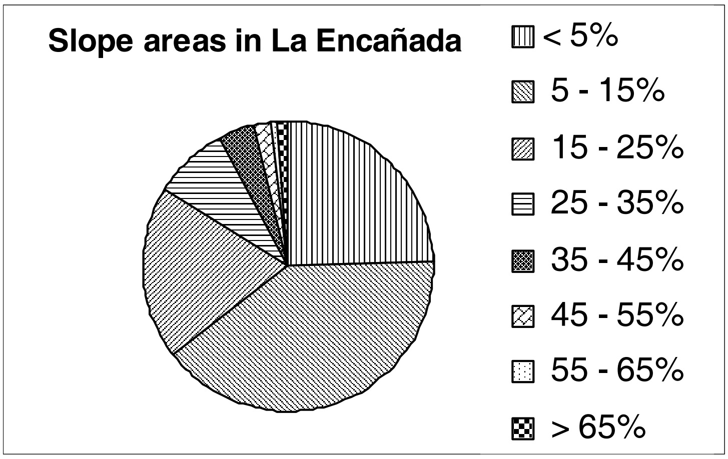

Figure 4.2. *Distribution of slope classes in La Encañada watershed, Peru.*

Table 4.4. *Topsoil* conditions from all the sample points in La Encañada watershed, Peru, showing the minimum, maximum, average and standard deviation data.*

Parameter	Units	Min	Max	Average	St. dv.
Clay	%	2	48	20.4	12.5
Sand	%	20	78	48.2	17.9
Silt	%	16	52	31.5	10.1
Very fine sand	%	3.5	27.4	10.19	6.4
Organic matter	%	0.6	10.6	4.0	2.1
CEC	meq. $100g^{-1}$	10	25.1	17.1	5.1
Effective hydraulic conductivity	mm h^{-1}	0.8	1.6	1.0	0.17
Interrill erodibility	10^6 kg s m^{-4}	5.67	0.19	1.28	1.26
Rill erodibility	10^{-3} s m^{-1}	0.26	13.86	3.1	3.9
Shear stress	Pa	0.64	19.9	9.6	6.6

* 10 cm depth.

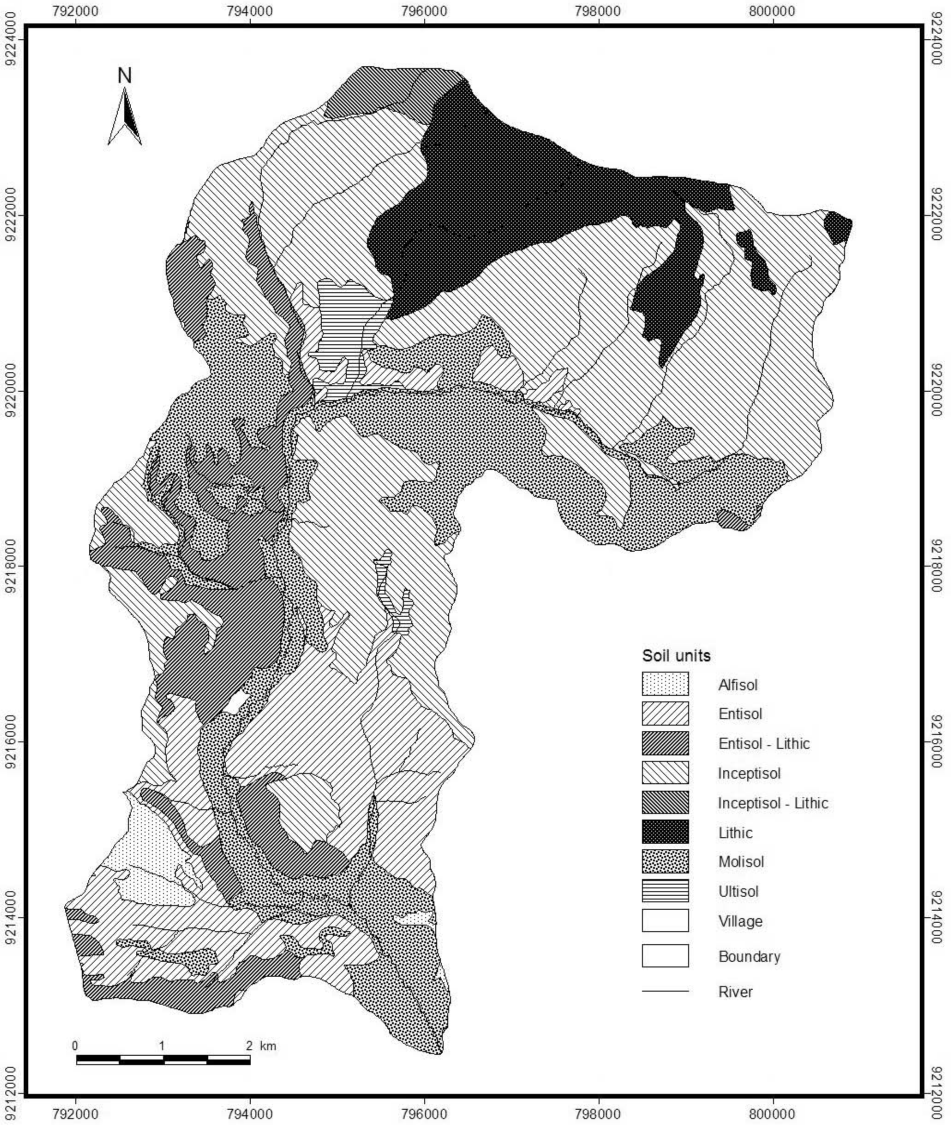

Figure 4.3. *Soil map of La Encañada watershed, northern Peru, based on Jimenez (1996) cited by Overmars (1999).*

Interrill erodibility (Ki) at 21 representative locations was measured using a portable rainfall simulator (Kamphorst, 1987). Each plot was cleaned prior to the installation of the simulator, trying not to disturb the soil surface. Only bare conditions were tested. A standard rain shower of 105 mm h^{-1} intensity was applied. Runoff was sampled every minute during a 5-minute simulation. Sediments splashed off the front of the tray were collected. Splash and runoff samples were oven-dried at 105 ^{o}C to obtain soil loss expressed in kg m^{-2}. Ki values were calculated by using the formula: $D_i = Ki\ i^2\ S_f$, where D_i = interrill erosion rate (kg $m^{-2}s^{-1}$) Ki = interrill erodibility (kg s^{-1} m^{-4}) I = rainfall intensity (m s^{-1}) and S_f = slope factor (dimensionless $=1.05 - 0.85 \exp^{(-0.85\ \sin[\theta])}$) (Elliot et al., 1989).

Rill erodibility (Kr) at 17 representative locations was measured using a procedure recommended by Lal and Elliot (1994). Using a shovel, artificial rills 0.1 m wide and 3 m, 6 m, and 9 m long were created up and down the slope. Approximately 10 minutes of artificial rain was applied on each rill using a hosepipe until an equilibrium outflow from the rill was observed. Then, while continuing the rain, tap water was added at the top of the plot, at 8, 10, 12 and 14 l min^{-1}. After reaching equilibrium outflow, the flow velocity and the concentration of sediment in the outflow were measured. For each combination of rill length and inflow, 5 samples were taken. The cross-sectional area (A) and wetted perimeter (P) were measured to determine the hydraulic radius (r) at each rill (r = A/P). Between each test, the rill was kept humid. Using these measured data, the following rill detachment equation was applied to calculate Kr values: $D_c = Kr (\tau - \tau_c)$, where D_c = rill detachment capacity for clean water (kg m^{-2} s); Kr = rill erodibility (s m^{-1}), τ_c = critical shear below which no erosion occurs, (Pa); τ = hydraulic shear of flowing water, (Pa; $\tau = \gamma$ r s, where γ = specific weight of water = 9810 N m^{-3}; r = hydraulic radius of rill, m; and s = hydraulic gradient of rill flow). Measured rill detachment values (kg m^{-2} s^{-1}) were plotted against the hydraulic shear (Pa) values. The slope of the regression line is Kr, and the intercept with the horizontal axis is the critical shear, tc. For more detailed information about Ki and Kr, see Chapter 3 of this thesis.

Hydraulic conductivity of soils was measured with a tension infiltrometer at 28 representative locations. The soil surface was cleaned without disturbing the surface structure. Stones and loose organic materials were removed. A layer of fine and moist sand was spread to ensure a good contact between the membrane of the tension infiltrometer and the soil surface. The infiltration started at a tension of -24 cm and when the steady-state was reached a tension of -14 cm was applied. There were two replicates per plot. We calculated the saturated hydraulic conductivity based on Wooding's equation (1968): $Q = \pi r^2 K [1+4/ \pi r\alpha]$, where Q: volume of water entering the soil per unit of time (cm^3 h^{-1}), K (cm h^{-1}) is the hydraulic conductivity, h (cm) is the tension at the source, r (cm) is the radius of the water supply tube of the tension infiltrometer, $\alpha = \ln [Q(h_2)/Q(h_1)]/h_2-h_1$, where Q(h) represents the volume of water entering the soil at an established tension. More detailed information is given in Chapter 7 of this thesis. Maximum and minimum values are shown in Table 4.4.

Management

Land use in La Encañada watershed is divided into cropland (55 %), cultivated pasture (13 %), natural pasture (20 %), scrub (12 %) (INRENA, 1998). Deep soils with high amount of organic matter are used as cropland, the most important crops being cereals, potato, maize and legumes. However, crop yields vary, depending on soil fertility and also on climatic conditions. Shallow soils of low fertility that have soil erosion characteristics due principally to their location on steep slopes are also cropped even though most of these areas are appropriate for natural pasture (Proyecto PIDAE, 1995).

The planting times of the main crops vary temporarily and spatially. A survey of potato and barley planting dates in La Encañada (Baigorria, 2003) showed that most farmers preferred to plant potato in June. They preferred to sow cereals in December (Figures 4.5 and 5.5). It is possible that these two crops are planted at different times of the year in order to assure crop production when climatic conditions are highly variable (Proyecto PIDAE, 1995).

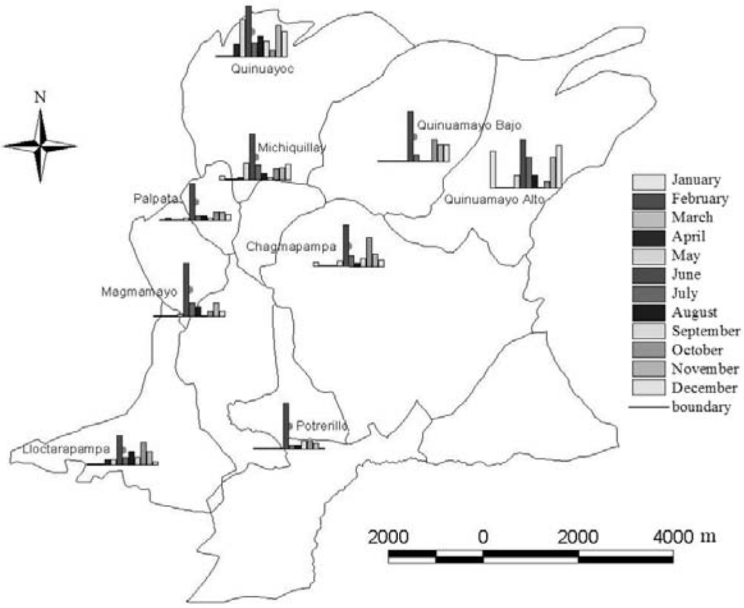

Figure 4.4. *Temporal and spatial distribution of potato planting date in La Encañada watershed, Peru*

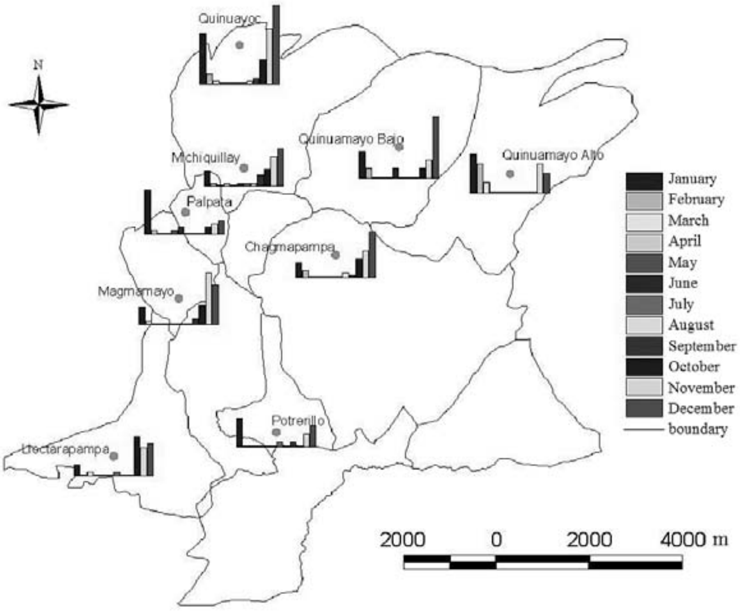

Figure 4.5. *Temporal and spatial distribution of barley planting date in La Encañada watershed, Peru.*

4.3 Materials and methods of the uncertainty analysis

The WEPP model

WEPP is a process-oriented model, based on modern hydrological and erosion science that calculates runoff and erosion on a daily basis. Based on fundamentals of infiltration, surface runoff, plant growth, residue decomposition, hydraulics, tillage, management, soil consolidation and erosion mechanics, it provides several major advantages over empirically- based erosion prediction models, like the estimation of spatial and temporal distributions of net soil loss (Nearing et al., 1989). Although WEPP was developed as an erosion prediction tool, it contains a full crop growth section (Williams et al., 1989). This is because vegetative cover has such an important effect on erosivity, since the vegetation cycle does not always match the rainfall cycle. So, dynamic simulation of vegetation is necessary for adequate erosion prediction.

In this chapter we use WEPP for an uncertainty analysis. The major inputs for running WEPP's hillslope version need to be specified in four data files: climate, slope, soil and management. In an uncertainty analysis, variation in model output is tested by changing input values between the observed maximum and minimum values. Because it was observed that input data were not independent, we decided not to perform a fully unrestricted uncertainty analysis. Instead, we defined different scenarios that can occur in the watershed. Below, we describe each file and the scenarios for this analysis.

The climate file

This file requires daily values for precipitation, maximum and minimum temperature, and solar radiation. In addition to rainfall amount, the model requires three variables related to rainfall intensity that is used to compute rainfall excess rates and thus runoff. Three years of actual data for two climates were applied in the simulations. First, La Toma, characterised by its smaller number of high intensity events, is the climate that prevails at the upper part of the watershed (3850 masl). Secondly, Manzanas (characterised by its higher number of high intensity rainfall events) is the climate that prevails in the lower part of the watershed. More detailed information is given in Chapter 2 of this thesis. Maximum and minimum values for rainfall events are shown in Table 4.4.

The slope file

This file consists of the establishment of a slope angle and slope length sequence of slope elements with uniform properties with respect to overland flow, the so-called Overland Flow Elements (OFE). These are defined as "regions on a hillslope of homogeneous soil, cropping and management", that is, the basic unit for the modelling of surface hydrology, erosion and vegetation growth. Each soil was tested under six different slope gradients (5, 10, 20, 35, 50 and 65 %) according to the information given by the DEM, and a constant slope length of 20 m (Table 4.4).

The soil file

This file contains information on the physical characteristics of the surface soil and subsoil. The model contains three erosion parameters, one for interrill erosion and two for rill erosion. Based on the results found in the soil survey (see Chapter 3 of this thesis) as well as the hydraulic conductivity test (mentioned previously), we proceeded to create three soil files according to the level of erodibility: high, moderate and low.

The management file

This file contains information needed to define initial conditions, tillage practices, plant growth parameters, residue management, and crop management. For the simulations we assumed three different management practices: fallow, potato and barley, to evaluate their effect on erosion and runoff. Potato and barley were chosen due to their importance as food for the farmer's family and as fodder for livestock. We also evaluated the effect of different planting dates in the soil loss process. Therefore, in order to assess the effect on soil erosion and runoff, we established five planting dates for each crop: May, June, July, August and September (for potato) and November, December, January, February and March (for barley).

Table 4.5 shows the minimum and maximum input values for the basic scenarios for the WEPP model. WEPP2002 was used in continuous simulation mode to predict runoff and soil erosion during 4 consecutive years. The outputs are given in mm y^{-1} for runoff and Mg ha^{-1} y^{-1} for soil loss. We calculated this soil loss using the predicted sediment yield at the bottom of the 20 m slope length (20 x 2 = 40 m^2) and converted this into soil loss per ha. We realise that this procedure may overestimate soil loss at the hectare-scale but we accept this in our uncertainty analysis. Each scenario was considered as an overland flow element (OFE) and had its own set of input files. The slope length (OFE length) was set in 20 m and the plot width in 2 m.

4.4. Results of uncertainty analysis

Runoff

We ran the model for four years but the predicted results are expressed in mm y^{-1}. Both La Toma and Manzanas weather conditions were tested, to see their effect on runoff. It will be recalled that at La Toma the rainfall events are less intense than at Manzanas, and that at Manzanas erosive events are more numerous (Chapter 2 of this thesis). Figure 4.6 shows the estimated runoff under fallow conditions, considering the two climate conditions and three levels of soil erodibility under increasing slope angles. The estimated runoff ranged between 80.2 and 36 mm (15% and 7 % of total annual rainfall) under Manzanas climate. When we considered La Toma climate, the predicted runoff was lower, with a maximum value of 41.5 mm, representing the 6.5 % of total annual rainfall whereas the lowest predicted value was 7.4

mm (= 1.2%). The difference in climate is due to the number of intense events (>25 mm h^{-1}) that Manzanas climate had compared to La Toma (11 versus 3) during the years of evaluation (1995-1999). It seems that when simulations were done under the Manzanas climate, the model represented the Hortonian overland flow in all the soil scenarios. This type of runoff was triggered when the rainfall rate eventually exceeded the rate at which water could infiltrate the soil (Hornberger et al., 1998).

Table 4.5. *Scenario table for uncertainty analysis.*

	Rainfall characteristics					
La Toma	*4 years (see Chapter 2)*					
Las Manzanas	*4 years (see Chapter 2)*					
	Soil characteristics for 3 different degrees of erodibility					
	Low		Moderate		High	
%Clay	20		18		22	
%Sand	65		50		36	
%Silt	15		32		42	
% Org.matter	6		3		1.5	
CEC (meq. 100g^{-1})	20		18		15	
Effective hydraulic conductivity (mm h^{-1})	1.6		1.1		0.7	
Interrill erodibility (10^6 kg s m^{-4})	0.18		1.1		5.6	
Rill erodibility (10^{-3} s m^{-1})	0.3		4.0		8.0	
Shear stress (Pa)	6		2.5		1.3	
	Slope					
Slope angle (%)	5	10	20	35	40	65
Slope length (m)	20	20	20	20	20	20
Management	Bare		Potato		Barley	
Planting date	All year		May		November	
			June		December	
			July		January	
			August		February	
			September		March	

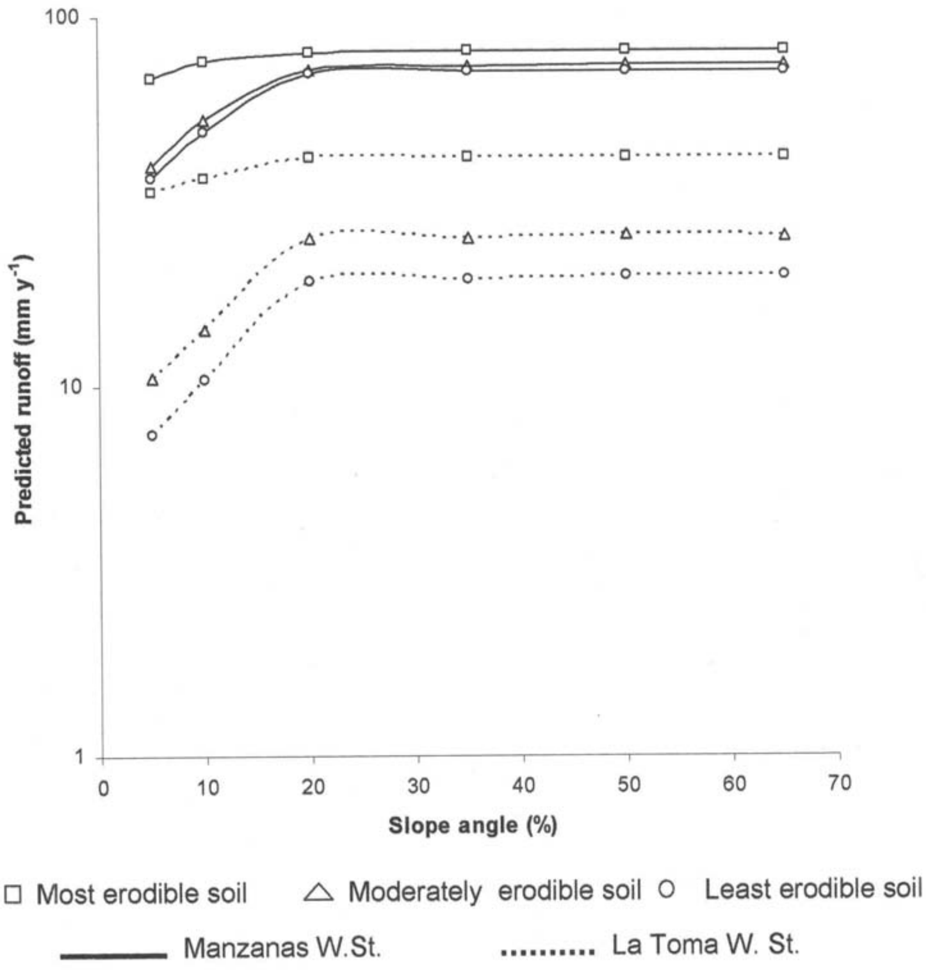

Figure 4.6. *Runoff estimated by WEPP under fallow conditions, considering three levels of soil erodibility and two climate conditions, in La Encañada watershed, Peru.*

The effect of climate, soil type, soil management, slope angle and planting date is shown in Table 4.6. Considering potato and barley, Manzanas climate induced the highest values of runoff for potato planted in August on the most erodible soil, on a 65% slope. In general, the estimated runoff under fallow conditions was higher since then the soil is directly exposed to the raindrops when a rainfall event occurs, which is not the case under a cover of potato or barley. In the simulation, fallow conditions were kept bare. The model reflected the erosivity of each type of climate well.

The topography of La Encañada is mountainous, with very steep slopes. Predicted runoff increased as the slope angle became steeper but at a slope angle > 20% it became constant (Figure 4.6). The minimum predicted value was 7.4 mm (at 5%) and the maximum was 80.2 mm at 65 % slope. Runoff generally increases with increased slope gradient, but this relationship is influenced by such factors as surface roughness, profile saturation and crop type (Wischmeier and Smith, 1978). Our estimations were done for slope lengths of 20 m. Slope length was considered a fixed value because we thought that slope angle has more influence on erosion in this watershed (Figure 4.2). The landscape in areas with > 20% slope angle tends to have slopes shorter than 20 m. Longer slopes can be found at the bottom of the watershed, where the slope angle is < 5 %; the soil in this area is protected year-round by cultivated pastures.

Table 4.6. *Estimated values of runoff (mm y^{-1}) by WEPP according to the land use, climate conditions, soil erodibility, minimum and maximum slope angle and planting date in La Encañada watershed, Peru.*

Runoff		**La Toma**						**Manzanas**					
		Most erodible soil			Least erodible soil			Most erodible soil			Least erodible soil		
Land use	Planting time	Min (5 %)	Max (65 %)	Mean	Min (5 %)	Max (65 %)	Mean	Min (5 %)	Max (65 %)	Mean	Min (5 %)	Max (65 %)	Mean
							(mm)						
Potato	May	26.9	35.7	35.7	8.6	19.5	16.2	34.9	47.5	44.2	23.5	39.7	35.0
	June	27.8	36.5	34.2	8.7	19.5	16.3	34.7	47.7	44.2	24.1	39.3	34.9
	July	29.8	38.0	35.8	8.6	19.5	16.2	37.4	50.0	46.5	26.6	41.1	36.9
	August	30.6	38.8	36.6	8.6	19.2	16.1	56.8	67.7	64.8	34.5	59.1	52.4
	September	31.0	39.1	37.0	8.5	19.2	16.0	41.3	54.9	51.0	28.3	46.8	41.3
Barley	November	22.2	28.2	26.9	6.1	12.4	10.6	51.0	65.0	61.1	32.2	54.9	48.3
	December	22.5	28.2	26.9	5.7	11.6	9.8	46.8	58.9	55.2	30.5	50.0	44.2
	January	19.8	27.3	24.9	4.5	12.1	9.6	38.1	49.5	46.1	25.2	41.9	36.8
	February	23.2	32.2	29.6	5.9	14.6	11.9	37.3	47.8	44.7	24.3	41.1	36.0
	March	24.5	34.9	31.8	6.9	16.8	13.8	37.9	48.9	45.8	26.0	42.9	37.8
Fallow		33.4	41.5	39.4	7.4	19.8	16	68.0	80.4	77.5	36.7	71.3	61.5

We examined three scenarios for soil erodibility. The most erodible soil, which was characterised by a silty texture, low organic matter content, low hydraulic conductivity and high erodibility indexes showed the highest predicted runoff values compared to the moderate and least erodible soils (Table 4.6). The highest predicted value was 80.4 mm y^{-1} when the soil management was under fallow conditions. A potato crop produced a maximum predicted runoff value of 67.7 mm y^{-1} and barley produced 65 mm y^{-1}. The lowest predicted values were generated when the least erodible soil was simulated (4.5 mm y^{-1}) at 5% slope angle under barley.

When fallow was tested, we observed that the WEPP model predicted higher runoff under the Manzanas climate than under La Toma climate (Figure 4.6), reflecting the greater aggressiveness of that climate. When potato and barley were simulated the model predicted slightly lower runoff values than under fallow (Table 4.6) indicating that vegetation cover can enhance the infiltrability of soils and reduce runoff (Reid et al., 1999; Cerda, 1999). When we simulated potato or barley, we observed that both crops induced more runoff under the Manzanas climate than under the La Toma climate.

The effect of planting date can enhance or decrease the predicted runoff (Table 4.6). Under the low erosive climate of La Toma, the most erodible soil exhibited little variation in predicted runoff. Potato produced only slightly more runoff by September (31 mm) versus 27 mm predicted by May. However, under the most erosive climate (Las Manzanas) the maximum predicted runoff was observed when the planting was in August (67.7 mm) versus 47.5 mm when the planting was in May: both under 65% (Figure 4.8). Therefore, for potato, the planting date associated with the most runoff was August, and May was less harmful. For barley, the sowing date with the highest predicted runoff (65 mm) was November. By comparison, the least runoff (37.3 mm) was predicted for February under Manzanas climate (Figure 4.9). For the same crop, under La Toma climate, the maximum predicted runoff value was in March (34.5 mm) (Table 4.6).

Soil loss

Figure 4.7 shows the uncertainty domain of estimated soil loss (Mg ha^{-1} y^{-1}) under fallow conditions at different slope angles. We plotted a semi-log graph to clearly show the differences between the scenarios. It will be recalled that in La Encañada there are very steep slopes (up to 70 %). Depending on the slope angle, erosion can be accelerated or retarded. We observed that the annual estimated soil loss varied with slope angle. A maximum value of 86 Mg ha^{-1} y^{-1} was estimated at 65 % slope angle whereas a minimum predicted value was 3.8 Mg ha^{-1} y^{-1} at 5% slope. The steeper the slope, the higher the estimated values. The effect of slope in soil erosion is enhanced if we consider the most erodible soil and the most erosive climate (Manzanas).

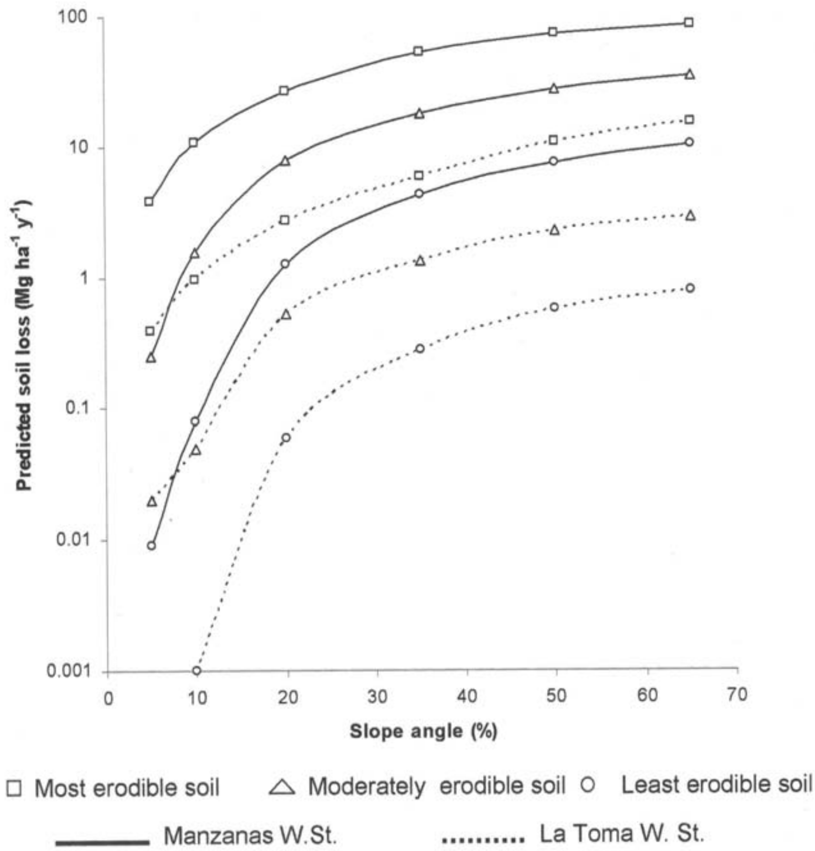

Figure 4.7. *Estimated sediment yield by WEPP under fallow conditions, considering three levels of soil erodibility and two climate conditions, in La Encañada watershed, Peru. (symbol explanation as in Figure 4.6)*

On the most erodible soil the predicted soil loss values were as high as 122 Mg ha^{-1} y^{-1} under a potato crop, at 65% slope angle under Manzanas climate (Table 4.7). This is the highest value predicted for La Encañada watershed. Under the least aggressive La Toma climate, this soil also exhibited high predicted soil loss values, specifically when potato was simulated (102 Mg ha^{-1} y^{-1} at 65% slope angle). The moderate and least erodible soil scenarios under La Toma climate showed the minimum estimated soil losses: values were as low as 0.01 Mg ha^{-1} y^{-1} under 5 % slope angle and as high as 0.77 and 2.8 Mg ha^{-1} y^{-1} at 65 % slope (Figure 4.7). Estimated soil loss values for the least erodible soil were very low (< 6.2 Mg Mg ha^{-1} y^{-1}) as can be observed in Table 4.7.

The danger of high soil loss rates is that erosion can exceed the rate of soil formation. An example is given by Bewket (2003), where the rate of soil loss in Ethiopian agricultural lands has been estimated as 42 Mg ha^{-1} y^{-1}, which represents 4 mm of soil depth per annum. At this rate, a big area of the highlands will be stripped bare of soil in less than two hundred years. Although no tolerable rate of soil loss for the Andes has been established, it seems that values lower than 10 Mg ha^{-1} y^{-1} will not lead to soil deterioration and production loss in the long term. Tolerated soil losses of 10 Mg ha^{-1} y^{-1} (Rose, 1994) and 2-5 Mg ha^{-1} y^{-1} (Wischmeier and Smith, 1978) have been established for Australia and the United States, respectively, considering factors such as soil depth, physical properties, organic matter and nutrient losses. In our uncertainty analysis this limit was clearly exceeded in some scenarios.

Table 4.7. *Estimated values of soil loss by WEPP according to the land use, climate conditions, the most and the least erodible soil, minimum and maximum slope angle and planting date in La Encañada watershed, Peru.*

Soil loss		**La Toma**						**Manzanas**					
		Most erodible soil			Least erodible soil			Most erodible soil			Least erodible soil		
Land use	Planting Date	Min (5 %)	Max (65 %)	Mean	Min (5 %)	Max (65 %)	Mean	Min (5 %)	Max (65 %)	Mean	Min (5 %)	Max (65 %)	Mean
							Mg ha^{-1}						
Potato	May	0.6	102.4	43.5	0.0	0.8	0.3	0.4	16.8	7.8	0	0.5	0.2
	June	0.5	84.9	35.5	0.0	0.8	0.3	0.6	32.5	14.8	0	0.5	0.2
	July	0.4	51.6	21.0	0.0	0.7	0.3	4.3	70.7	36.2	0.1	1.8	0.8
	August	0.4	60.4	25.0	0.0	0.7	0.2	6.1	122.1	62.2	0	6.2	2.5
	September	0.3	38.3	15.4	0.0	0.6	0.2	1.1	27.1	12.8	0	0.4	0.2
Barley	November	0.1	8.9	4.0	0.0	0.1	0.0	1.8	46.9	23.2	0.0	1.1	0.4
	December	0.1	7.1	2.9	0.0	0.0	0.0	0.6	10.2	4.3	0.0	0.2	0.1
	January	0.1	2.2	0.9	0.0	0.1	0.0	0.5	11.3	5.0	0.0	0.2	0.1
	February	0.1	7.4	3.1	0.0	0.2	0.1	0.4	11.8	5.2	0.0	0.1	0.0
	March	0.1	13.8	5.7	0.0	0.2	0.1	0.6	16.5	7.5	0.0	0.3	0.1
Fallow		0.39	15.4	6.0	0.0	0.77	0.3	3.8	86	42.1	0.01	10.1	3.8

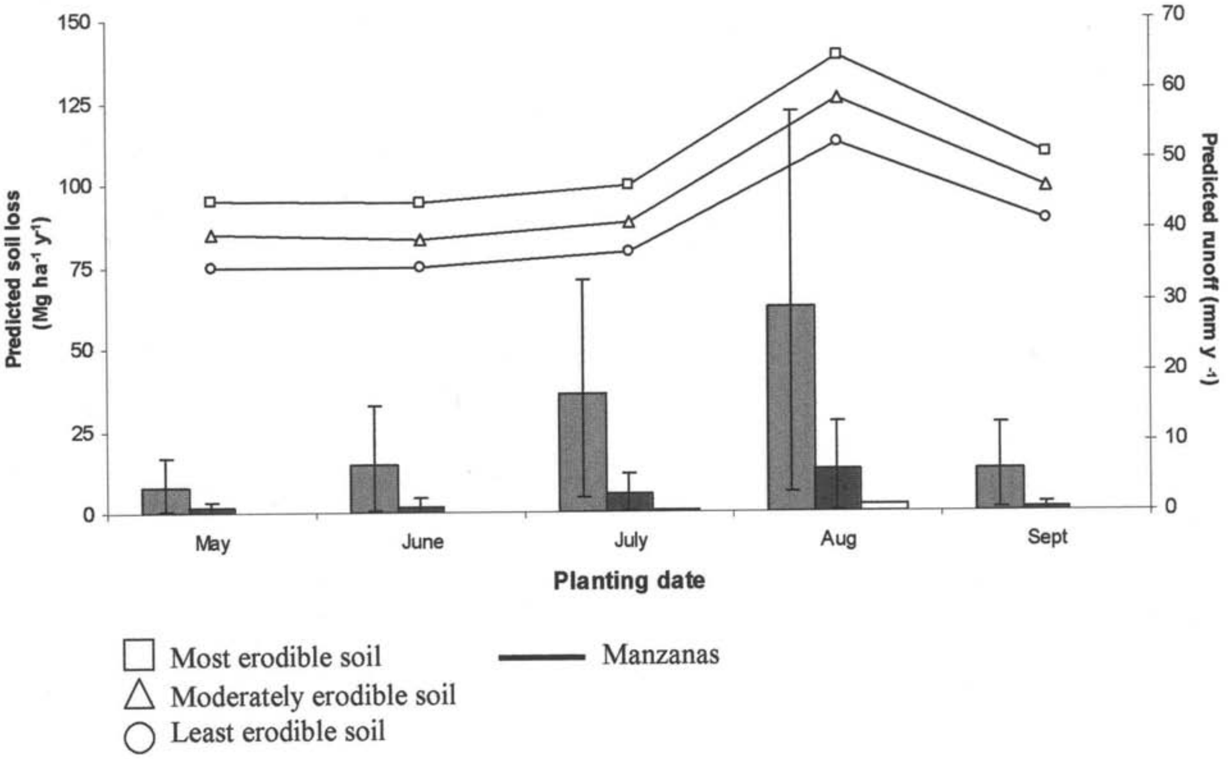

Figure 4.8. *Runoff and soil loss estimated by WEPP for potato crop under Manzanas climate in La Encañada, Peru. The hatched bars represent the most erodible soils,the cross-hatched bars represent the least erodible soils.*

As regards the crops we considered, we can say that potato is more erosive than barley (Table 4.7). When potato was simulated the predicted soil loss ranged from 16.8 to 122.1 Mg ha^{-1} y^{-1} under the most erodible soil and the most erosive (Manzanas) climate (Figure 4.8), whereas when barley was tested, the predicted values ranged between 10.2 and 46.9 Mg ha^{-1} y^{-1} for the same conditions (Table 4.7). For the least erodible soil under the less erosive climate (La Toma) the predicted soil loss values were quite low (< 6.2 Mg ha^{-1} y^{-1}). Potato can be considered a more erosive land use than barley or fallow because its management involves more disturbance of the soil surface (for instance, ploughing the soil to create rows that can act as big rills). However, the potential erosivity of this crop can be managed if additional factors such as slope angle, planting date or soil characteristics are taken into account when planting. Barley can be considered a crop that produces less soil loss than potato since the soil preparation for sowing is not so “destructive”. Andean farmers used to scatter the seed over the soil surface and did not till after sowing. After emergence, barley plants cover the soil surface faster than potato, protecting the soil against the erosive power of raindrops. Potato takes longer to cover the soil surface.

When we simulated for a potato crop, we observed that planting date was important for the soil loss process. The predicted soil loss values rose from May to August, and then fell during September (Figure 4.8). The highest predicted average soil loss value was 62.2 Mg ha^{-1} y^{-1} when potato was tested at 65 % slope and a planting date in August; however, the highest predicted soil loss value was 125 Mg ha^{-1} y^{-1} for the same scenario. The lowest average value was 7.8 Mg ha^{-1} y^{-1}, estimated when planting was in May. When potato was simulated under La Toma climate, the maximum average predicted value was 43.5 Mg ha^{-1} y^{-1}, for the month of May, whereas the minimum value was 15.4 Mg ha^{-1} y^{-1},for the month of September (Table 4.7). These results were predicted under the most erodible soil. Under the least erodible soil, the figures were quite low (< 1 Mg ha^{-1} y^{-1}). The effect of planting date in barley is shown in Figure 4.9 (white bars represent the most erodible soil under La Toma climate, black bars represent ditto under and Manzanas climate). November was the month that produced the highest soil loss values (23 Mg ha^{-1} y^{-1} under Manzanas climate). The following months showed that predicted soil loss was low and there was no big difference among predicted results (< 7.5 Mg ha^{-1} y^{-1}) although December showed the minimum predicted soil loss value (4.3 Mg ha^{-1} y^{-1}). When the least erodible soil was tested, the predicted results were very low (< 1.1 Mg ha^{-1} y^{-1}). Under La Toma climate, all the scenarios produced low average soil loss estimates, the maximum value being equal to 5.7 Mg ha^{-1} y^{-1}.

The farmers' decision about the best planting date agree well with the WEPP model outputs and this can be related to the monthly rainfall pattern and temperature regimes of the area (Figure 4.10). According to Baigorria (2003), most farmers plan t potato in June (Figure 4.4). If potato is planted during May or June, there are still a few rainfall events that can help the crop to emerge and to form a vegetative cover that will protect the soil for the coming rainy months (September and/or October), reducing the erosive force of raindrops. The disadvantage of planting during July or August is that these are the two driest months of the year, the soil is prepared too near the new rainy season and so is more vulnerable to raindrops. Potato produces a canopy some centimetres above the soil surface; however, it provides no protection against erosion from water flowing over the soil surface (Rose, 1994). This effect is reflected by the maximum estimated values for erosion: 122.1 and 60.4 Mg ha^{-1} y^{-1} in August under Manzanas and La Toma climate, respectively, at 65% slope. The estimated erosion declines again when the planting date is in September. At this time, soils are not dry, because there have been some rainfall events. This initial soil moisture condition can help keep soil particles together during preparations for planting.

Barley is normally sown in December by the majority of farmers, when the rainy season has already started (Figure 4.5). Unlike potato, barley seeds are put near the soil surface (2 cm deep) and water is required immediately after emergence. Barley produces more erosion if it is sown in November than if it is sown in the following months. This is due to small rain events from April to July after the harvest (Figure 4.10) that can cause more erosion since soils are unprotected and probably have a high moisture content. Sowing later than November would mean having to protect the soil against the heaviest rainfall events that occur during January to April. The fact that the lowest values of estimated runoff and erosion were observed during the months chosen by farmers is probably a coincidence. Farmers' decisions do not necessarily relate to the erosion process in the area. There is no evidence for this. We only know that they plant according to the weather and that they especially wait for rain (Proyecto PIDAE, 1995).

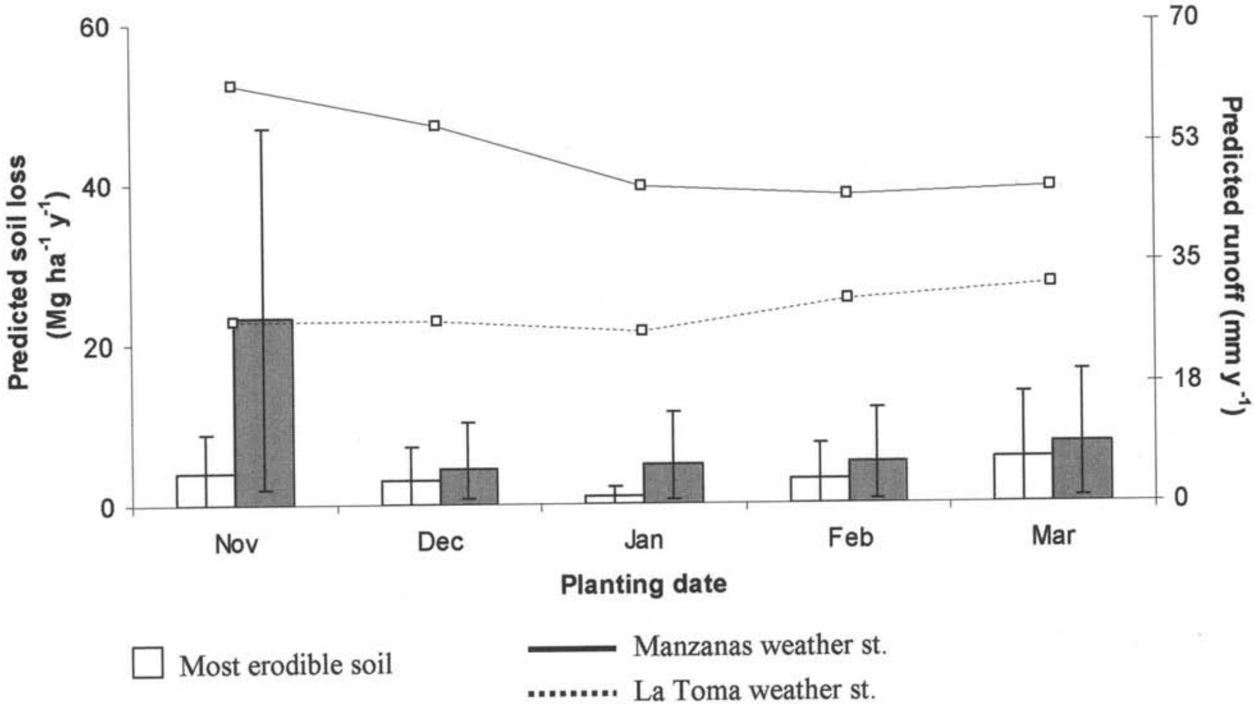

Figure 4.9. *Soil loss and runoff estimated by WEPP for a barley crop under Manzanas and La Toma climates in La Encañada, Peru. Hatched bars represent the more erodible soil. Different planting dates are shown.*

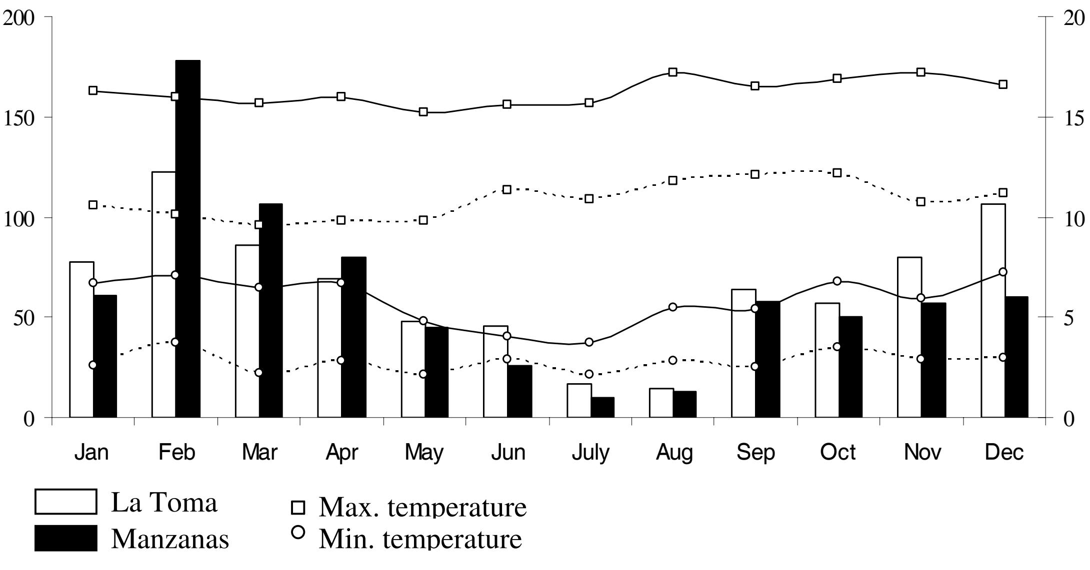

Figure 4.10. *Monthly distribution of rainfall at two weather stations (La Encañada watershed, Peru). Maximum and minimum temperatures are also shown. Continued line represents Manzanas weather station. Dashed line represents La Toma weather station*

Table 4. 8. *Summary of uncertainty analysis for La Encañada using WEPP*

Factor	Runoff	Soil loss
Climate	Manzanas climate produced higher runoff than La Toma climate.	Higher predicted values under Manzanas climate than under La Toma climate.
Slope	Increase until 20% >20 % no effect.	Continuous increase with slope increment.
Soil	Increased for the most erodible soil (max. = 80.4 mm y^{-1}), decreased for the moderately and least erodible soils.	Higher predicted losses for the most erodible soil than for the moderately and least erodible soils.
Management (crop choice)	Decrease under barley, increase under potato, maximum under fallow.	Lower estimates under barley than under potato or fallow. Maximum estimates under potato.
Management (planting date)	Highest predicted values when planting was in August (potato) and November (barley). Lowest values for potato planted in June and barley sown after November.	Increased if planting date in August (potato) and November (barley). Lowest soil loss rates for barley sown after November.

4.5 Conclusions

Various conclusions can be drawn from the uncertainty analysis of the WEPP model reported above and summarised in Table 4.8. The table shows that the rainfall distribution over the year does not appear to be either excessive or dramatic. However, there were more rainfall events > 25 mm h^{-1} during 1997-1998 (El Niño year), especially near Manzanas weather station (11 events versus only 3 recorded in La Toma). This small difference seems to have a great impact on the soil loss process, as observed in the results. The WEPP model reflected the high erosivity of the Manzanas climate compared to La Toma climate very well. The maximum estimated runoff was 80.4 mm y^{-1} (15 % of the total annual rainfall under Manzanas climate, under fallow), the minimum was 4.5 mm y^{-1} (1.2 % of the total annual rainfall under La Toma climate and barley). This low value is related to the high hydraulic conductivity of the deep organic soils (the least erodible soils). Sediment yield ranged from 0 in soils on flat areas (i.e. < 5 % slope angle) to 122 Mg ha-1 y-1 (erodible silty soils on very steep slopes i.e. 65 % gradient).

We have seen that gradient greatly influences the erosion rate in the area, especially if the soil is highly erodible and if the climate is erosive. The dynamic simulation of vegetative cover, by testing different planting dates, did allow us to evaluate the runoff and soil loss processes in time. We discovered that planting potato in August can produce more erosion than if planting in May or June. For barley, sowing from December to March produced less erosion than planting in November.

The findings presented in this paper are only the preliminary results of an evaluation of runoff and soil loss using WEPP. Since we do not have measured values of soil loss and runoff, we cannot conclude that WEPP estimates are in the right order of magnitude. But since all the data used as inputs, to run the model and to perform this analysis were measured in La Encañada watershed, we can conclude that the predicted results have given us a range of values in which real data should fall. Finally, the uncertainty analysis has revealed the great sensitivity of parameters like climate, slope angle, erodibility factors - Ki, Kr and τ_c-, soil management and planting dates in the model.

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Chapter 5

Validation of the hillslope version of WEPP in La Encañada watershed, northern Peru

5. Validation of the hillslope version of WEPP in La Encañada watershed, northern Peru

Abstract

Soil erosion by water is the most serious form of soil degradation in the Andes. In this study, we tried to understand the process through the validation of a simulation model. The hillslope version of the Water Erosion Prediction Project (WEPP) model was used to simulate runoff and soil loss for three different sites within the La Encañada watershed, in the northern Andes of Peru. Three different-sized runoff plots were installed at each site under bare soil conditions. Each site had a specific slope (from 10 to 70 %), soil and climate, as we tried to cover all representative conditions of the area. Runoff and soil loss were measured in 2001. The WEPP model over-estimated runoff and underestimated soil loss. The model performed reasonably well, with the biggest runoff plots (20 m long) showing coefficients of determination of 0.67 for runoff and 0.66 for soil loss. The smallest runoff plots (5 m long) did not show a good relationship between observed and predicted values. The values measured for runoff and soil loss were very low during 2001 (all were < 6 mm for runoff and < 0.1 Mg ha^{-1} for soil loss), from which we conclude that little erosion can be expected in the watershed.

5.1 Introduction

Soil erosion by water is the most serious form of soil degradation, especially in mountain areas, because it affects agricultural production and decreases soil quality, diminishes on-site land values and causes off-site damage to ecosystems (Bhuyan et al. 2002). Few investigations have been carried out under Peruvian Andean conditions. The few data available on Peru include those obtained by Felipe-Morales et al. (1977) in the 1970's. Those authors reported soil erosion values between 2.8 to 20 Mg ha^{-1} y^{-1} in runoff plots under different soil management practices at Huancayo, in the Central Andes. La Torre (1985) studied the effect of crop rotation at San Ramon, eastern Andes, measuring soil losses from 3.8 to 45.3 Mg ha^{-1} y^{-1} for the maize–peas rotation and 12.1 to 70.4 Mg ha^{-1} y^{--1} for the peas–cassava rotation. Observed values for soil loss of 0.69 Mg ha^{-1} y^{-1} for natural vegetation, 0.92 Mg ha^{-1} y^{-1} for sweet potato crop and a maximum value of 9.7 Mg ha^{-1} y^{-1} under fallow were reported for the same area (Pastor, 1992).

Some data have been published for other Andean countries. Extreme values of soil loss fluctuating between 860 Mg ha^{-1} y^{-1} for bare soil and 0.21 Mg ha^{-1} y^{-1} for the same soil under coffee trees under shade were found in Colombia (Suarez de Castro and Rodríguez, 1962), cited by Felipe-Morales et al. (1977). In a study case at Quilichao, Colombia, Ruppenthal et al. (1996) reported soil loss values up to 222 Mg ha^{-1} y^{-1} under permanent bare fallow, with a slope range of 7.7 to 17% and a mean rainfall of 1450 mm. In Ecuador, using a portable rainfall simulator, Harden (1992b) concluded that footpaths generated runoff more rapidly than adjacent fields or pasture and abandoned land. Earlier, using the same simulator, Harden (1987), cited by Byers (1990), had reported soil loss values of 20 Mg ha^{-1} y^{-1} for thin, dusty, Cangahua*-derived soil; 40 Mg ha^{-1} y^{-1} for soils rich in organic matter and 80 Mg ha^{-1} y^{-1} for dark, Andean soils at intermediate elevations. In a study of soil conservation strategies in Ecuador, Staver et al. (1991) referred to a qualitative estimation of potential erosion, indicating that 12% of the country is suffering active erosion processes, due to steep slopes, high winds and high precipitation. In their paper they also referred to the first field study using runoff plots at the Sta. Catalina Research Station; the average soil loss there of 82 Mg ha^{-1} y^{-1} has been applied as a standard throughout the highlands. In some areas of Chile, erosion rates have been reported to exceed 100 Mg ha^{-1} y^{-1} and to affect nearly 25% of the total country (Ellies, 2000); nearly 36% of the agricultural soils in the pampas of Argentina are affected by erosion (Bujan et al., 2000).

The erosion process is highly variable in the diverse agro-ecosystems of the Andean highlands. As these highlands cover a wide range of geographical locations and a wide range of altitudes, it is difficult to consider the area as a homogeneous ecosystem. Field measurements of erosion and sedimentation using classical techniques can be difficult, time-consuming and expensive (Bujan et al., 2000; Zhang et al., 1996), especially in this environment, but they are indispensable if prediction models need to be applied for natural resources evaluation and conservation. The modelling of erosion processes has progressed rapidly and a variety of models have been developed to predict hydrological characteristics such as runoff, sediment transport and sediment yield (Zhang et al., 1996). Among them we can find the statistical, the process-based and the spatially distributed models that have been applied either to predict or to validate the soil erosion process (Bhuyan et al., 2002; Cogle et al., 2003; Angima et al., 2003; Mati et al., 2000; Dragan et al., 2003).

The Water Erosion Prediction Project WEPP model (Flanagan and Nearing, 1995) is one of the well-validated erosion prediction models that have been widely used (Merrit et al., 2003). Many authors have tested the performance of the WEPP hillslope model, finding adequate predictions for average runoff and soil losses (Zhang et al., 1996), but also less accurate predictions (Ghidy et al., 1995; Kramer and Alberts, 1995). However, WEPP predictions were better than the predictions by models like EPIC and ANSWERS, with reasonable degree of confidence for soil loss quantification under a specific condition (Bhuyan et al., 2002). A first attempt to test the WEPP model for the Andes situation was made by Bowen et al. (1998). However, resources are limited some regions and there are few measured data for catchments, which hampers the calibration of the model (Merrit et al., 2003).

This chapter describes how the performance of the hillside version of the WEPP model in predicting runoff and soil loss in La Encañada watershed, northern Peru, was tested by comparing the outputs with data measured in runoff plots.

* Cangahua: a poorly understood duripan of volcanic origin covering approximately 25,000 km^2 of Ecuador (Vera and Lopez (1986) cited by Byers, 1990).

5.2 Materials and methods

The study site

This study was conducted in La Encañada watershed. It has an area of 6,000 ha, is 2950 to 4100 m above the sea level and lies 40 km east of Cajamarca, Northern Peru (7^{o}0' and 7^{o}8'S, 78^{o}11' and 78^{o}21'W). The mean annual rainfall is 767 mm, distributed through the months of October to March, when most of rainfall events have low intensities (80% < 10 mm h^{-1}) as we emphasised in Chapter 2 of this thesis. Main climatic data from three base meteorological stations for 4 years are shown in Table 5.1. The soils in this area are classified, in general terms, as Entisols (Fluvents), Inceptisols (Ochrepts and Umbrepts) and Mollisols (Aquolls and Ustolls) in the U.S. Taxonomic Classification System (INRENA, 1998). The agricultural areas are mainly on deep soils with high organic matter content, with the most important crops being cereals, potato, maize and legumes. Shallow soils with low fertility and high erosion characteristics are sometimes also used for cropping, although most of them are appropriate for natural pasture (Proyecto PIDAE, 1995). The slope gradient varies from 0 up to 70% but almost sixty five percent of the slopes have a gradient lower than 15 %. On the steep slopes there is an enhanced erosion risk.

Table 5.1. *Climatic conditions (1995-2000) in La Encañada watershed, north Peru.*

Weather stations	Mean solar radiation (MJ m^{-2} d^{-1})	Maximum temperature* (°C)	Minimum temperature* (°C)	Mean rainfall (mm)	Number of days with rainfall*
La Toma	19.9	10.8	2.8	832	193
Usnio	19.2	14.2	6.1	720	152
Manzanas	18.3	16.2	5.9	633	177
Average La Encañada	19.1	13.7	4.9	767	174

*mean values

Runoff plot study

Based on a soil map (Jimenez, 1996, cited by Overmars, 1999), four experimental sites were chosen to cover the most representative soils in La Encañada. Measurements of runoff and soil loss were obtained from runoff plots subject to natural rainfall events occurring during February – December 2001 under bare conditions. The plots in La Encañada and Rollopampa had already been installed the year before but, unfortunately, 2000 was a very dry year and no results could be obtained. In order to analyse the effect of slope length in runoff and soil loss, three different-sized runoff plots were installed at each site. A standard runoff plot is expensive to install, so we tested a new "low-cost" design that we called the "flying runoff plot". Delimited by plastic walls and with a portable runoff collector at the bottom, each plot was easy to remove and transport to another place. Runoff after an erosive event was collected in big robust plastic bags. This obviated the need to install big concrete tanks or buried drums.

The biophysical conditions for each location are described below and summarised in Table 5.2.

La Encañada: The soil belongs to the family of the Fluventic haplustolls (INRENA, 1998), developed from an alluvial material and located at the bottom of the watershed (3150 masl). The surface horizon (Ap) texture is sandy loam, with a moderate content of organic matter and pH near neutrality. The rainfall average in this area is about 633 mm. The characteristics of the plots are as follows: the smallest plot was 5 m long by 2 m wide; the second one was 10 m long by 4 m wide and the largest was 20 m long by 6 m wide. The slope steepness was about 10% for all the plots.

Rollopampa: The soil belongs to the family of the Typic ustochrepts (INRENA, 1998), developed from a colluvial-alluvial material and located at 3200 masl. The surface horizon (Ap) texture is a sandy loam, very crumbly, with a low organic matter content and a moderately acid pH. Average rainfall in this area is 720 mm. The smallest plot was 5 m long; the second one was 10 m long and the largest was 15 m long. All the plots were 2 m wide. The slope gradient was about 70%.

Magmamayo: The soil belongs to the family of the Lithic haplustolls (INRENA, 1998), developed *in situ* from limestone and located at 3290 masl. The surface horizon (A) texture is loam, with a medium content of organic matter and pH slightly alkaline. The parent material is at 34 cm depth. The rainfall pattern is similar to that observed in La Encañada site (633 mm). The smallest plot was 5 m long by 2 m wide; the intermediate plot was 10 m long by 4 m about and the largest was 20 m long by 6 m. In all plots the slope angle was about 47%.

La Toma: The soil belongs to the family of the Typic haplumbrepts (INRENA, 1998), developed from a colluvial-alluvial material and located at the top of the watershed (3550 masl). The surface horizon (Ap) texture is silty loam, very low pH with a medium content of organic matter. The mean annual rainfall in this area is 832 mm. The smallest plot was 5 m long and 2 m wide; the second size was 10 m by 4 m wide and the largest was 20 m x 6 m. In all plots the slope angle was about 10%.

Table 5.2. Biophysical characteristics for each runoff plot set up in La Encañada watershed, northern Peru.

Experimental site	Climate type (mean annual rainfall)	Soil type	Slope angle (%)	Altitude (masl)	Soil management
La Encañada	Manzanas (633 mm)	Fluventic haplustolls	10 %	3150	Bare
Rollopampa	Usnio (720 mm)	Typic ustochrepts	70 %	3200	Bare
Magmamayo	Manzanas (633 mm)	Lithic haplustolls	47 %	3290	Bare
La Toma	La Toma (832 mm)	Typic haplumbrepts	40 %	3550	Bare

Model description

WEPP is a process-oriented model, based on modern hydrological and erosion science, designed to replace the Universal Soil Loss Equation for the routine assessment of soil erosion by organisations involved in soil and water conservation and environmental planning and assessment (Nearing et al. 1989). The simulation model predicts soil loss, runoff and sediment deposition from surface flows on hillsides. The major inputs for running the WEPP hillslope version need to be specified in four data files: a climate file, a slope file, a soil file, and a management file. The climate file requires daily values for precipitation, maximum and minimum temperature, and solar radiation. In addition to rainfall amount, the model requires three variables related to rainfall intensity, used to compute rainfall excess rates and thus runoff. The slope file consists of a sequence of slope elements with uniform properties with respect to overland flow: the so-called Overland Flow Elements (OFE). These are defined as "regions on a hillslope of homogeneous soil, cropping and management", and are the basic units for modelling erosion. The soil file contains information on the physical (soil texture), chemical (CEC, organic matter content) of the topsoil and subsoil and hydrological characteristics (erodibility indexes, hydraulic conductivity) for the topsoil. The management file contains information needed to define initial conditions, tillage practices, plant growth parameters, residue management, and crop management (Flanagan and Nearing, 1995). The model is now undergoing an extensive programme of testing and evaluation (Morgan, 1995).

Model inputs

Weather data from La Encañada were obtained from Baigorria et al. (2004) to construct the climate files for single event simulations of WEPP. Amount and duration of rainfall, maximum and minimum temperature, solar radiation, wind velocity and dew temperature are required on a daily basis. Only 16 rainfall events caused soil loss and runoff at all the plots during the months of evaluation. Table 5.3 shows the amount and peak intensity of these events. In the case of La Toma site, runoff plots were installed during the rainy season of 2001 but neither runoff nor erosion was collected. We have described the site because the soil type is found in part of the watershed. No rainfall data for La Toma is shown; however, the characterisation of rainfall events for this area from 1995 to 2000 is given in Chapter 2 of this thesis.

Soil input files were compiled from soil data obtained on a previous soil survey (see Chapters 3 and 5). The data required were soil texture, organic matter content, CEC, percentage of rock per soil horizon of the soil profile and soil depth. Initial moisture conditions were estimated from rainfall data before each erosive event. As a default, initial moisture content (M.C.) was set at 80% of saturation. If a longer dry spell occurred, the initial moisture content was lower (Table 5.3).

Table 5.3. *Characteristics of rainfall events for the runoff plots study at three sites in La Encañada watershed, northern Peru.*

Site	Date	Rainfall (mm)	Duration (h)	Peak intensity mm h^{-1}	Initial M. C. % of saturation
La Encañada	9/03/01	12.7	9.0	1.8	50
	27/3/01	9.9	6.8	53	80
	31/03/01	11.4	10.7	10	90
	2/04/01	13.3	6.4	16.4	80
	5/04/01	5.2	1.7	117	80
Rollopampa	16/03/01	28.2	10.9	9.6	40
	17/03/01	9.14	8.1	11.2	80
	19/03/01	8.4	6.1	10.6	80
	20/03/01	11.4	6.8	4.9	90
	21/03/01	6.6	7.7	12.8	90
	22/03/01	4.8	3.6	9.9	90
	26/03/01	12.9	10.4	2.9	90
	31/03/01	9.6	6.4	5.3	85
	2/04/01	10.8	9.0	3.7	95
Magmamayo	16/12/01	11.5	6.8	26.0	60
	30/12/01	12.9	9.0	2.7	90

The model requires hydraulic parameters such as interrill erodibility, rill erodibility, shear stress and effective hydraulic conductivity (Ke). The latter parameter, which is described in Chapter 7, is related to the saturated conductivity (Ksat) of the soil, but it is important to note that it is not the same as or equal to the saturated conductivity of the soil (Flanagan and Nearing, 1995). Since no formula was available to calculate Ke from Ksat and due to the great variability of this parameter in the field (Vigiak et al., 2004), we performed a sensitivity analysis to evaluate the value of Ke that best fits in the model. We compared the observed runoff values with the predicted runoff values obtained from single storm simulations using the original Ksat values divided by 2, 4, 6, 8 and 10. The results are shown in Figure 5.1. We decided to use the value of Ksat divided by 8 (Ke=Ksat/8) because it showed the highest coefficient of determination ($r^2 = 0.66$). Therefore, for the validation of the WEPP model, the values of Ke used were the original measured Ksat values divided by the factor 8.

The slope input file required the length (m) and the angle (%) of each runoff plot to be simulated. For each site, three slope files were created, according to the three sizes of each plot. The management input file was made for each slope with the parameters simulating bare soil. A summary of the soil, slope and management databases is shown in Table 5.4.

Validation of the WEPP model

After the input files had been prepared, runoff and soil loss were simulated for all 16 runoff-producing events in 2001. The observed runoff and soil loss values were plotted against the predicted values, in order to judge a relationship. A residual analysis was carried out in order to see the variation of the predicted values with the observed values. Coefficient of determination (r^2), error and mean square error (MSE) were also determined. The smaller the MSE, the closer to the simulated values are to the observed values.

Table 5.4. *Input data for soil, slope and management WEPP files from La Encañada watershed, northern Peru.*

Soil characteristics	La Encañada	Rollopampa	Magmamayo	La Toma
Texture	Sandy clay loam	Silty loam	Loam	Sandy loam
% Org.matter	2.3	2.8	1.9	6.1
CEC (meq. $100g^{-1}$)	25.1	19.1	18.0	18.1
Effective hydraulic conductivity (mm h^{-1})	0.88	0.80	1.0	1.6
Interrill erodibility (10^6 kg s m^{-4})	0.83	5.67	0.47	1.68
Rill erodibility (10^{-3} s m^{-1})	0.9	1.4	1.6	8.1
Critical shear stress (Pa)	10	7	8	10
Soil depth (cm)	120	80	50	80
Slope angle (%)	10	70	47	40
Slope length (m)	5/10/20	5/10/15	5/10/20	5/10/20
Management	Bare	Bare	Bare	Bare

5.3 Results and discussion

Runoff

Observed runoff and soil loss values were low in spite of the steep slopes under evaluation (up to 70 %) and, in some cases, no erosion and runoff was obtained at all and we had to exclude some data from the analysis. In the case of La Toma site, runoff plots were installed during the rainy season of 2001 but neither runoff nor erosion ocurred, so no data were collected. However, we have described the site because the soil type covers part of the watershed and the lack of runoff and soil loss reflects 1: the good physical/hydraulic properties (e. g., soil texture and rill & interrill erodibility indexes) this soil presents (see Chapter 3 of this thesis), and 2: the low erosivity of the rainfall events surrounding that area (see Chapter 2 of this thesis).

We analysed the trend between observed and predicted runoff (Figure 5.2). In general, runoff values were overestimated by the WEPP model. The aggregation by plot size showed a better relationship between the observed and the predicted runoff ($r^2 = 0.674$) when 20 m plots were used, followed by the medium and smallest sizes. Trend lines can be observed in Figure 5.2 and the residual analysis and coefficients of determination, error and MSE are shown in Figure 5.3 and Table 5.5, respectively. The model performed reasonably when big and medium sized plots were evaluated but performed badly for small plots. One reason might be that the WEPP model was developed using the Wischmeier database of plots of 22 m length.

There was an inverse relationship between amount of observed runoff and plot size. This tells us the effect of slope length in runoff generation. All the runoff plots tested behaved as if they were flat (zero slope); the micro-relief seems to have been significant in the runoff process.

Runoff generation is related to amount and intensity of rainfall as well as to the infiltration characteristics of soils. In general terms, since the intensity of rainfall events was low and soils present good physical properties, water from rainfall tended to rapidly infiltrate into the soil, not allowing high runoff rates to be generated. The observed runoff was low per event, never exceeding 6 mm, so the small volume of runoff could also account for the low sediment load we observed previously. The transport capacity of the runoff can limit the soil loss even in the most erodible soils. While runoff is flowing over a hillside or watershed, changes in topography, soil properties or soil cover can reduce this transport capacity, producing opportunities for deposition (Mutchler et al., 1994).

Soil loss

The WEPP model predicts values for detachment within the plots (kg m^{-2}) and sediment yield (kg m^{-1}). The latter is the amount of soil leaving the plot at the bottom of the slope and is in fact the net detachment over the entire surface of the plot. We extrapolated sediment yield into soil loss in Mg ha^{-1}.

Soil loss was underestimated by WEPP and, in some cases, the model completely failed to predict soil loss, predicting values equal to 0 (Figure 5.4). This type of model response was also observed by Bowen et al. (1998), Bhuyan et al. (2002) and Chikratar (2004). The relationship (r^2 = 0.662) found for the biggest runoff plots indicates that the model can provide realistic estimates of soil loss for these plots under bare conditions. The residual analysis is shown in Figure 5.5. Coefficient of determination, error and MSE values show that the values for the biggest plots are much better than the corresponding values for the medium and smallest plots (Table 5.6).

The observed soil loss from the smaller plot sizes (5 to 10 m long) was greater than that from the biggest plots (15 to 20 m long); probably some deposition processes occurred along the longest plots. The model did not reflect this behaviour. Predicted values did not exceed the 0.1 Mg ha^{-1} except for one event that reached 0.25 Mg ha^{-1} at the Magmamayo site in the longest plot. This soil's parameters qualify it for classification as a resistant soil. But it is shallower than the other soils, so would become saturated faster.

The La Encañada, Rollopampa and Magmamayo sites exhibited little erosion per event. This agrees with the results found in early studies about the low amount of rainfall, the low intensity of events and the low erodibility of soils prevailing in this watershed (Chapters 2 and 3, this thesis). Nevertheless, the year under evaluation seemed to be a dry year, considering that there were 18 events that produced erosion. Most of these events were of less than 10 mm rainfall and long duration (see Table 5.3), so were less erosive. Probably, soil loss evaluation under an anomalous year (like the El Niño phenomenon, for instance) would produce more erosion.

Table 5.5. *Summary statistics of the WEPP model validation for runoff, stratified according to the runoff plot size.*

	Big plots	Medium plots	Small plots
r^2	0.6740	0.3555	0.1787
Error	12.8	15.9	18.5
MSE	3.0	5.2	3.6

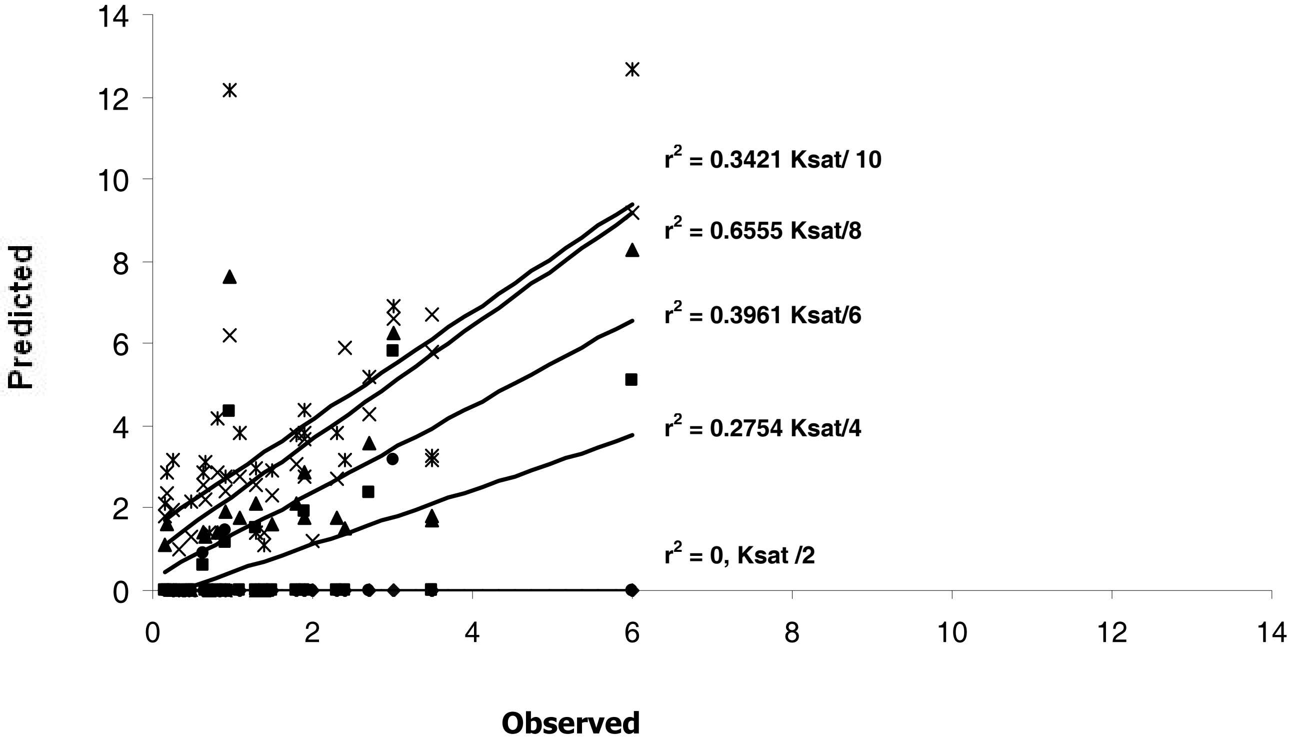

Figure 5.1. *Comparison of measured (runoff plots) and predicted (WEPP model) runoff using different calculations for Ke: Ke = Ksat / 2,4,6,8 and 10 respectively.*

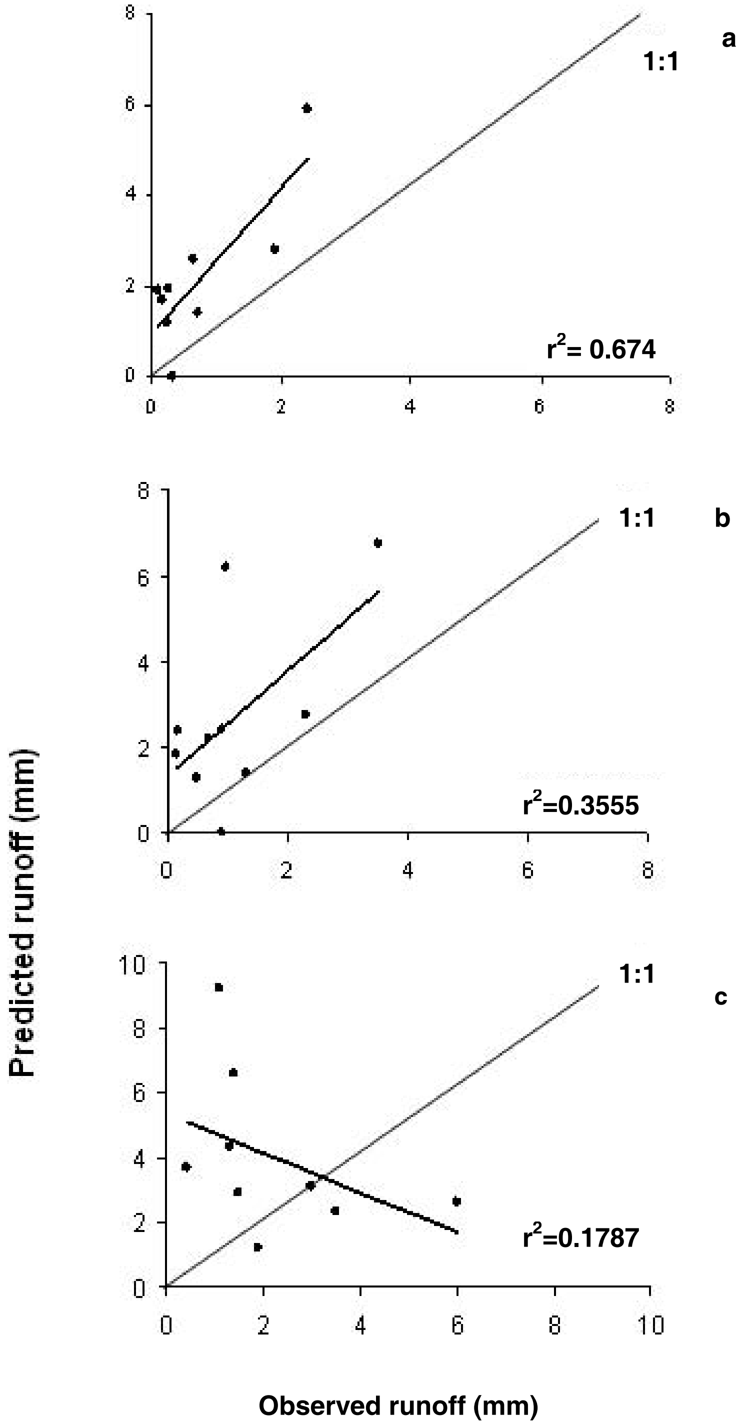

Figure 5.2. *Observed vs. WEPP predicted runoff for all erosive events in 2001 in 20 m (a), 10 m (b) and 5 m plots (c).*

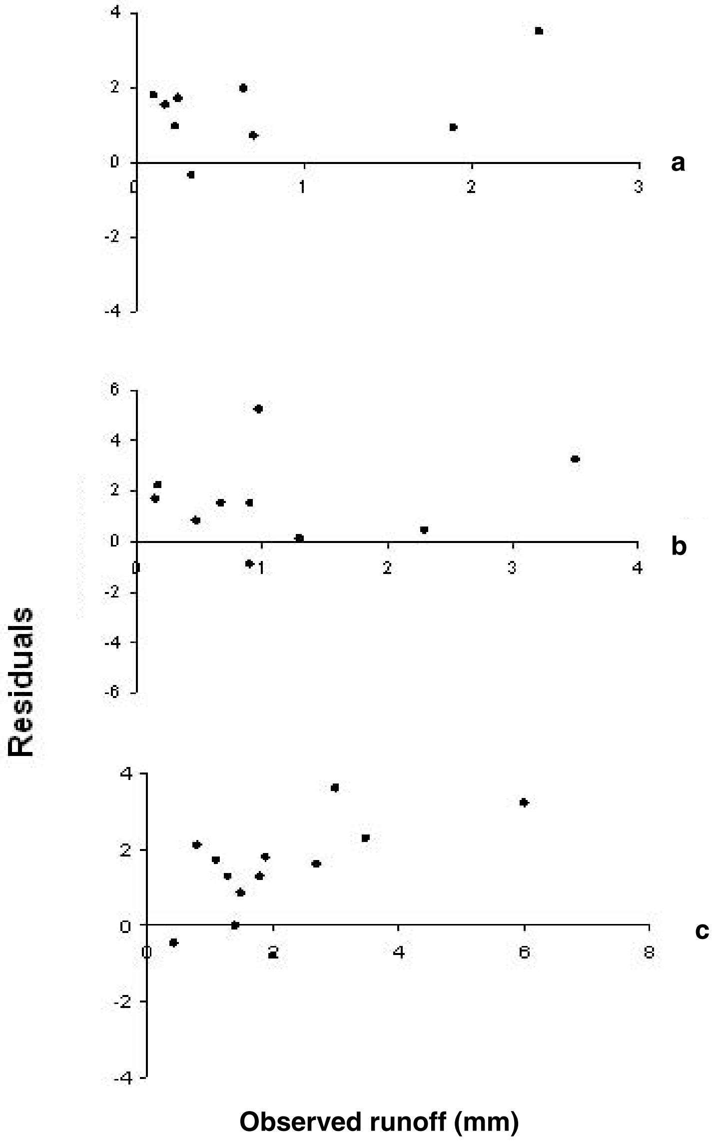

Figure 5.3. *Residuals for the three different sized runoff plots, comparing observed runoff and runoff predicted by WEPP (a: 20 m, b: 10 m, c:5 m long plots).*

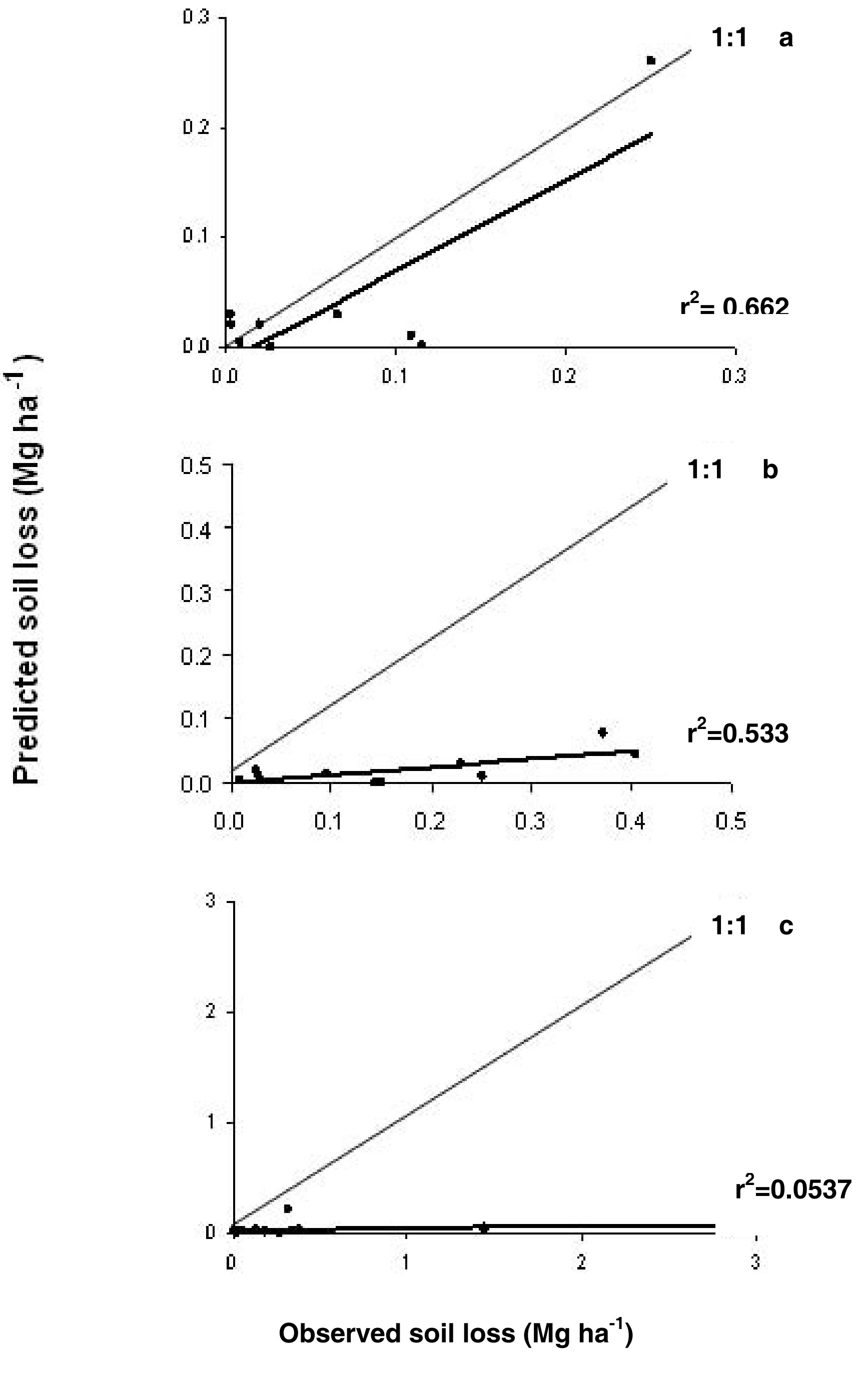

Figure 5.4. *Observed versus WEPP predicted soil loss for all erosive events in 2001 in 20 m (a), 10 m (b) and 5 m long (c) plots.*

Table 5.6. *Summary statistics of the WEPP model validation for soil loss stratified according to the runoff plot size.*

	Big plots	Medium plots	Small plots
r^2	0.6620	0.533	0.0537
Error	-0.223	-1.488	-5.731
MSE	0.0029	0.0361	0.7610

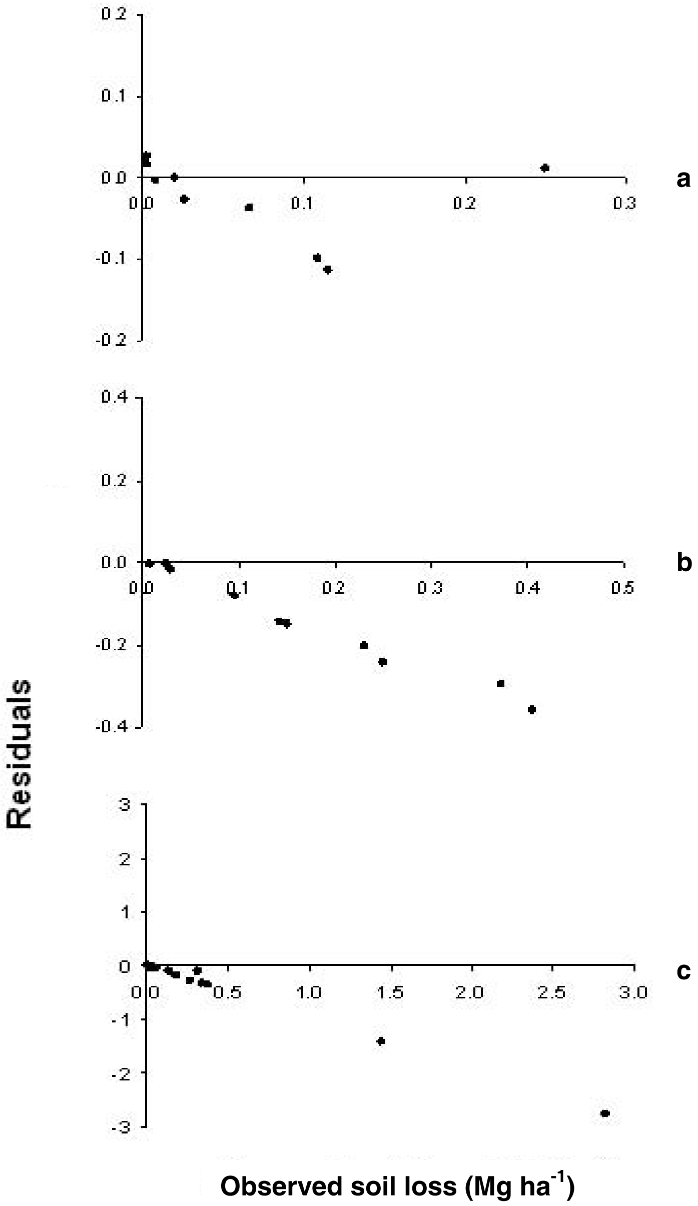

Figure 5.5. *Residuals for the three different sized runoff plots comparing observed and WEPP predicted soil loss (a: 20 m, b: 10 m, c:5 m long plots).*

It was found that steep slopes from 40 to 70% can still be stable when rain events are of low intensity (<10 mm h^{-1}) and soil is resistant (La Encañada, Magmamayo and La Toma sites, see Table 5.4) or less resistant (Rollopampa site) depending on its physical and chemical characteristics (e.g. organic matter content, soil texture, soil depth, infiltration). All these results were obtained considering bare soil conditions, as we wanted to evaluate the potential erosion of the area as well as to test the performance of the model. Since many fields are left bare after harvest, soils are exposed to the erosive forces of natural rainfall; this is the risky phase during the crop season.

5.4 Summary and conclusions

It will be recalled that the WEPP erosion model was used in this study to predict soil loss and runoff from different-sized runoff plots (5, 10 and 20 m long) in four experimental plots in La Encañada watershed, in northern Peru with bare soil. Soil loss and runoff were measured from 18 individual rainfall events during the rainy season of 2001. Experimental data sets of climate, soil and slope were compiled from previous field studies carried out in this area to collect data for the model; therefore, no estimation was done for these parameters. For management, the fallow initial condition from the WEPP database was taken. It assumed 0% initial interrill and rill cover.

The WEPP model underestimated soil loss whereas runoff was overestimated. These results were described by other authors as was mentioned in the results. In general, we conclude that the WEPP model estimates runoff and soil loss reasonably well when big plots (20 m long) are simulated compared to the shorter plots. Testing different slope lengths was useful for a better understanding of soil loss and runoff on the steep slopes of the Peruvian Andes. Small plots are effective to study basic erosion phases such as surface sealing, raindrop detachment and splash transport, while bigger plots are able to represent interrill and rill processes (Mutchler et al., 1994) and spatial compensation effect. The topographical effect (steepness and length) could also be observed in bigger plots.

The results presented here represent a first approach for evaluating soil erosion and runoff in the Peruvian Andes. WEPP demanded multiple input parameters that can be considered tedious and problematic. But the validation of WEPP showed that it can be suitable for the new scenario of the Andes.

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Chapter 6

Assessment of erosion hotspots in a watershed: integrating the WEPP model and GIS in a case study in the Peruvian Andes

6. Assessment of erosion hotspots in a watershed: integrating the WEPP model and GIS in a case study in the Peruvian Andes

Abstract

Physically-based environmental models allow us to analyze the causes and effects of erosion. However, such models are often point-specific, whereas agriculture occurs in space and time. Though Geographic Information Systems (GIS) help us understand the spatial relationship between all the various spatial data, the qualitative and subjective procedures often used for such spatial analysis result in a loss of relevance and statistical validity. The only way to profit from the ever-increasing computational power and more plentiful digital data as well as from advanced models is to improve the combination of a GIS and environmental model. This paper therefore presents an interface called Geospatial Modelling of Soil Erosion (GEMSE[1]): a tool that integrates any GIS with the Water Erosion Prediction Project (WEPP). The advantages of GEMSE are (1) it is independent of any special GIS software used to create maps and to visualize the results; (2) the results can be used to produce response surfaces relating outputs (soil loss, runoff, etc) with simple inputs (climate, soil, topography and land use management) and (3) the scale, resolution and area covered by the layers can be different, which facilitates the use of different sources of information. The use of GEMSE is illustrated for soil erosion estimation in La Encañada watershed (northern Peru) where the hillslope version of WEPP has been validated. The output from the interface shows the spatial distribution of runoff and soil erosion in the form of maps. Though these maps do not give the runoff and soil loss at watershed level, they can be used to identify hotspots that will aid decision makers to make recommendations and plan actions for soil and water conservation. Therefore, GEMSE is an option that can be used for strategic applications of the WEPP model.

Keywords: Geospatial modeling, WEPP, GIS, Soil loss, Runoff, Andes

6.1 Introduction

Modeling has formed the core of a great deal of research focusing on inherently geographic aspects of our environment, and has led to the understanding of distributions and spatial relationships in everything from astronomy to microbiology and chemistry (Parks, 1993). In the case of erosion, simulation models have become important tools for the analysis of hillslope and watershed processes and their interactions, and for the development and assessment of watershed management scenarios (He, 2003). Since erosion can adversely affect ecosystems on-site as well as off-site, the estimation of runoff and soil loss in catchments is becoming more important as concerns about surface water quality increase (Cochrane and Flanagan, 1999). For this, the "hotspots" (source areas

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[1] Software availability: Name of product: Geospatial Modelling of Soil Erosion (GEMSE), Coding language: Delphi, Program size: 1.1 Mb, Software requirements: Any GIS software only for visualization purposes, Hardware requirements: PCs with Windows 98 in advance, Available since: 2004. Contact: profcherichi@yahoo.com.

of sediments) within a watershed need to be identified. However, many of the predictive models do not examine the problem in a geographic context (Pullar and Springer, 2000).

Under these circumstances, a Geographical Information System (GIS) becomes a valuable tool. A GIS is a powerful set of tools for collecting, storing, retrieving at will, transforming and displaying spatial data from the real world (Burrough, 1986). GIS has made a tremendous impact in many fields of application, because it allows the manipulation and analysis of individual "layers" of spatial data, and it provides tools for analyzing and modeling the interrelationships between layers (Bonham-Carter, 1996). Coupled to an environmental model, a GIS can interpret simulation outputs in a spatial context (Pullar and Springer, 2000). It is presumed that better integration of GIS and environmental modeling is possible by exploiting the opportunity to combine ever-increasing computational power, more plentiful digital data, and more advanced models. GIS/modeling tools necessarily encourage the best implementation of new and better "hybrid" tools. According to Parks (1993), there are three primary reasons for integration: "(1) spatial representation is critical to environmental problem solving, but GIS currently lack the predictive and related analytic capabilities necessary to examine complex problems, (2) modelling tools typically lack sufficiently flexible GIS-like spatial analytic components and are often inaccessible to potential users less expert than their makers, and (3) modeling and GIS technology can both be made more robust by their linkage and co-evolution." Both GIS and simulation models have been developed with their own conventions, procedures and limitations. However, linking them at a technical level does not guarantee improved understanding or useful prediction (Burrough, 1986). More quantitative quality indicators, together with spatial statistics and error analysis, are needed to improve the value of GIS/modeling interfaces (Hartkamp et al., 1999).

The first application of GIS to estimate and predict erosion was made in a forested catchment that used a land classification system based on topography, soils, geology and vegetation as a mapping tool (Zhang et al., 1996). Subsequently, the TOPMODEL (Beven et al., 1984) was developed as a distributed hydrologic model that uses digital elevation data and spatial information on soil, vegetation and precipitation to estimate the soil moisture distribution at catchment level, thereby taking account of the spatial heterogeneity of both topography and soils. One of the most promising of the physically-based models currently used to model erosion is the Water Erosion Prediction Project (WEPP) model (Flanagan and Nearing, 1995). But it was not developed with a flexible graphical user interface for spatial and temporal scales applications (Renschler, 2003). The first application of WEPP with a raster-based GIS was by Savabi et al. (1995). Another attempt to integrate WEPP and GIS was by Cochrane and Flanagan (1999) for watershed erosion modeling, using an interface between Arc View and WEPP. In both cases, the integration of WEPP with a GIS was done to facilitate and improve the application of the model. The Geo-Spatial Interface for WEPP (GeoWEPP) (Renschler, 2003) is another example of a tool that combines GIS and WEPP. It utilizes readily available digital geo-referenced information from accessible Internet sources like topographic maps, digital elevation models, land use and soil maps (Renschler et al., 2002), with the aim of evaluating various land-use scenarios to assist with soil and water conservation planning.
The main aim of this paper is to present a new tool capable of integrating process-based models with Geographic Information Systems (GIS) for improving the analysis of point-estimated results at bigger scales. This interface, called Geospatial Modelling of Soil Erosion (GEMSE), makes use of the Water Erosion Prediction Project (WEPP) model, producing different maps in GIS format as a

result of this integration. Analysis of these maps gives insights useful for the evaluation of land resources and agricultural sustainability and for estimating risks in a specific area.

6.2 Materials and methods

The study area

Field data for running the model were obtained in the northern Andean Highlands of Peru, in La Encañada watershed. The study area is approximately 6000 ha and it is located at 7° 4’ S latitude and 78°16’ W longitude, 2950 and 4000 masl (Figure 6.1).

Two main climate regimes can be identified during the year in this area: the rainy season and the dry season. Three automatic weather stations were set up in the study area to record the climate data on a daily basis. A summary of climate conditions is shown in Table 6.1. A detailed description about rainfall characteristics in the study area is given in Chapter 2 of this thesis.

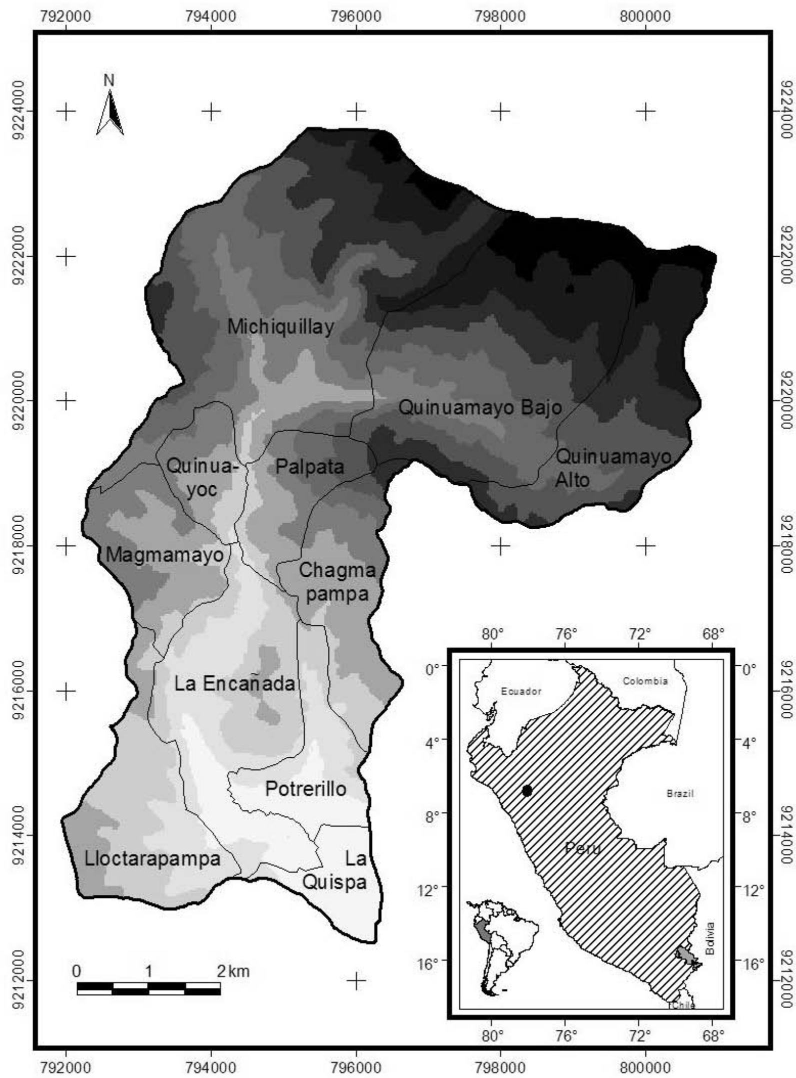

Figure 6.1. *Location of La Encañada watershed, northern Peru.*

Table 6.1. *Summary of climate conditions at the three weather stations.*

Weather station (Altitude masl)	Solar radiation ($MJ\ m^{-2}$)	Maximum temperature (°C)	Minimum temperature (°C)	Total rainfall (mm)
Las Manzanas (3020)	18.3	16.2	5.9	782.1
Usnio (3260)	19.2	14.2	6.1	717.3
La Toma (3590)	19.9	10.8	2.8	801.0

According to the Soil Taxonomy classification (USDA and NRCS, 1998) the main soil orders in the watershed are Entisols, Inceptisols and Mollisols (INRENA, 1998). The spatial distribution of the main soil groups is shown in Figure 6.2. In the highest part of the watershed there are deep soils with a high content of organic matter. Shallow soils are also found; their low organic matter content is mainly because the topsoil has been removed by erosion. Approximately sixty five percent of the area has a slope gradient less than 15%. Very steep slopes (up to 65%) are also present, increasing the risk of erosion in this mountainous area. As steep slopes often occur adjacent to the river, water erosion will contribute directly to the river sediment load.

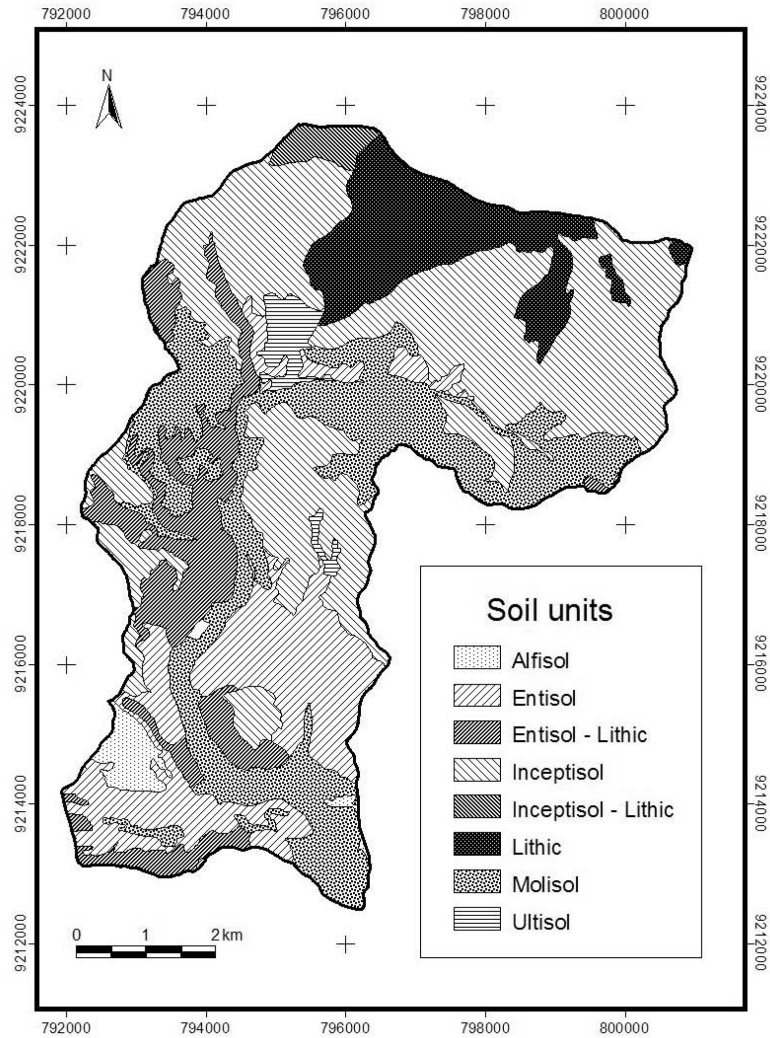

Figure 6.2. *Soil map of La Encañada after Jimenez (1996).*

The land use in La Encañada watershed is divided into croplands (55 %), cultivated pasture (13 %), natural pasture (20 %) and scrub (12 %) (INRENA, 1998). Deep soils with the largest amount of organic matter are used as croplands, with cereals, potato, maize and legumes the most important crops. However, crop yields are variable, depending on soil fertility and also on climatic conditions. Poorly fertile shallow soils that show soil erosion characteristics are also cropped, even though most of these areas are appropriate for natural pasture (Proyecto PIDAE, 1995). The planting date for the main crop varies temporally and spatially. For instance, a survey of the planting dates for potato and barley at La Encañada (Baigorria, 2003) showed that most farmers preferred to plant potato in June and to sow cereals in December. However, these two crops can also be planted at different dates, as an insurance against crop failure due to highly variable climatic conditions.

The Water Erosion Prediction Project (WEPP)

The Water Erosion Prediction Project (WEPP)[2] model (Flanagan and Nearing, 1995) is based on modern hydrological and erosion science and calculates runoff and erosion on a daily basis. It is a widely used erosion prediction model (Merrit et al., 2003) that has predicted average runoff and soil loss adequately (Zhang et al., 1996; Bhuyan et al., 2002) but also less accurately (Ghidey et al., 1995; Kramer and Alberts, 1995). Based on the fundamentals of infiltration, surface runoff, plant growth, residue decomposition, hydraulics, tillage, management, soil consolidation and erosion mechanics, it provides several major advantages over empirically based erosion prediction models, including the estimation of spatial and temporal distributions of net soil loss (Nearing et al., 1989). WEPP uses mainly physics-based equations to describe hydrologic and sediment generation and transport processes at the hillslope and in-stream scales. The model operates on a continuous daily time-step.

The model's main disadvantage is the large computational and data requirement that may limit its applicability in areas with scarce data. In addition, the watershed version of WEPP may be of limited applicability to large-scale catchments, as simulation involves individual hillslope scale models being "summed-up" to the catchment scale, increasing data requirements and error (Merrit et al., 2003).

WEPP has been tested for the Peruvian Andean conditions. The first application was by Bowen et al. (1998) in the central Andes of Peru, although this study was not considered as a validation. In a second approach, we validated the hillslope version of the model for the Northern Andes of Peru, finding adequate predictions for runoff and soil loss. More detailed description of the WEPP validation is given in Chapter 5 of this thesis.

The Geospatial Modeling for Soil Erosion (GEMSE) interface

GEMSE is a Windows-based interface designed to integrate the database structure and visualization advantages of GIS and the accuracy of process-based models (Baigorria et al., 2001). The basic databases required for GEMSE include climate, soil, topography and land use information, while

[2] Available from the Internet: http://topsoil.nserl.purdue.edu/nserlweb/weppmain/

the basic maps required are climatic zones, soil units and digital elevation model (DEM). The DEM is used to derive the slope angle and slope shape (convexity or concavity) used by WEPP.
Using the hillslope version of the WEPP model, the main output maps are soil loss (kg ha^{-1}) and runoff (mm). Maps of enrichment ratio, drainage pattern and cumulative runoff can also be generated. The output resolution depends on the input resolution. In the present study, the cell size was 50 x 50 m, to enable hotspots to be easily detected.

To use the software the user need not have a deep knowledge of modeling. For the development of databases and maps, basic knowledge of GIS is required. One of the advantages of the interface is that it is independent of any special GIS software basically used only to build maps and to visualize the results. The results can also be used to produce response surfaces relating the outputs (soil loss, runoff, etc) to inputs (climate, soil, topography and land use management). Another advantage is that the scale, resolution and the area covered by the layers (of course, totally covering the study area) can be different, making it easier to use different sources of information. Large areas can be simulated according to the current land use but also under different hypothetical or forecast scenarios (Baigorria, 2003). It is important to keep in mind that the accuracy of the results depends on the quality and resolution of the inputs and on the quality of the previously calibrated models.

Interface inputs

GEMSE uses the input maps in ASCII formats exported by ArcView, whereas the databases that relate climate, soil and topography data with the maps are in Dbase IV format. The scales and resolution of the spatial inputs can vary according to the variable.

Weather

The interface makes use of a digital climate map in which different polygons identify the different climatic zones. This map is related to a database containing the weather data assigned to each climatic zone. In the present study, three agro-ecological zones (Figure 6.3) proposed by Proyecto PIDAE (1995) were used. Three weather stations representing each agro-ecological zone were used to build their respective multi-year climate files in WEPP format (P1.cli).

Soils

The interface makes use of a digital soil map in which different polygons identify the different soil units. This map is related to two databases describing the physical and chemical characteristics of the different horizons in the soil profile. For the present case study, a digital 1:25 000 soil map made by Overmars (1999) was used; it classifies the soil by functional horizons according to the evaluated soil profiles. The advantage of using this high-resolution map is its applicability for modeling. Overmars mapped the soil according to the relationship between topography and soil variation, with the aim of being able to predict a typical soil profile at different locations in the study area.

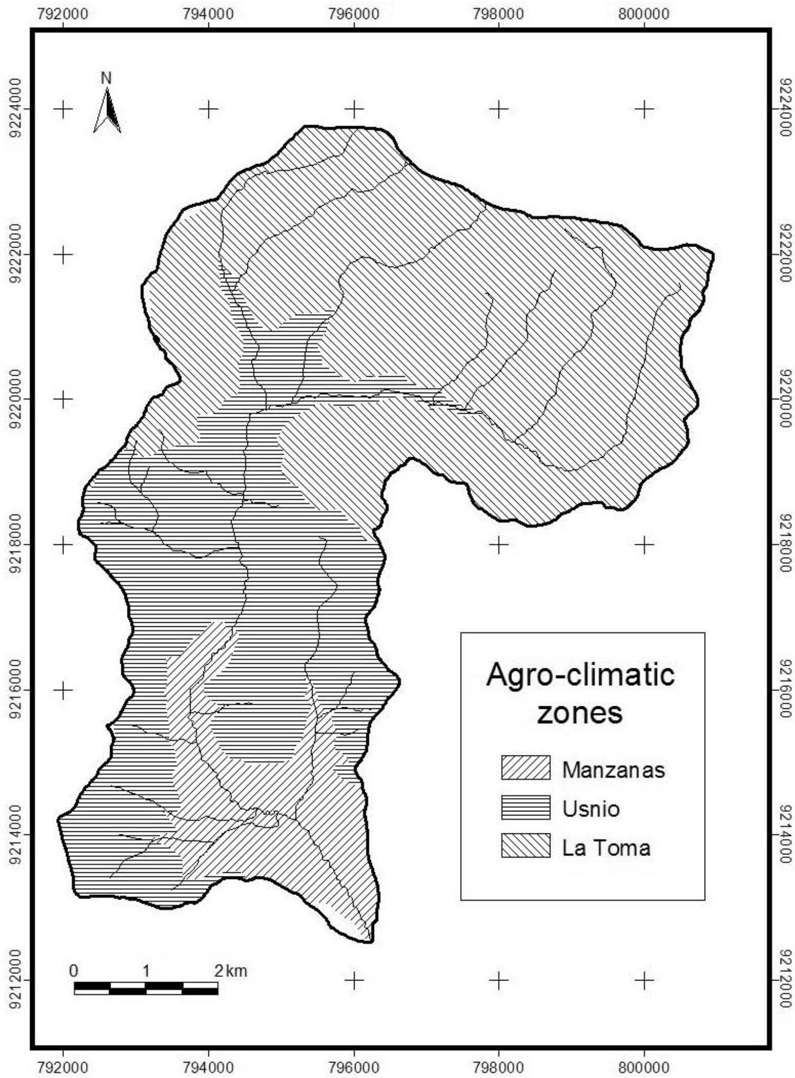

Figure 6.3. *Climatic zones in La Encañada watershed, northern Peru.*

Topography

The topography variables used are altitude and slope. In the present application, the digital elevation model (DEM) was provided by De la Cruz et al. (1999) and the slope map (Figure 6.4) was generated from this DEM.

Management

Land use management is set in the software as two different land uses: crop and fallow. In the case of crop, three variables need to be specified: planting date, N fertilizer and irrigation. An average crop management is set by default; however, it can be modified manually using the management file used by WEPP (P1.man).

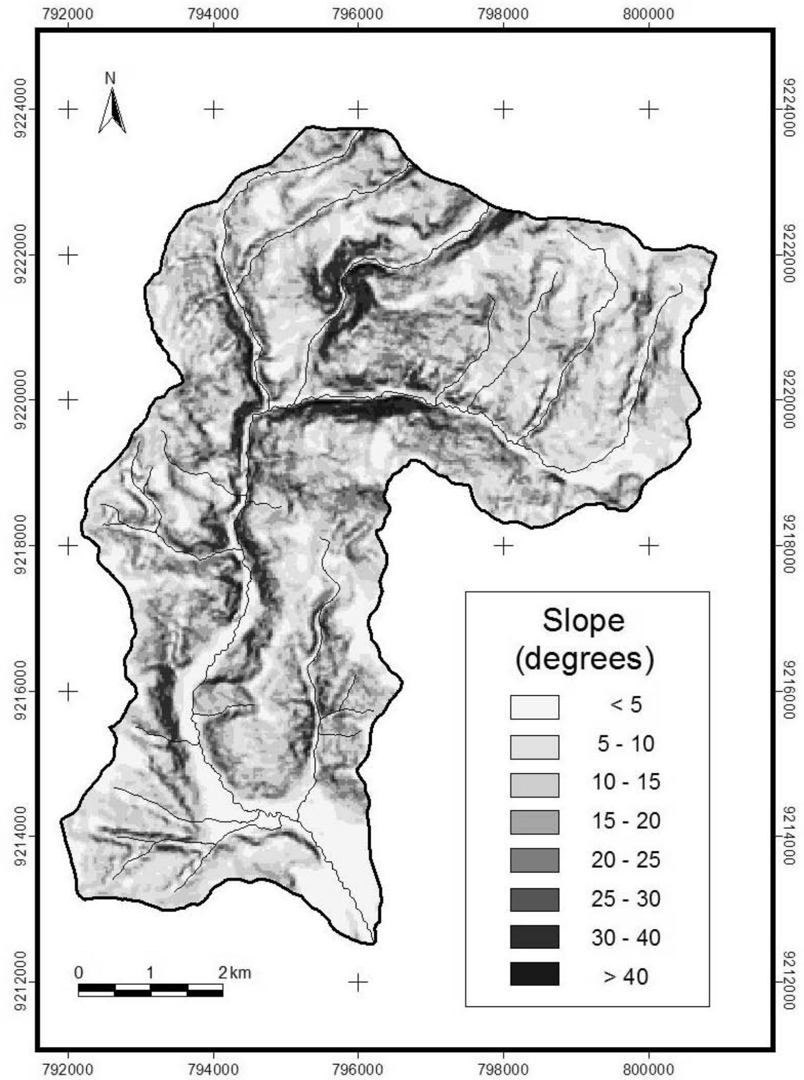

Figure 6.4. *Slope map of La Encañada watershed, northern Peru.*

Pixel points

A dbase file containing all the point coordinates covering the study area at a defined cell size is used. This file is generated using the "Grid Generator" option incorporated into the software. The geographic coordinates of the corners of the study area as well as the distance between cells are required as inputs. The output is a square or rectangular grid of points covering the entire area defined by the specified corners and resolution. A Boolean mask can be used optionally in order to define the exact areas to be simulated.

Interface execution

Once all the inputs are set, the user can run the interface. In this step, the interface reads the first pair of coordinates generated by the Grid Generator option. Coordinates are used to find the climatic zone and the soil unit in the respective maps. With this information, the interface creates internally the climate (P1.cli) and soil (P1.sol) files in the formats required by WEPP. The slope file of WEPP (P1.slp) is defined by the slope angle, slope shape and the slope length. The slope angle is read directly from the map, and the pixel size is assigned as the slope length (50 m). Slope shape is ascertained pixel by pixel, analyzing the altitude from the 3 x 3 pixel neighborhood to determine the flow direction vector. This determines two pixels on opposite sides of the central pixel. Using the definition of profile curvature (Pellegrini, 1995), information for the magnitude of rate of change of the slope is described as a quadratic equation using the slope of the three pixels. The points extracted at different distances from the center of the central pixel are used to define the concavity or convexity of the slope. The management file (P1.man) is created only once for each run for all the pixels. When all the files required by WEPP have been generated, the model is run automatically. The output files are kept internally by the interface and stored in a geo-referenced dbase file. After this process has finished, the next pair of coordinates are read and processed in the same way. When all the coordinates have been read, the process is over, and the results are ready to be imported to different GIS formats for visualization. Depending on the number of sample points, the total area studied and the resolution of the input maps, the time taken to run the model varies from minutes to hours.

Scenario simulation

In the present case study in La Encañada watershed, potato, cereals and fallow land uses were simulated in different areas according to the land use map of the study area (INRENA, 1998). In the case of crops, planting dates were determined according to the field survey performed by Baigorria (2003). These planting dates were established as the ones used most frequently by the farmers in the study area.

Output generation

After the simulations, runoff and soil loss maps under different land uses had been aggregated.

6.3 Results and discussion

Runoff

The runoff map for La Encañada watershed is shown in Figure 6.5. The estimated runoff values are the annual average of a 4-year continuous simulation on simulated hillslopes of 50 x 50 m (pixel size), expressed as mm y^{-1}. We can observe the runoff distribution on the map at pixel level or in apparently homogeneous areas presenting the same value. The estimated runoff values ranged from <5 mm y^{-1} to > 40 mm y^{-1}. Two important areas are clearly visible on the map: the northern area, presenting low values of runoff, and the central/southern area with the highest estimate of runoff. The northern part corresponds to the highest part of the watershed, where deep soils are present and La Toma climate prevails. La Toma climate is characterized by a lower erosivity than the Usnio and

Manzanas climates (Chapter 2, this thesis). The combined effect of the low erosive climate and the deep soils favor the infiltration of water and results in low runoff production, shown on the map as the white area. 80% of the surface area had estimated values of runoff < 5 mm, as we can see in the histogram (Figure 6.7a). Therefore, this area can be considered a stable zone or the buffer zone protecting the bottom of the watershed. The main land use of this zone is natural pasture, which acts as a protective cover for the soil.

The central and southern part of the watershed is the area where crops are cultivated and experiences the most aggressive climate regimes (Usnio and Manzanas). Greater amounts of estimated runoff can be identified on the map: almost 15% of the area of the map has estimated values from 5 to 20 mm, and 5% has estimates exceeding 20 mm (Figure 6.7a). The variability of climate, soils, slope and management is well represented by the model.

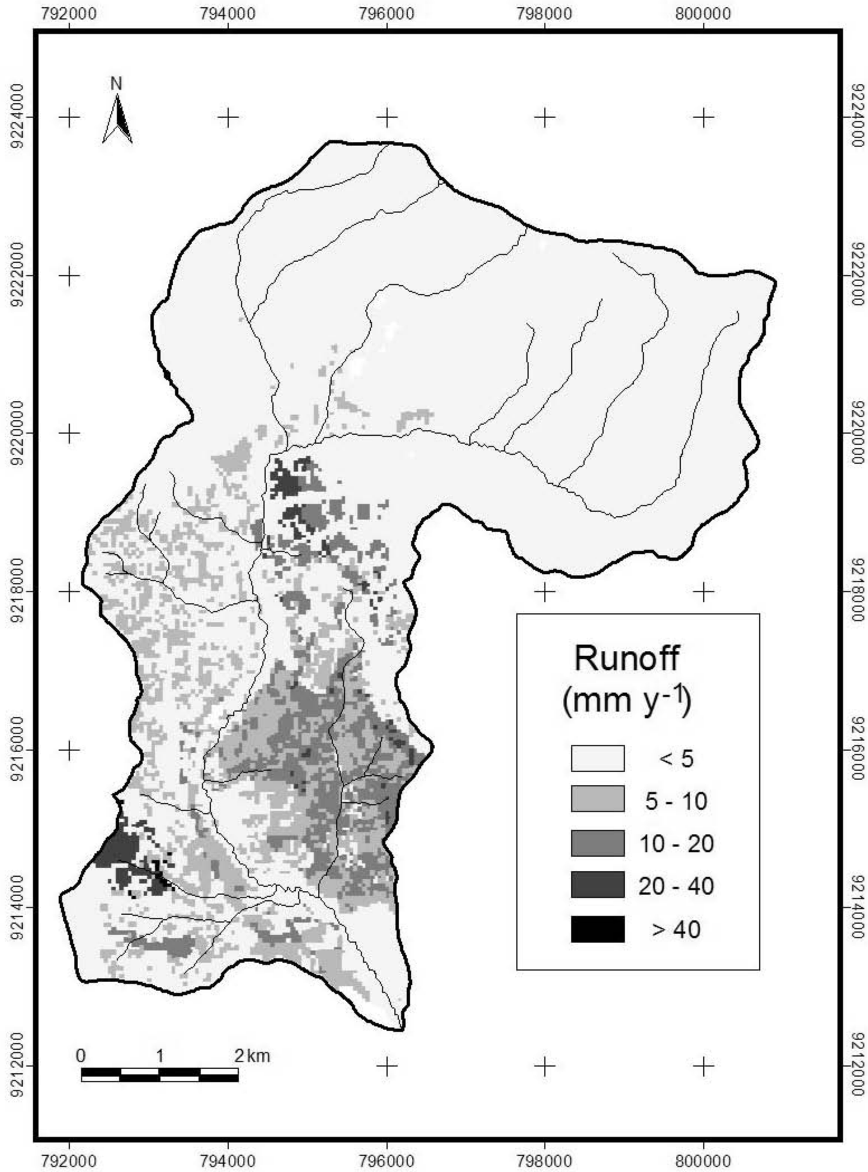

Figure 6.5. *Runoff map of La Encañada using the GEMSE interface and the WEPP model.*

Soil loss

The estimated soil loss map of La Encañada is shown in Figure 6.6. The results of running the model for 4 years' continuous simulation on each pixel of the DEM (representing hillslopes of 50 by 50 m) are expressed in Mg ha^{-1} y^{-1}. As in the runoff map, we can observe two regions within the watershed. The northern area, with low soil loss rates (< 10 Mg ha^{-1} y^{-1}) corresponds to the area with the lowest estimated runoff in Figure 6.5. However, there are some plots where higher values of soil loss can be observed; they correspond to the areas sloping steeply down to the river.

The central part of the watershed, where most of the farming occurs, presents pixels with different estimated soil loss values, representing the variability of soils, slopes and climate. The lowest part of the watershed presents low values of soil loss, since this area corresponds to the flattest part of the watershed (valley); due to the availability of water it is cropped year-round with improved pastures. For these two areas, the estimated soil loss values ranged from < 10 Mg ha^{-1} y^{-1} to > 150 Mg ha^{-1} y^{-1}.

Although it seems that the model predicts high rates of soil loss in the area, a different picture emerges when a histogram of the quantification of pixels is made: on almost 58% of the total area the estimates of soil loss are low (< 10 Mg ha^{-1} y^{-1}), nearly 10 % of the area has estimates 25-50 % Mg ha^{-1} y^{-1}, 12 % has estimates from 50-100 Mg ha^{-1} y^{-1}, 10 % has estimates from 100-150 Mg ha^{-1} y^{-1} and only 10 % has estimates > 150 Mg ha^{-1} y^{-1} (Figure 6.7b). The model estimates high values of soil loss (> 100 Mg ha^{-1} y^{-1}) specifically in those areas where slope angle exceeds 40^{o} (78 % gradient).

It seems unlikely that, for example, 30 mm y^{-1} of runoff is able to carry 125 Mg ha^{-1} y^{-1}. This would mean 417 g of sediment per liter of runoff. Our maximum value of sediment per liter of runoff was recorded at a runoff plot at the bottom of the watershed, during the previous study to validate the hillslope version of the WEPP model (Chapter 5, this thesis). This maximum value was 397 g l^{-1}.

Note that the climate map shown in Figure 6.3 had much influence on the resulting runoff and soil loss maps, giving two well-defined areas in the maps concerned. This would be improved if the interface could use high-resolution climate maps. After the study was completed a better climate map for this specific area became available (Baigorria et al., 2003); it is intended to test the interface with this new input.

6.4 Conclusions

GEMSE is operational software that integrates GIS properties with the Water Erosion Prediction Project (WEPP) model in order to analyze the spatial variation of runoff and soil loss. In the present study, which tested its application in La Encañada watershed (northern Peru), we generated a runoff map and a soil loss map whose estimated values were obtained from the WEPP model that had been validated for this watershed. Generating these maps facilitated the visualization of the erosion process at spatial and temporal scales according to the actual land use of the watershed.

Areas at risk of runoff and soil loss were identified from the maps. For runoff, the risk areas were associated with the flattest part of the watershed. For soil loss, the susceptible areas were related to the steepest slopes within the watershed. Although the map does not give the soil loss at watershed level, it can be used to identify hotspots, thus helping decision makers to formulate recommendations for soil and water conservation. This demonstrates that GEMSE is an option that can be used for strategic applications of the WEPP model.

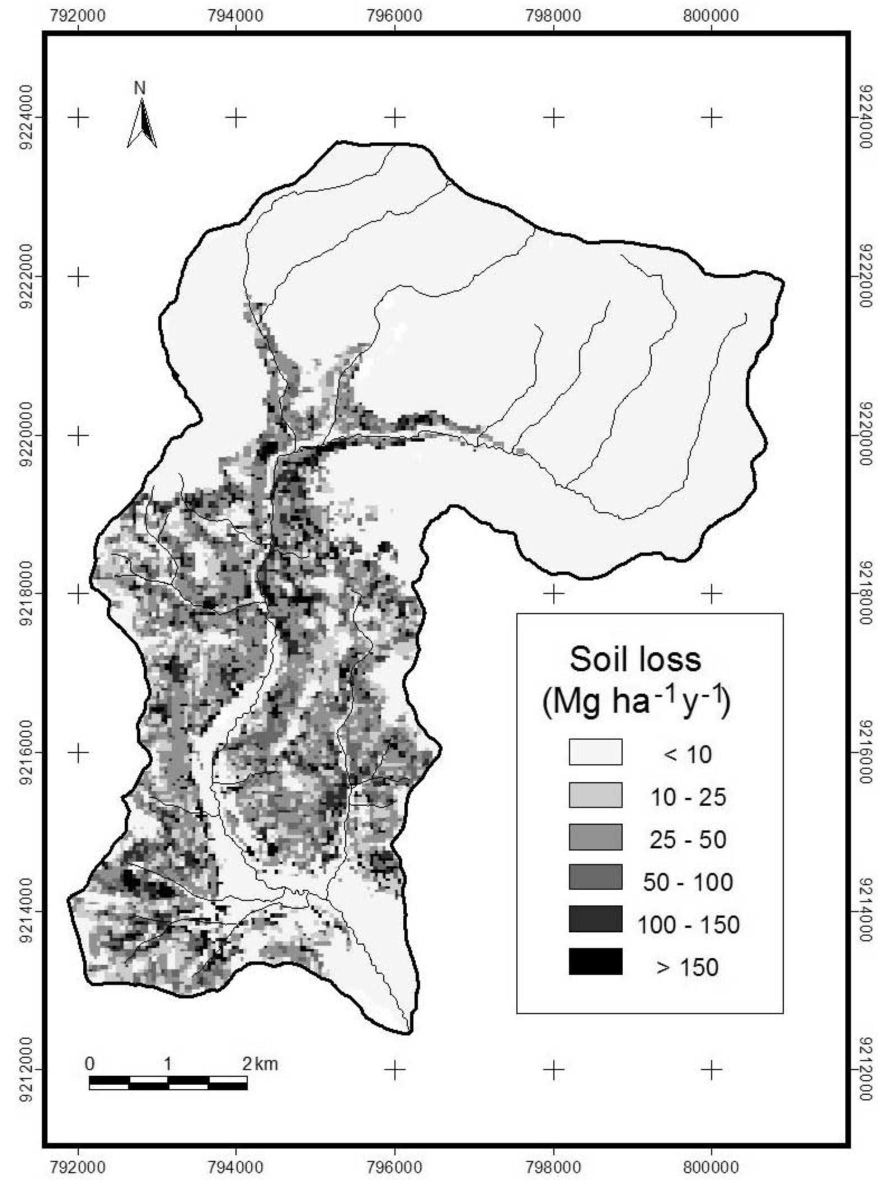

Figure 6.6. *Soil erosion map of La Encañada watershed using the GEMSE interface and the WEPP model.*

Acknowledgements

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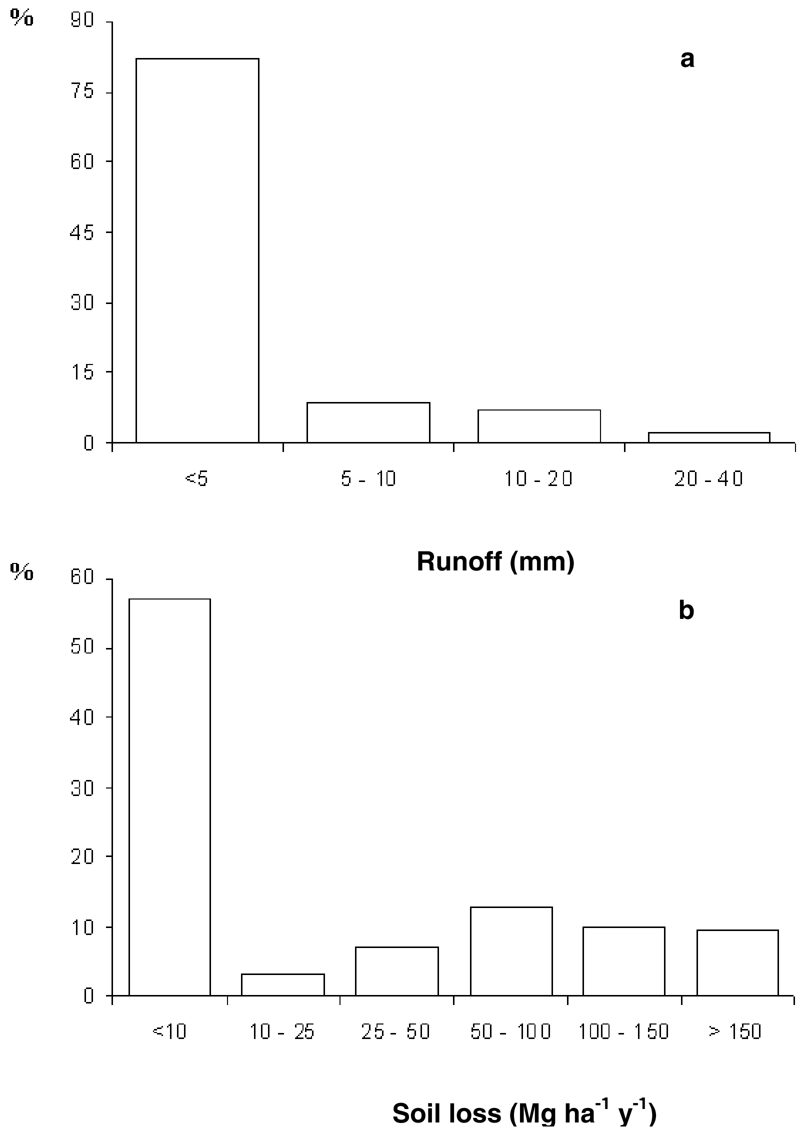

Figure 6.7. *Histograms showing the percentage of the area under different estimated values of runoff (a) and soil loss (b).*

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Chapter 7

Methods for erosion assessment in the Andes

7. Methods for erosion assessment in the Andes

Abstract

This chapter outlines the methods used to measure water erosion at three different scales in La Encañada watershed, northern Peru: the small plot scale, the runoff plot scale and the watershed scale. The smallest scale was used to study basic erosion processes like interrill and rill erosion under simulated rainfall, and to measure the important effective hydraulic conductivity. The next scale was used to study erosion (and runoff) in plots that were large enough to represent the combined processes of rill and interrill erosion under natural rainfall. Data collected during the first and second scales (and corresponding phases in the Ph.D. research) served for the validation of the Water Erosion Prediction Project (WEPP) model for the Andean highlands at the hillslope scale. At the third – watershed – scale, the suspended sediment load of the river was measured at three points. This scale is sufficiently large to include the combined effects of interrill erosion, rill erosion, gully and streambank erosion. It also reflects redistribution of eroded material as sedimentation within the landcape. Interrill erodibility was measured using a cheap portable rainfall simulator that produces a standard rain shower of 105 mm h^{-1} intensity that is only applied during 5 minutes. Given the low natural rainfall intensities (Chapter 2) one may wonder how realistic the obtained results are. Nevertheless this portable rainfall simulator showed a good performance in the field. Rill erodibility (Kr) was measured using a procedure recommended in the literature. The procedure worked well. To avoid expensive and time-consuming measurements in the future, a set of pedo-transfer functions for Andean soils was developed: Ki = -756916+1801775 silt + 15852646 vfs and Kr = -0.00778 + 0.00840 clay + 0.0341 vfs + 0.139 SOM, where silt, clay, vfs (very fine sand) and SOM (soil organic matter) are expressed as fractions. The effective hydraulic conductivity was derived from measured values of the field saturated conductivity (Ksat/field) using a tension infiltrometer. The procedure worked well but gave high values for La Encanada soils. We are not sure whether these high values are realistic. Runoff and soil loss were obtained from runoff plots. In general, very small amounts were measured. These small amounts certainly caused a low accuracy of the measurement and raise doubts about their interpretation.

7.1 Introduction

Soil erosion is a serious global problem which, in South America, is particularly evident in the Andes mountain chain. Here, the mountainous topography is considered to be one of the causes of high rates of soil erosion that results in the observable landscape degradation, reduction of agricultural productivity and sedimentation processes. It is considered to be common knowledge that soil losses threaten the already precarious livelihood of the rural poor and that the impact of this problem is also felt downstream on irrigated lowland farms.

Powerful tools exist for assessing environmental damage, but yet the access to them, the quality of their findings and their ability to handle different scales are limited. A major reason for erosion research is the collection of experimental data for predicting soil loss and sediment yield at a higher scale. For instance, data measured at plot scale is used to generate data at watershed scale.

Data sources, methods of data collection and extrapolation, as well as data accuracy, currently vary greatly in accuracy and reliability (Lal, 1994). Field measurements are the most reliable if realistic data is needed on soil loss, whereas laboratory tests, in which the effects of many factors can be controlled, are designed to lead to explanation (Morgan, 1995).

Water erosion can be evaluated using small plots, medium-sized plots (e.g. USLE plots) and/or large plots (unit-source watersheds) (Mutchler et al., 1994). The justification for small plots is that experiments performed under this condition provide insight into basic concepts and processes of soil erosion (e.g. sealing, aggregate stability, raindrop detachment and splash transport and erodibility). Next come the plots big enough to represent the combined processes of rill and interrill erosion (e.g. USLE plots) (Wischmeier and Smith, 1978). When this plot size is used, the effect of different conservation practices on soil loss can be compared with untreated land. Such plots should preferably be installed on a uniform sloping landscape element (e.g. hillside), to avoid deposition processes occurring in them.

The study described in this chapter also made use of such erosion plots. However, it is important to point out that the data were collected not for empirical research but for the validation of deterministic erosion technology (Stroosnijder, 1997), and therefore at locations where erosion was measured, a number of accompanying measurements were taken in order to be able to run WEPP.

The third type of plot, unit-source watershed, combines the results of all the erosion processes and conservation measures, although this gives little opportunity to learn about the different parts of the erosion process (Mutchler et al., 1994). Such plots should be large enough to include interrill erosion, rill erosion, gully erosion, stream bank erosion and deposition. At this scale, complexity is added by the variety of landscape forms. The measurement of sediment and water discharge can be done manually or using electronic devices, depending on the availability of trained personnel and financial support (Ciesiolka and Rose, 1998). The sediment yield at the outlet of a river basin can provide a useful perspective on the rate of erosion and soil loss in the watershed upstream (Walling, 1994).

The objective of the present chapter is to describe methods for quantifying water erosion and/or parameters related to erosion at the three scales described earlier (small plots, runoff plots and watershed) in La Encañada, northern Peru. Because the Water Erosion Prediction Project (WEPP) model (Nearing et al., 1989) was tested for this area, all WEPP parameters were collected for its calibration and validation.

7.2 The multi-scale approach

7.2.1 The small plot scale

Small plots were used for quantifying interrill and rill erosion that is the major input into the WEPP model. At each point where interrill and rill erosion were measured, soil samples were taken from the top 30 cm of the soil. The percentages of sand, silt and clay were determined in the laboratory, by the hydrometer method (Day, 1965). Very fine sand was determined by wet sieving. Soil organic matter was determined by the chromic acid digestion method (Walkley and Black, 1947).

Hydraulic conductivity was also measured at this scale. Initial moisture content for the hydraulic conductivity determination, rill and interrill erodibility was taken using a FD soil moisture probe (Delta-T Thetaprobe).

Interrill erodibility

Interrill erosion can be quantified either with natural or simulated rain. Rain simulations can be performed in the field or the laboratory. We performed our tests with a rainfall simulator in small plots with the objective of determining the interrill erodibility (Ki) factor for different soil types. Ki reflects the susceptibility of the soil to detachment by raindrop impact and shallow sheet flow. Interrill detachment was measured using a portable rainfall simulator (Kamphorst, 1987) at 21 points within the watershed. Before the simulator was set up, stones and loose organic material were carefully removed from each plot, taking care not to disturb the soil surface. After that, a standard rain shower of 105 mm h^{-1} intensity was applied for 5 minutes. Runoff was sampled every minute. Sediment that splashed off the front of the tray was collected; only downslope splash erosion was measured. Splash and runoff samples were oven-dried at 105 ^{o}C to obtain soil loss expressed in kg m^{-2}. Only bare-soil conditions were tested. The Ki values were calculated using the formula (Elliot et al., 1989):

$$D_i = Ki\ I^2\ S_f \qquad \text{Eq. 1}$$

D_i = interrill erosion rate (kg m^{-2} s^{-1}); Ki = interrill erodibility (kg s m^{-4}); I = rainfall intensity (m s^{-1}) and S_f = slope factor (dimensionless $=1.05 - 0.85 \exp^{(-0.85\ \sin[\theta])}$) where theta is expressed in degrees).

Rainfall simulator technology has the advantage of being more rapid, more efficient, more controlled and more adaptable than natural rainfall research (Meyer, 1994). For this experiment, the same shower was applied to different soil types. It was not intended to extrapolate the results to bigger scales, since the results would not be reliable.

Table 7.1 shows the results of Ki values and their related soil physical parameters. Soils containing large amounts of silt and very fine sand tend to be more erodible than those that did not show this characteristic (Chapter 3). The observed Ki values were lower than 2 000 000 kg s m^{-4}, with exception of 3 soils. Since the Ki range given for agricultural soils in the USA is between 2 000 000 and 11 000 000 kg s m^{-4} (Flanagan and Nearing, 1995), this indicates that soils in this area of the Andes are quite resistant to erosion by raindrops.

The portable mini rainfall simulator performed well in the field. Some care must to be taken when the soil is being prepared. In La Encañada watershed there are stony soils; this hampered the installation of the frame to delimit the plot. It took longer to set up the plot than to do the measuring.

Rill erodibility

Rill erosion is the process of detachment and transport of soil particles by concentrated flow. Rill erodibility (Kr) was measured using a procedure recommended by Lal and Elliot (1994). Seventeen points in the watershed were chosen. These points, which did not necessarily overlap with those used for the Ki determination, were sited where tap water was available. It was attempted to cover most soil types.

Table 7.1: *Measured Ki values determined using a small portable rainfall simulator at different points within La Encañada watershed. The percentages of clay, silt, very fine sand (VFS) and total sand, as well as organic matter (SOM) content at each point are also shown.*

Points	Clay %	Sand %	Silt %	VFS %	SOM %	Ki kg s m^{-4}
1	4	72	24	9	5.2	406 827
2	28	34	38	6.3	3.3	831 866
3	6	72	22	4.2	6.6	1683 028
4	2	78	20	10.7	7.2	951 990
5	2	72	26	10.3	5.4	1408 767
6	30	36	34	5.6	3.8	407 797
7	4	60	36	10.6	6.9	843 104
8	14	44	42	6.2	3.0	1422 257
9	8	60	32	5.1	5.7	539 990
10	22	46	32	7.4	2.6	860 996
11	36	22	42	10.2	2.7	465 994
12	22	36	42	27.4	3.5	5671 833
13	28	28	44	6	3.0	444 193
14	30	50	20	21.9	2.3	2849 459
15	30	47	23	6.3	2.5	447 225
16	29	49	22	14.5	2.2	1631 445
17	26	42	32	8.3	5.3	3066 641
18	6	62	32	8.7	6.1	895 718
19	10	74	16	4.2	6.1	1373 889
20	13	72	15	14.1	5.4	531 839
21	12	70	18	4	4.1	188 519

Using a shovel, artificial rills 0.1 m wide and 3 m, 6 m, and 9 m long were created up and down the slope. Approximately 10 minutes of artificial rain was applied on each rill using a hosepipe, until an equilibrium outflow from the rill was observed. Then, while continuing the rain, tap water was added at the top of the plot, at 8, 10, 12 and 14 l min^{-1}. After reaching equilibrium outflow, the flow velocity and the concentration of sediment in the outflow were measured. For each combination of rill length and inflow, sampling was done five times. The cross-sectional area (A) and wetted perimeter (P) were measured in order to determine the hydraulic radius (r) in each rill (r = A/P) at five different points along the rill. Between tests, the rill was kept moist. The following rill detachment equation was applied to calculate Kr values (Elliot et al., 1989):

$$D_c = Kr\,(\tau - \tau_c) \qquad \text{Eq. 2}$$

D_c = rill detachment capacity for clean water (kg m^{-2} s^{-1}); Kr = rill erodibility (s m^{-1}); τ_c = critical shear stress (Pa); τ = hydraulic shear stress of flowing water (Pa; $\tau = \gamma\, r\, s$, where γ = specific weight of water = 9810 (N m^{-3}); r = hydraulic radius of rill (m); and s = hydraulic gradient of rill flow).

Measured rill detachment values (kg m^{-2} s^{-1}) were plotted against the hydraulic shear (Pa) values. The slope of the regression line is Kr, and the intercept with the horizontal axis is the critical shear, τ_c. Note that for each graph there were from 45 to 60 data points (5 points * 3 rill lengths * 3 to 4 inflows). Figure 7.1 shows one example of how to determine the values of τ_c and Kr by plotting the detachment values versus τ values.

Table 7.2 shows the values of rill erodibility for all the measurement points and their respective soil properties (% sand, silt, clay, very fine sand and organic matter). As in the case of Ki, the values of Kr for most soils are less than 2 10^{-3} s m^{-1}, while the standard for agricultural soils in the USA is supposed to range between 2 10^{-3} and 45 10^{-3} s m^{-1} (Flanagan and Nearing, 1995). Only three soils showed values higher than 2 10^{-3} s m^{-1} . These results indicate that soils in La Encañada are resistant to detachment and transport by water. This is confirmed by the high values of the critical shear stress for these soils, compared with the standard range of between 2.1 to 4.9 Pa (Flanagan and Nearing, 1995).

The multistep regression analysis that is explained in Chapter 3 showed that Kr correlated best with very fine sand, organic matter and clay percentage, although the coefficient of determination was around 0.5.

Hydraulic conductivity

The WEPP model uses an effective hydraulic conductivity (Ke). This parameter is related to the saturated conductivity (Ksat) of the soil, but it is not the same. Since no formula was available to calculate Ke from Ksat and also because Ksat varies greatly in the field (Vigiak et al., 2004), we performed a sensitivity analysis to evaluate the value of Ke from measurements of the field-saturated hydraulic conductivity that best fits in the model.

A tension infiltrometer was used to determine the field-saturated hydraulic conductivity (Ksat/field). This equipment was used to include the effect of soil sealing. Twenty-eight representative locations were chosen within the watershed and the soil surface was cleaned without disturbing the surface structure. Stones and loose organic material were removed. A thin layer of moist fine sand was spread over the soil surface to ensure good contact between the membrane of the tension infiltrometer and the soil surface. The infiltration started at a tension of -24 cm and when steady-state was reached a tension of -14 cm was applied. Two replications were made at each plot.

Table 7.2: *Measured Kr values determined in the field, using artificial rills at different points within La Encañada watershed. The percentages of clay, silt, very fine sand (VFS) and total sand, as well as soil organic matter (SOM) content at each point are also shown..*

Points	Clay %	Sand %	Silt %	VFS %	SOM %	Kr x 10^{-3} s m^{-1}	τ_c Pa
1	36	19	45	6	1.6	0.343	7.87
2	20	32	48	21.9	2.9	1.628	15.8
3	48	22	30	14.5	0.6	0.449	4.43
4	34	24	42	12.5	2.4	1.647	4.45
5	30	50	20	3.5	2.3	0.901	19.96
6	8	60	32	5.1	5.7	0.841	16.71
7	30	40	30	3.5	2.9	1.068	19.59
8	26	36	38	18.2	1.9	8.589	8.37
9	36	20	44	21.9	1.6	6.41	17.53
10	5	70	25	8	5	1.43	5.27
11	15	38	47	20.2	2.5	1.422	7.19
12	6	72	22	4.2	6.6	0.317	5.17
13	34	36	30	8.3	4	0.274	4.42
14	10	38	52	21.2	3	8.111	18.5
15	36	34	30	4.8	3	0.256	4.43
16	26	40	34	6.3	2.7	4.234	3.68
17	10	70	20	6.1	10.6	13.86	0.64

We calculated the saturated hydraulic conductivity based on Wooding's equation (1968):

$$Q = \pi r^2 K [1+4/ \pi r\alpha] \qquad \text{Eq. 3}$$

Q: volume of water entering the soil per unit of time (cm^3 h^{-1}), K (cm h^{-1}) is the hydraulic conductivity, h (cm) is the tension at the source, r (cm) is the radius of the water supply tube of the tension infiltrometer, α = ln $[Q(h_2)/Q(h_1)]/h_2\text{-}h_1$, where Q(h) represents the volume of water entering the soil at an established tension.

Table 7.3 shows that the measured values of hydraulic conductivity are high, which accounts for the low values of Ki and Kr for these soils. The sandy loam and loamy soil textures with a good soil organic matter content that cover most of the area of La Encañada promote water infiltration into the soil. In those areas where silty and clayey soils are dominant, hydraulic conductivity is lower and subsequently the risk for erosion increases.

We are not sure whether these high values are realistic. When using these data in the WEPP validation procedure we had to optimize the measured Ksat/field values in order to obtain the effective hydraulic conductivity. The best validation was obtained when we divided measured Ksat/field values by a factor of 8 (Chapter 5).

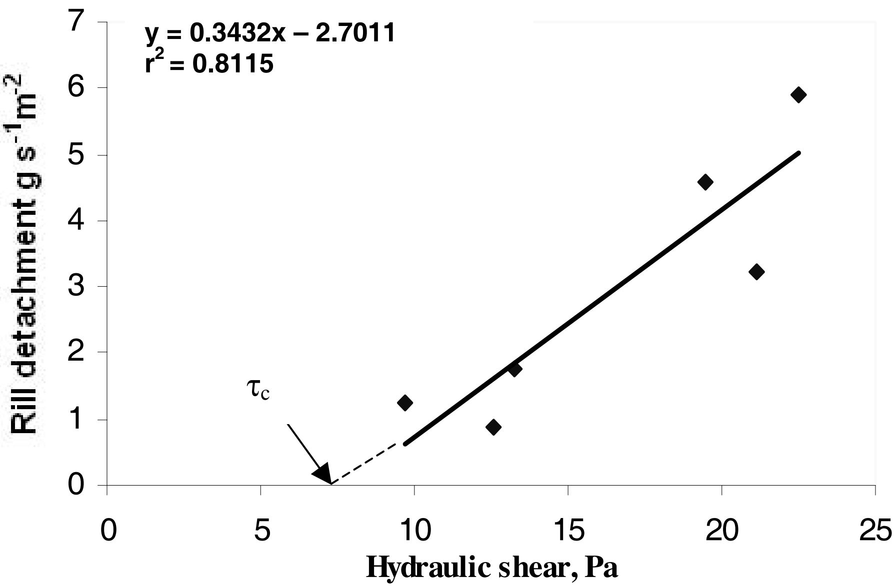

Figure 7.1: *Detachment versus hydraulic shear (τ) for one rill erosion plot in La Encañada watershed. The intercept of the trend line with the horizontal axis is the Critical Shear value (τ_c). The slope of the trend line is the value of Kr for this soil.*

7.2.2 The runoff plot scale

Measurements of runoff and soil loss were obtained from runoff plots installed at four experimental sites. The sites were chosen based on information given by a soil map (Jimenez, 1996, cited by Overmars, 1999) as well as information from a previous reconnaissance survey. Measurements made use of natural rainfall events occurring during February – December 2001 under bare conditions. Plots in La Encañada and Rollopampa sites were already installed at the beginning of 2000, but unfortunately 2000 was a very dry year and no results could then be obtained. Additional plots were installed in Magmamayo and La Toma sites in 2001.

Three different-sized runoff plots were installed at each site, in order to analyze the effect of slope length on runoff and soil loss. Because of the high costs of installing a normal runoff plot, we used a new "low-cost" design, called the "flying runoff plot". Delimited by plastic walls and with a portable runoff collector at the bottom, each plot was easy to remove and transported elsewhere. Runoff after an erosive event was collected in big sturdy plastic bags. This made it unnecessary to install big concrete tanks or buried drums. We needed only a few rain showers for our research, since this data collection was not for empirical research but aimed at the validation of deterministic erosion technology, i.e. the WEPP model.

The plot characteristics for each location are described next; the biophysical conditions are summarized in Table 7.4.

Table 7.3: *Values of hydraulic conductivity for 28 points in La Encañada watershed, showing replication and corresponding soil properties.*

	Ksat/field (mm h^{-1})			Clay	sand	silt	VFS	SOM
Point	**1 rep**	**2 rep**	**average**	**%**	**%**	**%**	**%**	**%**
1	8.0	7.7	7.9	26	44	30	3.3	2.1
2	6.8	6.8	6.8	27	40	33	3.5	2
3	7.4	6.6	7.0	30	40	30	3.5	2.9
4	7.3	6.9	7.1	26	40	34	6.3	2.7
5	8.7	8.3	8.5	28	34	38	6.3	3.3
6	7.2	7.2	7.2	28	38	34	8.2	5.2
7	6.9	6.2	6.5	20	32	48	21.9	2.9
8	7.9	7.6	7.7	26	36	38	18.2	1.9
9	9.0	9.6	9.3	34	36	30	8.3	4
10	6.3	6.0	6.2	30	50	20	3.5	2.3
11	8.2	7.8	8.0	48	22	30	14.5	0.6
12	8.4	8.3	8.4	16	40	44	14.5	1.9
13	8.0	7.0	7.5	34	24	42	12.5	2.4
14	7.0	6.9	6.9	22	46	32	7.4	2.6
15	10.3	7.5	8.9	13	72	15	14.1	5.4
16	10.3	10.3	10.3	4	72	24	9	5.2
17	7.1	7.7	7.4	4	72	24	9	5.2
18	7.3	7.2	7.3	10	70	20	6.1	10.6
19	13.9	11.9	12.9	6	72	22	4.2	6.6
20	7.7	7.3	7.5	2	78	20	10.7	7.2
21	8.8	8.3	8.6	2	72	26	10.3	5.4
22	7.0	6.7	6.8	30	36	34	5.6	3.8
23	7.0	7.7	7.4	4	60	36	10.6	6.9
24	8.7	8.4	8.6	8	60	32	5.1	5.7
25	7.7	8.0	7.9	36	20	44	21.9	1.6
26	7.5	6.9	7.2	36	20	44	21.9	1.6
27	9.0	7.2	8.1	26	46	28	8	2.1
28	10.3	9.5	9.9	5	70	25	8	5

La Encañada: Plots were installed at the beginning of the rainy season of 2000. The smallest plot was 5 m long by 2 m wide; the second one was 10 m long by 4 m wide and the largest was 20 m long by 6 m wide. The slope steepness was about 10 % for all the plots.

Rollopampa: Plots were installed at the beginning of the rainy season of 2000.The smallest plot was 5 m long; the second one was 10 m long and the largest was 15 m long. All the plots were 2 m wide. The slope angle was about 70 %.

Magmamayo: Plots were installed at the beginning of the rainy season of 2001. The smallest plot was 5 m long by 2 m width; the second size as 10 m long by about 2 m wide and the largest was 20 m long by 2 m. The slope angle was about 47 % for all the plots.

La Toma: Plots were installed at the beginning of the rainy season of 2001. The smallest plot was 5 m long and 2 m wide; the second size was 10 m by 4 m wide and the largest was 20 m x 6 m. The slope angle was about 10 % for all the plots.

Table 7.4: *Biophysical characteristics for each runoff plot set up in La Encañada watershed, northern Peru.*

Experimental site	Climate type (annual avg. rainfall)	Soil type	Slope gradient (%)	Altitude (masl)	Soil management
La Encañada	Manzanas (633 mm)	Fluventic haplustolls	10 %	3150	Bare
Rollopampa	Usnio (720 mm)	Typic ustochrepts	70 %	3200	Bare
Magmamayo	Manzanas (633 mm)	Lithic haplustolls	47 %	3290	Bare
La Toma	La Toma (832 mm)	Typic haplumbrepts	40 %	3550	Bare

Table 7.5 shows the runoff and soil loss from runoff plots installed at the four sites in La Encanada watershed. In general, the values observed were very low for both runoff and soil loss. Most of the runoff values were < 1 mm and soil loss < 0.5 Mg ha^{-1}, with one exception: the event that occurred on 16 March 2001, with 28 mm precipitation that caused 6 mm runoff and 2.8 Mg ha^{-1} on the smallest plot at the Rollopampa site. These small amounts reduced the accuracy of the measurement, thus hampering the validation of the WEPP model.

Some comments on the methodology can be made for each site:

La Encañada: this site showed the least erosion and runoff. This is attributable to a combination of factors: the texture of the soil is sandy clay loam with 2.3 % of organic matter, a soil depth of 120 cm and a slope of 10 %. These characteristics favor the infiltration of water into the soil. The values of interill (Ki) and rill (Kr) erodibility were low for this soil (830 000 kg s m^{-4} and 0.9 10-3 s m^{-1}, respectively) indicating the soil's resistance to detachment by raindrops and shallow water flow.

Soil loss and runoff differed with plot size. The medium-sized plot (10 x 4 m) showed the most runoff and soil loss, followed by the big plot (20 x 6 m) and then the smallest plot (5 x 2 m). This result is counterintuitive, because normally as plot size increases, the runoff and erosion decrease. It is possible that the varying width of the plots influenced the results, by affecting the lateral movement of soil particles and causing unequal deposition of sediments downslope. It must be reiterated that the amounts measured were so small that the accuracy of the measurement was low.

Rollopampa: Here the plots were the same width in all sites, and the observed soil loss and runoff were as expected. The Rollopampa soil has a high content of silt (42 %) and shows the highest value of interrill erodibility (Ki = 5671833 kg s m^{-4}) and rill erodibility (Kr = 1.4 10^{-3} s m^{-1}). This implies that it is a more erodible soil. In addition, the plots were on a slope of 70 % so were at greater risk of erosion than flatter areas. Much more soil loss and runoff were collected in the smallest plot (e.g. 2.8 Mg ha^{-1} of soil loss and 6 mm runoff in one event), followed by the medium-sized plot and finally by the biggest plot. In the latter plot, despite the erodible soil and the steep slope, seven of the nine events presented no soil loss at all (0 Mg ha^{-1}).

Magmamayo: It was only possible to evaluate two rainfall events, since there had been no runoff and soil loss previously. The slope gradient was 47 % and the Ki and Kr values are low. The low intensity of rainfall events caused low rates of runoff and soil loss. The two observations were as expected: more erosion in the smallest plot, followed by the medium-sized plot and finally by the biggest one.

La Toma: Neither runoff nor erosion occurred in 2001, so no data could be collected. The soil type covers part of the watershed and the lack of runoff and soil loss reflects the good physical/hydraulic properties (Chapter 3) and the low erosivity of the rainfall events in the area (Chapter 2).

From the foregoing it can be concluded that the reason small plots seem to overestimate runoff and soil loss is because the short plot length let all the detached soil particles move into the runoff collector. On the other hand, longer plots seem to underestimate these processes, since soil particles have the chance to move down the slope and to be trapped by the soil surface roughness. In other words, a combination of erosion and sedimentation occurs within these longer plots.
All the sediment collected was analyzed. The results are shown in Table 7.6, where the proportions of clay, silt, sand and organic matter in the suspended sediment are compared with those of the original soil texture at each site. In some cases the contents in the original soil are higher than in the suspended sediment; in other cases, the reverse is true. In other words: the results show little consistency and no conclusions can be drawn.

7.2.3 The watershed scale

Three points at La Encañada river were chosen for measuring water discharge and suspended sediment concentration in an attempt to determine the sediment source area for the watershed. Figure 7.2 shows the name and altitude of each point of sampling. The initial idea was to correlate the monitored water discharge and sediment concentration with the respective rainfall events. Unfortunately, all climatic data from two weather stations were lost for the time span the evaluation was done and so we could not achieve this objective. However, it is interesting to show the degree of scatter in the suspended sediment concentration/discharge relationship during December 2002 to April 2003.

Table 7.5. *Characteristics of rainfall events and data on runoff (Roff) and soil loss (S.L.) for the runoff plots study at three sites in La Encañada watershed, northern Peru.*

Site	Date	Rainfall (mm)	Duration (h)	Peak intensity	Initial M. C. % of saturation	Biggest plot		Medium-sized plot		Smallest plot	
						Roff	S. L.	Roff	S.L	Roff	S.L
				$mm\ h^{-1}$		mm	$Mg\ ha^{-1}$	mm	$Mg\ ha^{-1}$	mm	$Mg\ ha^{-1}$
La Encañada	9/03/01	12.7	9.0	1.8	50	0.3	0.03	0.1	0.03	0.0	0.00
	27/3/01	9.9	6.8	53	80	0.6	0.07	0.9	0.23	0.1	0.04
	31/03/01	11.4	10.7	10	90	0.3	0.01	0.1	0.02	0.2	0.01
	2/04/01	13.3	6.4	16.4	80	1.9	0.11	2.3	0.25	1.1	0.06
	5/04/01	5.2	1.7	117	80	0.9	0.06	0.9	0.15	0.5	0.02
	total	52.5				4.0	0.28	4.3	0.68	1.9	0.13
Rollopampa	16/03/01	28.2	10.9	9.6	40	0.3	0.07	1.0	0.37	6.0	2.82
	17/03/01	9.14	8.1	11.2	80	0.03	0.00	0.2	0.01	1.9	0.14
	19/03/01	8.4	6.1	10.6	80	0.02	0.00	0.2	0.03	1.5	0.19
	20/03/01	11.4	6.8	4.9	90	0.17	0.00	0.4	0.01	3.0	0.31
	21/03/01	6.6	7.7	12.8	90	0.07	0.00	0.2	0.00	1.3	0.38
	22/03/01	4.8	3.6	9.9	90	0.09	0.02	0.2	0.10	2.0	0.04
	26/03/01	12.9	10.4	2.9	90	0.06	0.00	0.2	0.00	0.8	0.01
	31/03/01	9.6	6.4	5.3	85	0.23	0.00	0.7	0.03	1.8	0.18
	2/04/01	10.8	9.0	3.7	95	0.23	0.00	0.5	0.01	2.7	0.34
	total	101.84				1.20	0.09	3.6	0.56	21.0	4.41
Magmamayo	16/12/01	11.5	6.8	26.0	60	2.4	0.25	3.5	0.40	3.5	1.44
	30/12/01	12.9	9.0	2.7	90	0.7	0.12	1.3	0.14	1.4	0.27
	total	24.4				3.1	0.37	4.8	0.54	4.0	1.71

Table 7.6: Analysis of suspended sediments collected at three experimental sites. SOM stands for soil organic matter. Values in bold refer to the original soil.

	SOM %	Silt %	Clay %	Sand Very coarse	Coarse	Mod.	Fine	Very fine
La Encañada	**3.3**	**38**	**28**					
Average	3.0	35.5	33.3	3.4	11.3	20.9	30.9	33.4
Max.	4.1	41.0	40.0	12.5	19.8	29.3	48.3	42.0
Min.	1.9	20.0	18.0	0.6	5.0	12.2	25.1	23.8
St.dev.	0.7	6.4	6.0	2.8	3.8	4.4	6.0	5.5
Rollopampa	**3.5**	**42**	**22**					
Average.	2.2	43.7	19.9	0.3	1.2	4.4	17.8	76.4
Max.	3.1	50.0	30.0	0.4	2.4	7.0	26.4	90.1
Min.	1.5	40.0	10.0	0.1	0.6	0.8	8.4	67.7
St.dev.	0.4	3.5	7.8	0.1	0.7	2.2	6.4	8.1
Magmamayo	**2.7**	**42**	**36**					
Average.	3.0	42.7	12.7	11.5	20.7	22.6	24.8	20.4
Max.	3.2	46.0	14	13.1	25.0	23.5	27.5	22.0
Min.	2.8	40	12	9.7	18.2	21.8	21.2	19.3
St.dev.	0.6	3.1	1.2	1.7	3.7	0.8	3.2	1.4

Suspended sediment was sampled manually by a team of people who had been trained to measure stream velocity, water depth and to take samples in the river. Measurements started as soon as a rain event began, and sampling then continued every hour until two hours after the rain ended. The sampling technique consisted of taking three one-liter samples of water containing suspended sediment in the middle of the channel. The sampling depth was not a problem, since at point A the water depth rarely exceeded 20 cm; at point B it was never more than 30 cm, whereas in point C no more than 50 cm water depth was recorded. Almost all samples contained few suspended particles, as evidenced by the transparency of the river water.

It could be concluded that the evaluated rainy season showed very few erosive events, except for two events that produced considerable water discharge and brought so much sediment in suspension that the river water turned brown. Figure 7.3 shows the water discharge ($m^3 s^{-1}$) plotted against the suspended sediment concentration ($g l^{-1}$) for 136 water samples, representing 13 rain events of evaluation.

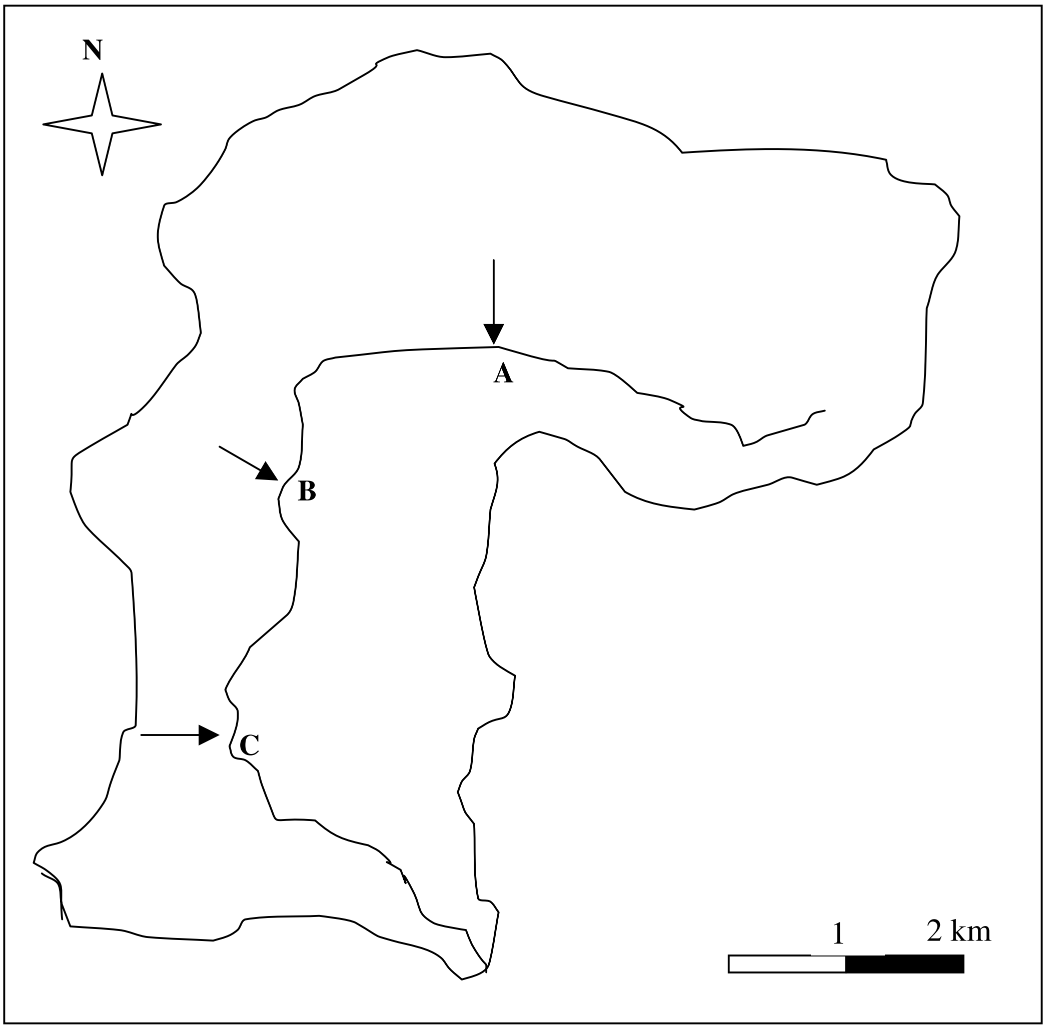

Figure 7.2: *Scheme of La Encañada watershed showing the stations where the river sediment load was measured. point A: Quinuamayo (3379 masl); point B: Puente (3172 masl) and point C: Captacion (3014 masl)*

The highest values of discharge were detected at the bottom of the watershed (point C, with 26.5 m^3 s^{-1}), as was the highest sediment concentration (49.5 g l^{-1}). At point A, in the upper part of the watershed, water but no sediment was detected. This is because most of the area above this point is covered by natural vegetation (pastures). The area prone to erosion is the middle part, between points A and B. In this area there are steep slopes with soils containing large amounts of very fine sand and silt that suffered erosion and landslides during the last El Niño in 1998. Collecting samples at point C revealed what was going on in the watershed as a whole.

The suspended sediment concentration in the river can be compared with that in the runoff collected from the runoff plots. The highest measured concentration (46.9 g l^{-1}) was from the smallest plot, in Rollopampa site on 16 March 2001. The runoff was like liquid mud. This concentration is comparable to the highest concentration of suspended matter sampled in the river. It shows that the only event that produced 49.5 g l^{-1} suspended sediment in the river was really erosive.

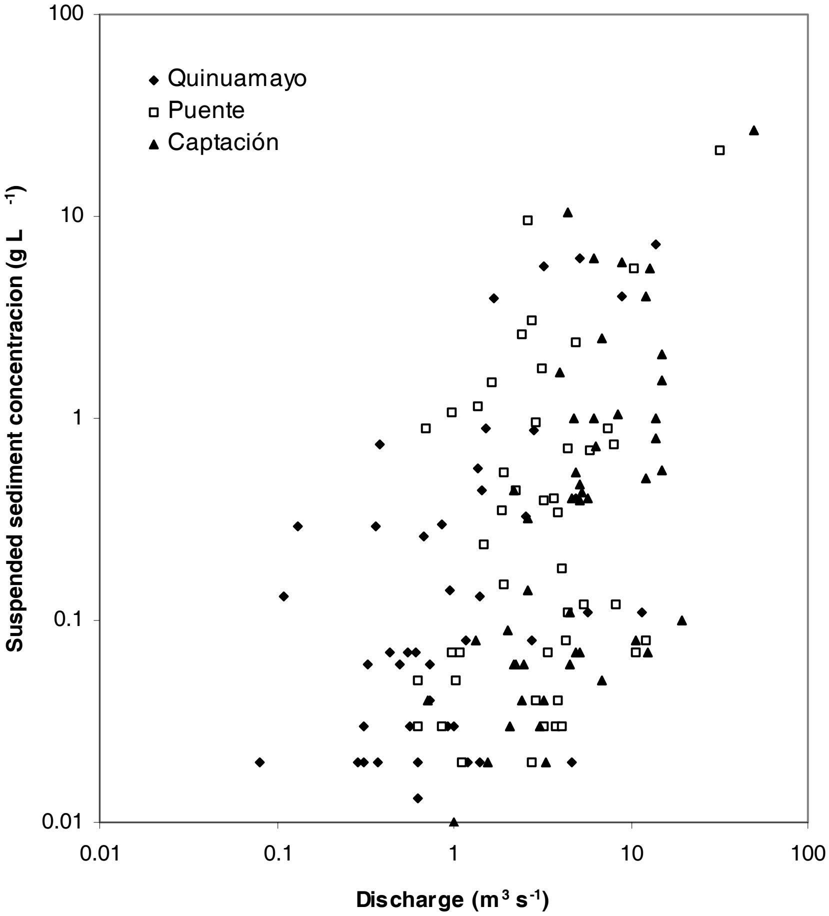

Figure 7.3: *Suspended sediment concentration versus discharge for La Encañada river at three different sampling stations: Quinuamayo (point A - upper part of the catchment), Puente (point B -medium part) and Captación (point C - at the bottom of the catchment).*

7.3 Conclusions

All soil-related erosion parameters were measured for the WEPP hillside model validation in La Encanada watershed. Interrill and rill erodibility, shear stress as well as hydraulic conductivity were determined in the field. The results obtained did not match the US standard range of values in WEPP (the default values), suggesting that the origin and physical-chemical characteristics of La Encañada soils differ from those of the soils in the original WEPP database.

Interrill erodibility was measured using a cheap portable rainfall simulator that produces a standard rain shower of 105 mm h^{-1} intensity that is only applied during 5 minutes. Given the low natural rainfall intensities (Chapter 2) one may wonder how realistic the obtained results are. Nevertheless this portable rainfall simulator showed a good performance in the field.

Rill erodibility (Kr) was measured using a procedure recommended by Lal and Elliot (1994). The procedure worked well. A multi-step regression analysis (Chapter 3) showed that Kr is best correlated with very fine sand, organic matter and clay percentage, although the coefficient of determination was around 0.5.

To avoid expensive and time-consuming measurements in the future, a set of pedo-transfer functions for Andean soils was developed: Ki = -756916+1801775 silt + 15852646 vfs and Kr = -0.00778 + 0.00840 clay + 0.0341 vfs + 0.139 SOM, where silt, clay, vfs (very fine sand) and SOM (soil organic matter) are expressed as fractions.

The effective hydraulic conductivity was derived from measured values of the saturated conductivity (Ksat/field) using a tension infiltrometer. This equipment was used to include the effect of soil sealing. The procedure worked well but gave high values for La Encañada soils. We are not sure whether these high values are realistic. When using these data in the WEPP validation procedure we had to optimize the measured values in order to obtain the effective hydraulic conductivity. The finding that the best validation was obtained when we divided the measured Ksat/field values by a factor of 8 (Chapter 5) implies that either the measurement (i.e. method or equipment) or the model is not realistic; unfortunately, we have insufficient evidence to be able to say which.

Runoff and soil loss were obtained from runoff plots. In general, very small amounts were measured. These small amounts certainly caused a low accuracy of the measurement and raise doubts about their interpretation. The question is, what is the optimum size for a runoff plot, given that our aim was to validate the WEPP model. The answer was given in Chapter 5. In this Chapter 5 the validation of the hillside version of the WEPP model showed a better correlation between observed and estimated runoff and soil loss when big plots were tested. One reason for this, already mentioned in Chapter 5, is that the WEPP model was developed using the Wischmeier database of plots 22 m long. So, there is probably no ‘optimal’ plot size. The optimum depends on the purpose of the measurement.

It will be recalled that the suspended sediment in the La Encañada was measured in samples taken manually, and that our intention to monitor water discharge and sediment concentration and correlate these with rainfall events had to be abandoned because all data from two weather stations were lost for the time span of the evaluation.

Chapter 2 indicates that in the Andes there is a large inter-annual variation and large intra-seasonal variation due to the El Niño/La Niña phenomena. Chapter 6 showed a large spatial variation in factors determining erosion. According to Stroosnijder (2003) erosion measurements should therefore be taken frequently, for a sufficiently long time and over a sufficiently large area. Regrettably, due to limited funding and the high cost of erosion measurements, these conditions were not fulfilled during the research described in this thesis.

Not so long ago, Beven (2001) wrote that it seems impossible to build a catchment-level hydrological (and hence an erosion) model because of the lack of adequate data and measuring techniques. Indeed there is a crisis of sorts in erosion measurements because there is a lack of development of new technologies and equipment and a lack of skilled personnel (Stroosnijder, 2003). However, the methods described in this chapter yielded data of reasonable quality that were collected with very limited funds. Given the fact that there are almost no recent erosion studies and measurements in the Andes, this is quite an achievement.

Given the high data demand of erosion prediction models and the difficulties in obtaining such data of sufficient quality and spatial and temporal coverage, many models use empirical pedotransfer functions. Hence, although many erosion models are classified as deterministic, they may also be called empirical.

Acknowledgements

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Chapter 8

Conclusions

8. Conclusions

Insufficient attention has been given to elucidating the factors that affect soil erosion in the Andean highlands. To remedy this shortcoming, the aim of the study described in this thesis was to analyze the erosion process at different scales in La Encañada watershed (northern Peru), using the deterministic WEPP erosion model. For this, a special three-stage methodology was developed for data collection and model validation (Chapters 1 and 7). Step one consisted of a broad investigation of all WEPP input parameters at the watershed scale (Chapters 2 and 3), followed by an uncertainty analysis of the WEPP model (Chapter 4). This analysis provided the decision support for the second step that consists of the validation of the hillslope version of WEPP (Chapter 5). Finally, in a third step the hillslope version of WEPP was upscaled to obtain erosion maps at watershed scale in order to determine erosion hotspots in the area (Chapter 6). Answers to the five research questions that were formulated at the start of this research are given below. A general conclusion finalizes this chapter.

Question 1: Is the erosion process in this part of the Andes related more to climatic characteristics than to soil properties, or to both? (Chapters 2 and 3).

Studying the spatial and temporal distribution of rainfall characteristics in La Encañada from 1995 to 2000 revealed that in neutral years (1995-96 and 1996-97) the mean annual rainfall was < 600 mm. During El Niño (1997-98) and La Niña (1998-99 and 1999-2000) years the annual amount increased, with the maximum being 1200 mm. In general, rainfall intensities were very low, with 96 % of events < 7.5 mm h^{-1}. But during the El Niño year, the number of high intensity events increased in the lower part of the watershed (18%) where normally only 4 % of events were high intensity. The La Niña years were characterized by a large total rainfall, but with lower intensities.

Depending on the year, some spatial variation can be observed in the amount of rainfall falling at different altitudes. This variation seems to be related to the topography and to phenomena like El Niño/La Niña that affect wind circulation and the convective movement of air masses. Our analysis showed that in the lower part of the watershed, rain events are more erosive, especially during abnormal years such as El Niño. Being near to a big plateau of approximately 60 km^2, the lower part of La Encañada is a large convective area. This area experiences the highest intensity rainfall events, whereas the lowest intensity events occur in the upper part of the watershed. However, in the latter area the total annual rainfall is higher. The overall conclusion is that the majority of rains are not erosive.

Measurements of interrill and rill erodibility taken at 37 points within La Encañada showed that in this area the soil erodibility is low. The most erodible soils were those with the greatest amount of silt + very fine sands. The most resistant were clay soils. USLE erodibility values confirm that most soils in the area have low erodibility values. The high critical shear stress values measured confirmed the low erodibility of soils.

Two regression equations are proposed that relate easily determined soil physical properties to both interrill and rill erodibility. It was observed that silt and very fine sand are strongly correlated with the interrill erodibility values, whereas clay, very fine sand and soil organic matter are strongly correlated with rill erodibility. More soil parameters need to be included if more accurate results are required.

When combined with the observed low erosivity (Chapter 2) the above findings imply that the risk of water erosion on agricultural fields is low. Climate and soil properties contribute equally to this low erosion risk.

Question 2: What is the minimum data set that describes erosion processes with sufficient accuracy? (Chapter 4)

Various conclusions can be drawn from the uncertainty analysis of the WEPP model and these are summarized in Table 4.8. The table shows that the rainfall distribution over the year appears to be neither excessive nor dramatic. However, there were more rainfall events > 25 mm h^{-1} during 1997-1998 (El Niño year), especially near Manzanas weather station (11 events versus only 3 recorded in La Toma). This small difference seems to have a great impact on the soil loss process, as observed in the results. The WEPP model reflected the higher erosivity of the Manzanas climate compared to La Toma climate very well. The maximum estimated runoff was 80.4 mm y^{-1} (15 % of the total annual rainfall under Manzanas climate, under fallow), the minimum was 4.5 mm y^{-1} (1.2 % of the total annual rainfall under La Toma climate and barley). This low value is related to the high hydraulic conductivity of the deep organic soils (the least erodible soils). Sediment yield ranged from 0 in soils on flat areas (i.e. < 5 % slope angle) to 122 Mg ha^{-1} y^{-1} (erodible silty soils on very steep slopes i.e. 65 % gradient).

It was shown that gradient greatly influences the erosion rate in the area, especially if the soil is highly erodible and if the climate is erosive. The dynamic simulation of vegetative cover, testing different planting dates, did allow us to evaluate the runoff and soil loss processes over time. Planting potato in August produces more erosion than planting in May or June. For barley, sowing from December to March produced less erosion than planting in November.

Since we did not use measured values of soil loss and runoff in the uncertainty analysis, we could not conclude whether the WEPP estimates were in the right order of magnitude. But since all the data used as inputs to run the model and to perform this analysis were measured in La Encañada, we conclude that the predicted results gave us a range of values in which real data should fall. In addition, the uncertainty analysis revealed the sensitivity of parameters like climate, slope angle, erodibility factors (Ki, Kr and τ_c), soil management and planting dates in the model.

Question 3: Is the WEPP model suitable for Andean conditions? (Chapter 5)

The WEPP erosion model was used to predict soil loss and runoff from different-sized runoff plots (5, 10 and 20 m long) in four experimental plots in La Encañada under bare soil conditions. Soil loss and runoff were measured from 18 individual rainfall events during the rainy season of 2001. The values measured for runoff and soil loss were very low during 2001 (all were < 6 mm for runoff and < 0.1 Mg ha^{-1} for soil loss), from which we conclude that little erosion can be expected in the watershed in a neutral (neither El Niño nor La Niña anomaly) year. However, the small amounts result in the accuracy of the measurement being low, which hampers the validation of the WEPP model.

Experimental data sets of climate, soil and slope were compiled from previous field studies carried out in this area to collect data for the model; therefore, none of the WEPP parameters needed to be estimated, since they had all been measured. For management, the fallow initial condition from the WEPP database was taken. It was assumed there was 0 % initial interrill and rill cover.

In spite of the general observation that runoff and soil loss were very low, there was one exception. The event that occurred on 16 March 2001, with 28 mm precipitation caused 6 mm of runoff and 2.8 Mg ha^{-1} erosion at the Rollopampa site from the smallest plot.

The WEPP model underestimated soil loss but overestimated runoff. Other authors have also found this. Only for big plots (20 m long) does the WEPP model estimate runoff and soil loss reasonably well. We attribute this to the fact that WEPP development relied heavily on the USLE database (with similar slope lengths). Testing different slope lengths was useful for a better understanding of soil loss and runoff on the steep slopes of the Peruvian Andes. Small plots are effective for studying basic erosion processes such as surface sealing, raindrop detachment and splash transport, while bigger plots were able to represent interrill and rill processes and spatial compensation effects. The topographical effect (combination of steepness and length) could also be observed in bigger plots.

The results presented here represent a first approach for evaluating soil erosion and runoff in the Peruvian Andes. WEPP demanded multiple input parameters that can be considered laborious and problematic to collect. But the validation showed that WEPP could be suitable for scenario analysis of Andean erosion.

Question 4: What is the most relevant factor that could be responsible for much of the present day erosion under the Andean conditions? (Chapter 6)

GEMSE is operational software that integrates GIS properties with the Water Erosion Prediction Project (WEPP) model in order to analyze the spatial variation of runoff and soil loss. Its application was tested for La Encañada by generating a runoff map and a soil loss map. Estimated values for runoff and erosion were obtained from the WEPP model that had been validated for this watershed (Chapter 5). Generating such maps facilitated the visualization of the erosion process at spatial and temporal scales according to the actual land use in the watershed.

Areas at risk of runoff and soil loss were identified from the maps. For runoff, the risk areas were associated with the flattest part of the watershed. For soil loss, the susceptible areas were related to the steepest slopes within the watershed. Although the map does not give the soil loss at watershed level, it can be used to identify hotspots, thus helping decision makers to formulate recommendations for soil and water conservation. This demonstrates that GEMSE is an option that can be used for strategic applications of the WEPP model.

Our conclusion is that we find little erosion in agricultural fields of La Encañada watershed. This does not mean that we may conclude the same for other watersheds all around the Andes. La Encañada is the typical semi-arid watershed that for a long time has exhibited features of erosion due to the occurrence of erosive rainfall events in anomalous years such as El Niño. But because few measurements have been reported (either for erosion, or for erosivity of rainfall), only erosion features in the field are noticeable and people believe that erosion occurs on a yearly basis, at a constant rate. And this perception is extrapolated to become a common characteristic of all the Andes, which is not necessarily true.

Question 5: How can the various terms involved in soil erosion processes best be measured under the specific biotic Andean conditions (methods and techniques)? (Chapter 7)

All soil-related erosion parameters were measured for the WEPP hillside model validation in La Encanada watershed. Interrill and rill erodibility, shear stress as well as hydraulic conductivity were determined in the field. The results obtained did not match the US standard range of values in WEPP (the default values), suggesting that the origin and physical-chemical characteristics of La Encanada soils differ from those of the soils in the original WEPP database.

Interrill erodibility was measured using a cheap portable rainfall simulator that produces a standard rain shower of 105 mm h^{-1} intensity that is only applied for 5 minutes. Given the low natural rainfall intensities (Chapter 2) one may wonder how realistic the results obtained are. Nevertheless this portable rainfall simulator showed good performance in the field.

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To avoid expensive and time-consuming measurements in the future, a set of pedo-transfer functions for Andean soils was developed: Ki = -756916+1801775 silt + 15852646 vfs and Kr = -0.00778 + 0.00840 clay + 0.0341 vfs + 0.139 SOM, where silt, clay, vfs (very fine sand) and SOM (soil organic matter) are expressed as fractions.

The effective hydraulic conductivity was derived from measured values of the saturated conductivity (Ksat/field) using a tension infiltrometer. This equipment was used to include the effect of soil sealing. The procedure worked well but gave high values for La Encanada soils. We are not sure whether these high values are realistic. When using these data in the WEPP validation procedure we had to optimize the measured values in order to obtain the effective hydraulic conductivity. The finding that the best validation was obtained when we divided the measured Ksat/field values by a factor of 8 (Chapter 5) implies that either the measurement (i.e. method or equipment) or the model is not realistic; unfortunately, we have insufficient evidence to be able to say which.

Runoff and soil loss were obtained from runoff plots. In general, very small amounts were measured. These small amounts certainly caused a low accuracy of the measurements and raise doubts about their interpretation. The question is what is the optimum size for a runoff plot, given that our aim was to validate the WEPP model. The answer was given in Chapter 5. In that chapter the validation of the hillside version of the WEPP model showed a better correlation between observed and estimated runoff and soil loss when big plots were tested. One reason for this, already mentioned in Chapter 5, is that the WEPP model was developed using the Wischmeier database of plots 22 m long. So, there is probably no “optimal” plot size. The optimum depends on the purpose of the measurement.

At watershed scale we measured the suspended sediment load of the river. Because this is an ungauged watershed (like most rivers in Peru) we did so manually. It would be helpful to install an automatic device for the continuous monitoring of suspended sediment at the bottom of the watershed. Our data showed the degree of scatter that is frequently associated with a relationship between suspended sediment concentration and discharge. Our intention to monitor water discharge and sediment concentration and correlate these with rainfall events had to be abandoned because all data from two weather stations were lost for the time span of the evaluation.

Chapter 2 indicates that in the Andes there are large inter-annual and intra-seasonal variation due to the El Nino / La Nina phenomena. Chapter 6 showed there was a large spatial variation in factors determining erosion. Stroosnijder (2003) has pointed out that to deal with such large variation, erosion measurements should be taken frequently, for a sufficiently long time and over a sufficiently large area. Regrettably, due to limited funding and the high cost of erosion measurements, these conditions were not fulfilled during the research described in this thesis.

Not so long ago, Beven (2001) wrote that it seems impossible to build a catchment-level hydrological (and hence an erosion) model because of the lack of adequate data and measuring techniques. Indeed there is a crisis of sorts in erosion measurements because there is a lack of development of new technologies and equipment and a lack of skilled personnel (Stroosnijder, 2003). However, the methods described in this chapter yielded data of reasonable quality that were collected with very limited funds. Given the fact that there are almost no recent erosion studies and measurements in the Andes, this is quite an achievement.

Given the high data demand of erosion prediction models and the difficulties in obtaining such data of sufficient quality and spatial and temporal coverage, many models use empirical pedotransfer functions. Hence, although many erosion models are classified as deterministic, they may also be called empirical.

General conclusion

Measured as well as predicted erosion from agricultural fields in La Encanada watershed is low. This can be attributed to the low erosivity and erodibility of the various soil types in the watershed. Yet on 16 March 2001 a suspended sediment concentration of 50 g l^{-1} was measured in the river. The conclusion is that this sediment load came from sources other than interrill and rill erosion or agricultural fields. Sources mentioned in the literature are abandoned (fallow) fields. The erosion there could be high due to the low infiltration capacity caused by soil compaction and slow restoration of the (natural) vegetation due to overgrazing. Other sediment sources are roads, such as the Panamericana highway or the many small rural roads and built-up areas.

Rare events do not occur each year but happen during the frequently occurring El Niño and La Niña phenomena. They may cause severe erosion that leaves visible erosion features (such as landslides) and thus shapes the landscape. Only a fraction of this erosion shows up as sediment load in the year the event takes place. Most of the eroded material is distributed over the landscape and gradually becomes available as sediment load in subsequent years. Examples are gully and streambank erosion that contribute to the river sediment load. The foregoing should be taken into account when priorities for soil and water conservation are being set.

It was stated in Chapter 1 that soil erosion studies should be described at different scales. There are five relevant spatial scales for water erosion: (1) the point (1 m^2) scale for interrill (splash) erosion, (2) the plot (< 100 m^2) for rill erosion, (3) the hillslope (< 500 m) for sediment deposition, (4) the field (< 1 ha) for channels and (5) the small watershed (< 50 ha) for spatial interaction effects. For this thesis, a special three-stage methodology was proposed for data collection and model validation. Step one consisted of a broad investigation of all WEPP input parameters at the watershed scale, followed by an uncertainty analysis. This analysis provided the decision support (in this case scenarios) for the second step that consisted of the validation of the hillslope version of WEPP. Finally, in a third step the hillslope version of WEPP was upscaled to obtain erosion maps at watershed scale in order to determine erosion hotspots in the area. In general we can say that this method worked well. The advantage of having the WEPP model validated is that many scenarios typical of the highlands can be simulated without the need to install new runoff plots in the field. The big effort and investment needed in the first step pays off in this last step, because of the relationship between suspended sediment concentration and discharge.

Erosion research entails having to work hard to get reliable information about what is happening in a specific area. In areas where erosion factors are apparently homogeneous (e.g. flat areas under the same climate), the evaluation of parameters related to erosion is not a major problem. In mountainous regions such as the Andean highlands there is a complexity in topography that brings more variability in soils, slope gradient and length, and vegetation, including variability in microclimates. Accessibility of remote areas is also a problem. Given these conditions, it is desirable to have some information available (e.g. on soil, slope and climate) before starting fieldwork, as this makes it is easier to decide the sampling or monitoring design.

Though the research described in this thesis has added to our knowledge, erosion research in the Andean highlands must continue, in order to improve pedotransfer functions, model input/outputs and finally, to standardize research methods so that guesses, emotional statements, and qualitative assessments can be replaced by facts and figures supported by verifiable data.

Summary

This thesis has eight chapters. A general introduction to the research area (La Encañada watershed) in the northern Andean Highlands of Peru and the development of the methodology are given in Chapter 1. Chapter 2 presents a detailed study of the rainfall characteristics; the aggressiveness of rainfall to produce erosion, called erosivity, is highlighted. The susceptibility of soils to be eroded both by rainsplash (interrill) and by concentrated flow (rill) is described in Chapter 3. An uncertainty analysis using the physically based Water Erosion Prediction Project (WEPP) erosion model and the collected input parameters is described in Chapter 4. Chapter 5 presents the validation of the hillslope version of WEPP, whereas Chapter 6 introduces a new tool, the GEMSE interface, which permits the visualization of the erosion process at the watershed scale. The methodologies applied during the fieldwork for this thesis are presented in Chapter 7. Conclusions are drawn in the final Chapter 8.

Chapter 2: Rainfall erosivity in the northern Andean Highlands of Peru: The case of La Encañada watershed

Information about rainfall erosivity in Peru is scarce. Therefore the erosive potential of rainfall in La Encañada was determined using daily rainfall data from 1995 to 2000. Total amount, duration, intensity, kinetic energy and probability of return of the daily rainfall were analyzed. Almost 80 % of rainfall events had an average intensity less than 2.5 mm h^{-1} and only 4 % had an average intensity greater than 7.5 mm h^{-1}. A relationship was found between the El Niño phenomenon and the total amount of rainfall as well as the probability of high intensity events. During a La Niña phenomenon the rainfall intensities were lower but the total rainfall was higher than in an El Niño year. The spatial rainfall distribution and the optimal density of weather stations within the watershed were also analyzed.

Chapter 3: Soil erodibility in the northern Andean Highlands of Peru: the case of La Encañada watershed

There is little information about erodibility in La Encañada watershed, even though this is one of the most important factors affecting soil erosion. Therefore, the interrill (Ki) and rill (Kr) erodibility factors of the major soil types were determined. In order to relate these erodibility factors to more simple soil characteristics, a number of additional soil physical characteristics were measured as well. For comparison, the erodibility factor of the Universal Soil Loss Equation was also determined. At each measurement site, the percentages of sand, clay, silt, very fine sand and organic matter were determined. A stepwise analysis was applied to ascertain the influence of the independent variables on the measured Ki and Kr values. Best equations were chosen in accordance with the lowest standard deviation and the highest correlation indexes of these variables. The observed interrill erodibility ranged from 1.9 to 56 10^5 kg s m^{-4}. Rill erodibility ranged from 0.3 to 14 10^{-3} s m^{-1}. Most of the evaluated soils had low erodibility values. The most erodible soil contained the highest content of silt and very fine sand. The following equations are proposed: Ki =

-756916+1801775 silt + 15852646 vfs and Kr = -0.00778 + 0.00840 clay + 0.0341 vfs + 0.139 SOM, where silt, clay, vfs (very fine sand) and SOM (soil organic matter) are expressed as fractions. It was also found that Ki and K (USLE) had a polynomial relationship, whereas Kr and K (USLE) had an exponential relationship. The results suggest that in La Encañada watershed the erodibility is generally low. Only silty soils can still be a source of sediments in the area. When combined with the observed low erosivity, this implies that the risk of water erosion on agricultural fields is low.

Chapter 4: Uncertainty analysis of WEPP for La Encañada, Peru

A modern tool to achieve a better quantitative understanding of erosion processes is the physically based WEPP model that has replaced older empirical approaches such as the USLE. However, the high data demand of this model in combination with the lack of local data hampers the application of WEPP. A methodology for stratified data collection was proposed and tested in La Encañada (Chapters 1 and 7). It consisted of a broad investigation of all WEPP input parameters at the watershed scale, followed by an uncertainty analysis of the WEPP model. Estimated runoff values ranged between 15 % and 1.2% of the total annual rainfall. Under the most erosive rainfall regime and when potato is cropped, the estimated loss of very erodible soil (containing nearly 40 % silt) could be as high as 122 Mg ha^{-1} y^{-1}. This extreme value is unlikely to occur often and over a significant surface area. Growing potato produced more erosion than growing barley or fallow. The least erosive planting time was June for potato and December for barley, since lowest erosion and runoff were estimated for these months. Since we used an uncalibrated version of WEPP we cannot conclude that the WEPP estimates are in the right order of magnitude. However, all input data used to run the model and to perform this analysis were measured *in situ* and the model predictions provide a range of values. The uncertainty analysis revealed the sensitivity of parameters like climate, slope angle, erodibility, soil management and planting date in the model.

Chapter 5: Validation of the hillslope version of WEPP in La Encañada watershed, northern Peru

To understand the erosion processes in the Andes better, the hillslope version of the WEPP model was validated for three different sites within La Encañada. Three different-sized runoff plots were installed at each site under bare soil conditions. Each site had a specific slope (from 10 to 70 %), soil type and climate, covering all representative conditions of the area. Runoff and soil loss were measured in 2001. The WEPP model overestimated runoff and underestimated soil loss. The model performed reasonably well, with the biggest runoff plots (20 m long) showing coefficients of determination of 0.67 for runoff and 0.66 for soil loss. The smallest runoff plots (5 m long) did not show a good relationship between observed and predicted values. The values measured for runoff and soil loss were very low during 2001 (all were < 6 mm for runoff and < 0.1 Mg ha^{-1} for soil loss), from which we conclude that normally little erosion can be expected in the watershed in a neutral (neither El Niño nor La Niña anomaly) year. But during two neutral years (1995 and 1996) at least one intense event that could potentially cause erosion was registered.

Chapter 6: Assessment of erosion hotspots in a watershed: integrating the WEPP model and GIS in a case study in the Peruvian Andes

Physically-based environmental models allow us to analyze the causes and effects of erosion. However, such models are often point-specific, whereas agriculture occurs in space and time. Though Geographic Information Systems (GIS) help us understand the spatial relationship between all the various spatial data, the qualitative and subjective procedures often used for such spatial analysis result in a loss of relevance and statistical validity. The only way to profit from the ever-increasing computational power and more plentiful digital data as well as from advanced models is to improve the combination of a GIS and environmental model. Chapter 6 therefore presents an interface called Geospatial Modelling of Soil Erosion (GEMSE): a tool that integrates any GIS with the Water Erosion Prediction Project (WEPP). The advantages of GEMSE are (1) it is independent of any special GIS software used to create maps and to visualize the results; (2) the results can be used to produce response surfaces relating simple outputs (soil loss, runoff, etc.) with inputs (climate, soil, topography and land use management) and (3) the scale, resolution and area covered by the layers can be different, which facilitates the use of different sources of information. The use of GEMSE is illustrated for soil erosion estimation in La Encañada where the hillslope version of WEPP was validated. The output shows the spatial distribution of runoff and soil erosion in the form of maps. Though these maps do not give the runoff and soil loss at watershed level, they can be used to identify hotspots that will aid decision makers to make recommendations and plan actions for soil and water conservation. Therefore, GEMSE is an option that can be used for strategic applications of the WEPP model.

Chapter 7: Methods for erosion assessment in the Andes

This chapter outlines the methods used to measure water erosion at three different scales in La Encañada: the small plot scale, the runoff plot scale and the watershed scale. The smallest scale was used to study basic erosion processes like interrill and splash erosion under simulated rainfall, and to measure the important effective hydraulic conductivity. The next scale was used to study erosion (and runoff) in plots that were large enough to represent the combined processes of rill and interrill erosion under natural rainfall. Data collected during studies at the first and second scales (and corresponding phases in the PhD research) served for the validation of the Water Erosion Prediction Project (WEPP) model for the Andean highlands at the hillslope scale. At the third – watershed – scale, the suspended sediment load of the river was measured at three points. This scale is sufficiently large to include the combined effects of interrill erosion, rill erosion, gully and streambank erosion. It also reflects redistribution of eroded material as sedimentation within the landscape. Interrill erodibility was measured using a cheap portable rainfall simulator that produces a standard rain shower of 105 mm h^{-1} intensity that is only applied during 5 minutes. This portable rainfall simulator showed a good performance in the field. Rill erodibility (Kr) was measured using a procedure recommended in the literature. The procedure worked well. To avoid expensive and time-consuming measurements in the future, a set of pedo-transfer functions for Andean soils was developed: Ki = -756916+1801775 silt + 15852646 vfs and Kr = -0.00778 + 0.00840 clay + 0.0341 vfs + 0.139 SOM, where silt, clay, vfs (very fine sand) and SOM (soil organic matter) are expressed as fractions. The effective hydraulic conductivity was derived from measured values of the field saturated conductivity (Ksat/field) using a tension infiltrometer. The procedure worked well but gave high values for La Encanada soils. We are not sure whether these high values are realistic. For WEPP calibration the effective hydraulic conductivity was optimized by dividing the measured Ksat/field values by a factor 8. Runoff and soil loss were obtained from runoff plots. In general, runoff and soil loss rates were low at the three sites (< 1 mm and < 0.5 Mg ha^{-1}, respectively). These small amounts certainly caused a low accuracy of the measurement and raise doubts about their interpretation. We found that the low rain intensity of events that prevailed during 2001 was an important factor causing the low rates of runoff and soil loss. The small plots produced more runoff and soil loss compared to the big plots; according to the WEPP validation, big plots are more suitable for erosion research. Sediment analysis of soil loss showed that the sand, silt, clay and the organic matter fraction are lost in proportion to the original soil composition. The river analysis showed that little sediment in suspension was lost during the rainy season (2003) under evaluation (<10 g l^{-1}), with the exception of one event that produced a high sediment concentration (49.5 g l^{-1}). In the runoff plot study (2001), the highest concentration of soil loss/runoff was 47 g l^{-1} in the Rollopampa site, in the smallest plot.

Chapter 8: Conclusions

Both measured and predicted erosion from agricultural fields in La Encanada watershed are low. This can be attributed to the low erosivity and erodibility of the various soil types in the watershed. Yet on 16 March 2001 a suspended sediment concentration of 50 g l^{-1} was measured in the river. The conclusion is that this sediment load came from sources other than interrill and rill erosion or agricultural fields. Sources mentioned in the literature are abandoned (fallow) fields. The erosion there can be high due to the low infiltration capacity caused by soil compaction and slow restoration of the (natural) vegetation due to overgrazing. Other sediment sources are roads, such as the Panamericana highway, or the many small rural roads and built-up areas.

Rare events do not occur each year but happen during the frequently occurring El Niño and La Niña phenomena. They may cause severe erosion that leaves visible erosion features (such as landslides) and thus shapes the landscape. Only a fraction of this erosion shows up as sediment load in the year the event takes place. Most of the eroded material is distributed over the landscape and gradually becomes available as sediment load in subsequent years. Examples are gully and streambank erosion that contribute to the river sediment load. The foregoing should be taken into account when priorities for soil and water conservation are being set.

Samenvatting

Deze thesis bestaat uit acht hoofdstukken. Hoofdstuk 1 geeft een beschrijving van de ontwikkelde en toegepaste methodologie alsmede een beschrijving van het onderzoeksgebied (La Encañada stroomgebied) in het noorden van de Peruaanse Andes. Hoofdstuk 2 geeft een gedetaileerde beschrijving van de regenval met nadruk op de erosiviteit van de neerslag. De gevoeligheid van de bodems voor erosie door zowel druppelinslag (interrill) als geconcentreerde afstroming (rill) wordt beschreven in hoofdstuk 3. Met het fysische WEPP (Water Erosion Prediction Project) model is een onzekerheidsanalyse uitgevoerd met behulp van de verzamelde invoer gegevens. Deze analyse wordt beschreven in hoofdstuk 4. Hoofdstuk 5 geeft een validatie van de versie van WEPP voor hellingen. Het GEMSE interface maakt visualisatie van het erosieproces op stroomgebiedniveau mogelijk. De interface wordt beschreven in hoofdstuk 6. De methoden die tijdens de veldwerkperiode van dit onderzoek werden toegepast worden beschreven in hoofdstuk 7. Hoofdstuk 8 tenslotte geeft de conclusies van het onderzoek.

Hoofdstuk 2: Regenvalerosiviteit in de noordelijke hooglanden van de Peruaanse Andes: La Encañada stroomgebied

Gegevens over de erosiviteit van de neerslag in Peru zijn schaars. Dit was de reden om voor de periode van 1995 tot 2000 de potentiële erosiviteit van de neerslag te bepalen. De metingen en bepalingen hebben plaatsgevonden in La Encañada in de noordelijke Peruaanse Andes.

Van de dagelijkse neerslag werden de totale hoeveelheid, duur, intensiteit, kinetische energie en de herhalingskans bepaald. Ongeveer 80% van het totale aantal buien had een gemiddelde intensiteit die lager was dan 2.5 mm h^{-1} en slechts 4% had een intensiteit hoger dan 7.5 mm h^{-1}. Er is een relatie vastgesteld tussen het El Niño fenomeen en zowel de totale hoeveelheid neerslag als de kans op buien met een hoge intensiteit. Tijdens een La Niña periode is de neerslag hoger dan tijdens een El Niño jaar. De ruimtelijke variatie in de neerslag en de daaraan gekoppelde optimale dichtheid van meetstations in het stroomgebied was eveneens object van analyse.

Hoofdstuk 3: Bodemerodabiliteit in de noordelijke hooglanden van de Peruaanse Andes: La Encañada stroomgebied

Alhoewel erodabiliteit één van de belangrijkste factoren is die het risiso van bodemerosie bepalen is er slechts beperkte informatie over de erodabiliteit van de bodems in La Encañada. Dit was de reden om de interrill (K_i) en rill (K_r) erodabiliteit van de belangrijkste bodemsoorten te bepalen. Tevens werd een aantal fysische kenmerken van de bodems gemeten zodat het mogelijk was om een relatie te leggen tussen de erodabiliteit en eenvoudige bodemkarakteristieken. Ter vergelijking is eveneens de erodabiliteitsfactor van de USLE (Universal Soil Loss Equation) bepaald.

Op elke meetlocatie werden de percentages klei, silt, zeer fijn zand, zand en organische stof bepaald. Om de invloed van deze onafhankelijke variabelen op de gemeten waarden van K_i en K_r vast te stellen is een stapsgewijze analyse toegepast. Op basis de (laagste) standaarddeviatie en de (hoogste) correlatie is een keuze gemaakt voor een relatievergelijking.

Interrill erodabiliteit varieerde van 1.9 tot 56 10^5 kg s m^{-4}. Rill erodabiliteit van 0.3 to 14 10^3 s m^{-1}. De onderzochte bodems hebben veelal lage erodabiliteitswaarden. Bodems met een hoog silt en een hoog zeer fijn zand gehalte zijn bodems met de hoogste erodabiliteit. We vonden de volgende relaties: K_i = -756916+1801775 silt + 15852646 zfz en K_r = -0.00778 + 0.00840 klei + 0.0341 zfz + 0.139 SOM, waarin klei, silt, zfz (zeer fijn zand) en SOM (organische stof) in fracties zijn uitgedrukt.

We vonden een polynomale relatie tussen K_i en K(USLE) en een exponentiële relatie tussen K_r en K(USLE). Dit resultaat toont dat de erodabiliteit in La Encañada laag is. Slechts de siltige bodems vormen een bron van het sediment in het gebied. Gecombineerd met de lage erosiviteit betekent dit dat de kans op watererosie van landbouwgronden laag is.

Hoofdstuk 4: Onzekerheidsanalyse van WEPP voor La Encañada, Peru

Het fysische WEPP model is een modern instrument voor het verkrijgen van kennis over de kwantificatie van erosieprocessen. De oudere technieken, zoals bijvoorbeeld USLE, zijn door WEPP vervangen. Toepassing van WEPP wordt echter beperkt door de hoge input vraag van het model. Deze input data ontbreken nou juist vaak op het lokale toepassingsniveau.

In La Encañada is een methode voor gestratificeerde data collectie ontwikkeld en getest (hoofdstuk 1 en 7). De methode bestaat uit het bepalen van de WEPP inputparameters op stroomgebiedniveau gevolgd door een onzekerheidsanalyse van het WEPP model. De geschatte waarden voor de runoff varieerden van 1.2% tot 15% van de totale jaarlijkse neerslag. Bij de meest erosieve neerslag liep op akkers met aardappelteelt de geschatte hoeveelheid bodemverlies op zeer erodeerbare bodems (met siltpercentages van 40%) op tot 122 Mg ha^{-1} y^{-1}. Het is niet waarschijnlijk dat deze extreme waarde vaak en/of over een groot oppervlak zal voorkomen. De teelt van aardappelen veroorzaakte meer erosie dan de teelt van gerst of braak. Poten in juni veroorzaakt de minste erosie terwijl voor gerst geldt dat zaaien in december tot de minste erosie leidt. Dit komt omdat de schattingen voor erosie en runoff voor die betreffende maanden het laagst was.

De WEPP versie die gebruikt werd was ongecalibreerd en dus kan er niet worden geconcludeerd dat de schattingen in de juiste orde van grootte zijn. Echter, alle inputdata die werden gebruikt om het model te draaien en de analyse uit te voeren werden in het veld gemeten en de voorspellingen van het model betreffen dus een scale aan waarden.

De onzekerheidsanalyse toonde aan dat het model gevoelig is voor klimaat-, hellinghoek-, erodabiliteit- en bodembeheerparameters en voor de plantdatum.

Hoofdstuk 5: validatie van de hellingversie van WEPP in La Encañada, Noord Peru

Om het erosieproces in de Andes beter te doorgronden werd de hellingversie van het WEPP model gevalideerd voor drie verschillende locaties in de Andes.

Drie runoff plots van verschillende afmetingen zijn op iedere locatie zonder begroeiing geïnstalleerd. Iedere locatie had een specifieke helling (van 10% tot 70%), bodemtype en klimaat. De locaties waren hiermee representatief voor het gebied. In 2001 is op de plots runoff en bodemverlies gemeten. Het WEPP model maakte een overschatting van de runoff en een onderschatting van het bodemverlies. Het model gaf een redelijke output voorde grootste plots (20 m lang) met r^2-coëfficienten van 0.67 voor de runoff en 0.66 voor het bodemverlies. Voor de kleinste runoff plots kon geen goede relatie tussen de voorspelde en gemeten waarde worden gevonden.

Zowel de gemeten runoff als ook het gemeten bodemverlies waren erg laag (alle waarden waren < 6 mm voor de runoff en < 0.1Mg ha^{-1} voor het bodemverlies). Hieruit concluderen wij dat in een neutraal neerslagjaar (dwz geen El Niño en geen La Niña) weinig erosie te verwachten is. Echter tijdens twee neutrale neerslagjaren (1995 en 1996) werd wél tenminste één bui geregistreerd die potentieel erosie zou kunnen veroorzaken.

Hoofdstuk 6: Beoordeling van erosie hotspots in een stroomgebied: integratie van WEPP en GIS voor een casestudie in de Peruaanse Andes

De oorzaken en effecten van erosie kunnen worden geanalyseerd met behulp van fysische omgevingsmodellen. Dergelijke modellen zijn echter vaak punt specifiek terwijl landbouw plaatsvindt op een grotere ruimtelijke schaal. GIS is een instrument om een beter begrip te krijgen van de relatie tussen de verschillende spatiale data. Kwalitatieve en subjectieve berekeningsprocedures leidden echter nogal eens tot een verlies van relevantie en statistische waarde. De enige manier om profijt te kunnen blijven houden van de toenemende rekenkracht, de grote hoeveelheid digitale data én van de verfijnde modelleringtechnieken is door een verbeterde combinatie van GIS en omgevingsmodellen.

In de interface GEMSE (Geospatial Modelling of Soil Erosion) wordt GIS geïntegreerd met WEPP. De voordelen van GEMSE zijn: (1) onafhankelijkheid van specifieke GIS software, (2) de resultaten kunnen worden gebruikt om een grafische voorstelling te maken welke output (bodemverlies, runoff etc) aan input (klimaat, bodem, topografie en landgebruik) koppelt en (3) de schaal, resolutie en het oppervlak kunnen per gegevens ‘laag’ verschillen waardoor het eenvoudiger wordt om verschillende informatiebronnen te gebruiken.

GEMSE wordt geïllustreerd met behulp van bodemerosie schattingen van La Encañada, waar de hellingsversie van WEPP werd geëvalueerd. De output is in de vorm van runoff- en bodemverlieskaarten. Alhoewel deze kaarten niet de geïntegreerde runoff en bodemverlies op stroomgebiedniveau geven kunnen ze wel gebruikt worden om hotspots te identificeren en op deze wijze een hulpmiddel zijn voor beleidsmakers die zich bezig houden met het plannen van bodem- en waterconserveringmaatregelen. GEMSE is een optie welke kan worden ingezet bij strategische toepassingen van het WEPP model.

Hoofstuk 7: Methoden voor erosiebeoordeling in de Andes

Dit hoofstuk behandelt de methoden die gebruikt zijn om op drie verschillende schaalniveaus afstroming en ersoie te meten: het ‘kleine plot’ niveau, runoff plotniveau en stroomgebiedniveau. Het ‘kleine plot’ niveau is gebruikt om basiserosieprocessen, zoals interrill- en spaterosie te bestuderen. Het tweede niveau om erosie en runoff te bestuderen in plots net groot genoeg om representatief te zijn voor het gecombineerde interrill en rill erosieproces onder natuurlijke neerslag. Met de data die werden verzameld op het eerste en het tweede schaalniveau is de validatie van de WEPP hellingversie uitgevoerd. Op het stroomgebiedniveau werd de hoeveelheid meegevoerd sediment bepaald op drie punten in de rivier. Dit niveau is groot genoeg om het gecombineerde effect van interrill-, rill-, geul- en oevererosie vast te stellen. Het niveau geeft eveneens weer in welke mate er herverdeling van het geërodeerde materiaal als sediment in het landschap plaatsvindt.

De interrillerosie is gemeten met een goedkope draagbare regenvalsimulator die een standaard bui van 5 minuten met een intensiteit van 105 mm h^{-1} produceert. Of de resultaten erg realistisch zijn kun je je afvragen, gezien de lage intensiteit van de natuurlijke regenval (Hoofdstuk 2). De rillerodabiliteit (K_r) is bepaald met behulp van de aanbevolen procedure uit de literatuur. Zowel de regenvalsimulator als de rill-procedure werkten naar behoren.

Om dure en tijdsintensieve metingen in de toekomst te vermijden is een aantal pedo-transfer functies voor Andes bodems ontwikkeld: K_i = -756916+1801775 silt + 15852646 zfz and K_r = -0.00778 + 0.00840 klei + 0.0341 zfz + 0.139 SOM, waarin klei, silt, zeer fijn zand en SOM zijn uitgedrukt in fracties.

De effectieve hydraulische doorlatendheid is afgeleid van metingen van de verzadigde doorlatendheid in het veld. De metingen werden uitgevoerd met een disk-infiltrometer. De metingen gaven hoge waarden voor de bodems van La Encañada. We zijn er niet zeker van dat deze waarden realistisch zijn. Voor de WEPP calibratie zijn de waarden voor de effectieve hydraulische doorlatendheid geoptimaliseerd door de gemeten $K_{sat/veld}$ waarden door 8 te delen.

Runoff en bodemverlies waarden zijn verkregen uit de metingen in de runoff plots. Op alle drie de locaties zijn lage waarden gevonden voor zowel runoff (<1 mm) als bodemverlies (<0.5 Mg ha^{-1}). Deze lage waarden betekenen eveneens een lage nauwkeurigheid van de metingen en dus kan de interpretatie twijfelachtig zijn. De lage neerslagintensiteit van de buien in 2001 was een bepalende factor voor de lage runoff en bodemverliezen. Op de kleine plots werd in vergelijking met de grote plots meer runoff en bodemverlies gegenereerd; volgens de WEPP validatie zijn grote plots geschikter voor erosieonderzoek dan kleine. De bodem erodeert gelijkmatig over alle textuurfracties; de verdeling van de fracties in het sediment is gelijk aan de verdeling van de fracties in de bodem.

De analyse van het sediment in de rivierafvoer toont dat weinig meegevoerd materiaal (<10 g l^{-1}) verloren gaat gedurende het regenseizoen (2003). Uitzondering hierop is één bui die wel een hoge sedimentconcentratie veroorzaakte (49.5 g l^{-1}). Op de runoff plots is de hoogste gemeten concentratie van bodemverlies 47 g l^{-1}, gemeten op de Rollopampa locatie op het kleinste plot.

Hoofdstuk 8: Conclusies

Zowel de gemeten als de voorspelde erosie van landbouwgronden in La Encañada is laag. Dit kan worden toegeschreven aan de lage erosiviteit van de neerslag en de lage erodabiliteit van de verschillende bodemtypes in het stroomgebied. Echter op 16 maart 2001 werd 50 g l^{-1} meegevoerd sediment gemeten in de rivier. De conclusie is dat dit sediment een andere oorsprong heeft dan interrill- of rillerosie op de landbouwgronden, bijvoorbeeld van verlaten braak liggende gronden afkomstig is. De erosie kan hier hoog zijn als gevolg van de lage infiltratiecapaciteit veroorzaakt door bodemverdichting en een trage regeneratie van de (natuurlijke) vegetatie als gevolg van overbegrazing. Andere bronnen van sediment zijn wegen (b.v. de Panamerika Highway) of de vele kleine rurale wegen en bebouwde gebieden.

Tijdens El Niño en La Niña jaren komen zeldzame buien voor. Deze buien kunnen hevige erosie veroorzaken en zichtbare erosieschade in het landschap achterlaten (landafschuivingen). Slechts een fractie van deze erosie is terug te vinden als sediment tijdens het jaar dat de extreme bui plaats vindt. Het grootste deel van het geërodeerde materiaal wordt verspreid over het landschap en is gedeeltelijk terug te vinden als erosie in de jaren volgend op het jaar met de extreme bui. Voorbeelden zij geul- en oevererosie welke beiden bijdrage aan de hoeveelheid sediment in de rivier.

Met de genoemde verschijnselen zou rekening gehouden moeten worden als prioriteiten worden gesteld voor bodem- en waterconserveringsmaatregelen in de Andes.

Resumen

Esta tesis tiene ocho capítulos. Una introducción general del área investigada (cuenca del río La Encañada) en los Andes del norte del Perú y el desarrollo de la metodología para evaluar erosión son presentados en el Capítulo 1. En el Capítulo 2 se presenta un detallado estudio de las características de las lluvias en la cuenca; la agresividad de la lluvia para producir erosión, llamada también erosividad, es realtada en este capítulo. La susceptibilidad de los suelos a ser erosionados, tanto por el efecto de las gotas de lluvia (erodabilidad entre surcos) como por el efecto del flujo concentrado de agua (erodabilidad en los surcos) son descritos en el Capítulo 3. La ejecución del análisis de incertidumbre usando el modelo de erosión WEPP y la obtención de los parámetros necesarios para el modelo son descritos en el Capítulo 4. El Capítulo 5 presenta la validación de la versión de ladera del modelo de erosión WEPP, mientras que el Capítulo 6 presenta una nueva herramienta, la interfase denominada GEMSE, la cual permite la visualización del proceso de erosión a nivel de cuenca. Las metodologías aplicadas durante la ejecución del trabajo de campo para el desarrollo de esta tesis son presentadas en el Capítulo 7. Finalmente, el Capítulo 8 muestra las conclusiones de este trabajo.

Capítulo 2: Erosividad de las lluvias en los Andes del norte del Perú: El caso de la cuenca del río La Encañada.
La información sobre la erosividad de lluvias en el Perú es escasa. Debido a esto, la erosividad potencial de las lluvias ocurridas en la cuenca del río La Encañada fue determinada usando datos diarios de lluvias desde el año 1995 hasta el 2000. La cantidad total, duración, intensidad, energía cinética y probabilidad de retorno de los datos diarios fueron analizadas. Casi el 80 % de los eventos de lluvia tuvieron una intensidad promedio menor a 2.5 mm h^{-1} y sólo un 4 % de los eventos tuvieron una intensidad promedio mayor a 7.5 mm h^{-1}. Una relación fue encontrada entre el fenomeno El Niño con la cantidad de lluvia total como también con la probabilidad de ocurrencia de eventos de alta intensidad. Durante un fenómeno La Niña, las intensidades de lluvia fueron menores pero el total acumulado fue mayor que en un año bajo el efecto de El Niño. La distribución espacial de las lluvias así como la densidad óptima de estaciones meteorológicas dentro de la cuenca también fueron analizados.

Capítulo 3: Erodabilidad del suelo en los Andes del norte del Perú: el caso de la cuenca del río La Encañada.
Existe poca información sobre la erodabilidad de los suelos de la cuenca La Encañada, aún cuando es uno de los factores más importantes que afectan la erosión del suelo. Por lo tanto, los factores de erodabilidad entre surcos (Ki) y dentro de los surcos (Kr) de los principales tipos de suelos fueron determinados. A fin de relacionar estos factores de erodabilidad (Ki y Kr) con simples parámetros del suelo, ciertas características físicas del suelo fueron también evaluadas. Como patrón de comparación, el factor de erodabilidad del suelo de la Ecuación Universal de la Pérdida del Suelo fue determinado para cada tipo de suelo. En cada lugar de medición los porcentajes de arena, limo, arcilla, arenas muy finas y materia orgánica fueron determinadas. El análisis de regresión (stepwise) fue aplicado para asegurar la influencia de las variables independientes en los valores medidos de Ki y Kr. Las mejores ecuaciones fueron escogidas de acuerdo con el valor más bajo de desviación

estándar el más alto índice de correlacion de estas variables. La erodabilidad entre surcos observadas varió de 1.9 to 56 10^5 kg s m^{-4}. La erodabilidad en los surcos varió de 0.3 to 14 10^{-3} s m^{-1}. La mayoría de suelos evaluados tuvieron bajos valores de erodabilidad. El suelo más erosionable contiene el mayor contenido de limo y arenas muy finas. Las siguientes ecuaciones son propuestas: Ki = -756916+1801775 limo + 15852646 amf y Kr = -0.00778 + 0.00840 arcilla + 0.0341 amf + 0.139 matorg, donde limo, arcilla, amf (arena muy fina) y matorg (materia orgánica) se expresan en fracción. Se encontró también que entre los valores de Ki y K (USLE) había una relación polinomial mientras que entre los valores de Kr y K (USLE) había una relación exponencial. Los resultados sugieren que en la cuenca del río La Encañada la erodabilidad es generalmente baja. Sólo los suelos limosos pueden ser la fuente de sedimentos en el área. Combinándo esta característica con la baja erosividad observadas en el área implica que el riesgo de erosión hídrica en los campos agrícolas es bajo.

Capítulo: Análisis de incertidumbre del modelo WEPP para La Encañada, Perú.

Una moderna herramienta para lograr un mejor entendimiento cuantitativo del proceso de erosión es el modelo WEPP (Proyecto de Predicción de la Erosión Hídrica) el cual está basado en procesos físicos y que está reemplazando modelos empíricos más antiguos como la USLE (Ecuación Universal de la Pérdida del Suelo). Sin embargo, la alta demanda de datos que necesita este modelo en combinación con la falta de datos locales obstaculizan la aplicación de WEPP. Una metodología para la colección de datos estratificados fue propuesto y probado en La Encañada (Capítulos 1 y 7). Consistió en una amplia investigación de todos los parámetros que requiere WEPP a nivel de cuenca seguido por un análisis de incertidumbre con este modelo. Los valores estimados de escorrentía variaron entre 1.2 % y 15% de la lluvia total anual. Bajo los regímenes de lluvia más erosivos y cuando la papa es cultivada, la pérdida estimada en el suelo más erosionable (que contiene cerca de 40% de limo) podría ser tan alto como 122 Mg ha^{-1} y^{-1}. Este valor extremo es improbable que ocurra de manera constante sobre una significativa parte del área de la cuenca. El cultivo de papa produjo más erosión que el cultivo de cebada o bajo condiciones de descanso. La fecha de siembra menos erosiva fue Junio, para el cultivo de papa y Diciembre para el cultivo de cebada, debido a que para esos meses fueron estimadas la más baja erosión y escorrentía. Debido a que en la prueba de incertidumbre usamos la versión no calibrada de WEPP, no podemos concluir que los estimados de WEPP estén dentro del correcto valor. Sin embargo, todos los datos ingresados y usados para correr el modelo asi como para llevar a cabo este análisis fueron medidos *in situ* y las predicciones del modelo proporcionaron un rango de valores. El análisis de incertidumbre ha revelado la sensibilidad de los parámetros que considera el modelo, como son el clima, el ángulo de inclinación de la pendiente, la erodabilidad, el manejo del suelo y la fecha de siembra.

Capítulo 5: Validación de la versión para laderas del modelo WEPP en la cuenca del río La Encañada en el norte de Perú.

Para entender mejor el proceso de erosión en los Andes, la versión para laderas del Proyecto de Predicción de la Erosión Hídrica (modelo WEPP) fue validado para tres localidades diferentes dentro de la cuenca La Encañada. Parcelas de escorrentía de tres tamaños diferentes fueron instalados en cada localidad con condiciones de suelo desnudo. Cada lugar tenía una pendiente específica (desde 10 a 70 %), tipo de suelo y clima, cubriendo la mayoría de condiciones del área. La escorrentía y la pérdida de suelo fueron medidos en el año 2001. El modelo WEPP sobre-estimó la escorrentía y sub-estimó la pérdida de suelo. El modelo actuó razonablemente bien con las parcelas más grandes (20 m largo) mostrando coeficientes de determinacion de 0.67 para escorrentía y 0.66 para pérdida de suelo. Las parcelas de escorrentía más pequeñas (5 m largo) no mostraron una buena relación entre los valores observados y predichos. Los valores medidos para escorrentía y pérdida de suelo fueron muy bajos durante el año 2001 (todos fueron < 6 mm para escorrentía y < 0.1 Mg ha^{-1} para pérdida del suelo) a partir de lo cual concluímos que, normalmente, poca erosión puede esperarse en esta cuenca en un año normal (sin considerar años anómalos como El Niño o La Niña). Pero al menos un evento intenso ha sido registrado durante dos años neutrales (95 y 96) que potencialmente pudieron causar erosión.

Capítulo 6: Análisis de las áreas de mayor riesgo a erosionarse dentro de una cuenca: integrando el modelo WEPP con GIS en un caso de estudio en los Andes de Perú.

Los modelos ambientales basados en procesos físicos nos permite analizar las causas y efectos de la erosión. Sin embargo, tales modelos son a menudo de aplicación puntual, mientras que la agricultura se desarrolla en el espacio y en el tiempo. A pesar que los Sistemas de Información Geograficos (SIG) nos ayudan a entender la relación espacial entre diversos datos dispuestos en el espacio, los procedimientos cualitativos y subjetivos, a menudo utilizados para tales análisis espaciales resultan en una pérdida de importancia y validez estadística. La única manera de sacar ventaja del cada vez mayor poder computacional y abundancia de datos digitales, así como también de los modelos avanzados, es mejorando la combinación de SIG con los modelos ambientales. El Capítulo 6, por lo tanto, presenta una interfase denominada Modelamiento Geoespacial de la Pérdida del Suelo (GEMSE): una herramienta que integra cualquier SIG con el Proyecto de Predicción de la Erosión Hídrica (WEPP). Las ventajas de GEMSE son (1) es independiente de cualquier software especial de SIG que es usado para crear mapas y visualizar los resultados; (2) los resultados pueden ser utilizados para producir superficies de respuesta que relacionan simples resultados (pérdida de suelo, escorrentía, etc.) con los datos iniciales que demanda el modelo (clima, suelo, topografía y uso de la tierra) y (3) la escala, resolución y área cubierta por los mapas temáticos pueden ser diferentes, lo cual facilita el uso de las diferentes fuentes de información. El uso de GEMSE es aplicado para la estimación de pérdida de suelo en La Encañada donde la versión de ladera de WEPP ha sido validada. Los resultados muestran la distribución espacial de la escorrentía y de la pérdida de suelo en forma de mapas. Aunque estos mapas no muestran la escorrentía y la pérdida de suelo a nivel acumulativo en la cuenca, ellos pueden ser usados para identificar las áreas de mayor riesgo a erosión y así ayudar a los tomadores de decisiones para hacer recomendaciones para la conservación del agua y del suelo. Por lo tanto, GEMSE es una opción que puede ser utilizada para aplicaciones estratégicas del modelo WEPP.

Capítulo 7: El enfoque a múltiple escala: métodos para el análisis de la erosión en los Andes.

La erosión hídrica fue medida en tres diferentes escalas en la cuenca del río La Encañada. La primera escala, a nivel de parcela, involucrando el estudio de infiltración, erosión entre surcos y erosión dentro de surcos; la segunda escala, involucrando el estudio de erosión en parcelas de escorrentía, lo suficientemente grandes para representar los procesos combinados de erosión dentro y fuera de los surcos; en la tercera escala, el nivel de cuenca, con la evaluación de sedimentos en suspensión en el río. Fue necesario evaluar todos los parámetros del suelo relacionados a la erosión a nivel de parcela y parcelas de escorrentía para la validación de la versión de ladera del modelo WEPP en la cuenca La Encañada. Los valores de los factores de erodabilidad entre surcos (Ki) y dentro del surco (Kr) así como el esfuerzo cortante fueron más bajos que los valores estándar del modelo WEPP, mostrando que los suelos evaluados tuvieron bajos valores de erodabilidad (Capítulo 3). En el caso de la conductividad hidráulica los valores fueron altos para todos estos suelos. Nosotros no estamos seguros si estos valores fueron realistas. Para la calibración de WEPP la conductividad hidráulica fue optimizada dividiendo estos valores por el factor 8. La evaluación en las parcelas de escorrentía nos permitió ver lo que pasaba con el proceso de escorrentía y pérdida de suelo comparados con la primera escala, con parcelas más pequenas. En general, las tasas de escorrentía y pérdida de suelo fueron bajas en las tres localidades (< 1 mm y < 0.5 Mg ha^{-1}, respectivamente). Encontramos que las bajas intensidades de lluvia que prevalecieron durante el 2001 fue un factor importante por el cual las bajas tasas de escorrentía y pérdida de suelo fueron observadas. Las parcelas más pequeñas produjeron más escorrentía y pérdida de suelo comparados con las parcelas más grandes; de acuerdo a la validación con WEPP las parcelas más grandes son las más adecuadas para la investigación de la erosión. Los análisis de sedimentos en el agua de escorrentía mostró que las partículas de arena, limo, arcilla, arena y materia orgánica son perdidas proporcionalmente a la composición original del suelo. El análisis del agua del río mostró que poco sedimento en suspensión fue perdido durante la estación de lluvia (2003) bajo evaluación (<10 g l^{-1}) con excepción de un evento que produjo una alta concentración de sedimentos (49.5 g l^{-1}). En el estudio de parcelas de escorrentía (2001), la concentración más alta de pérdida de suelo/escorrentía fue 47 g l^{-1} en la localidad de Rollopampa, en la parcela más pequeña.

Capítulo 8: Conclusiones

La erosión medida y predicha de los campos agrícolas en la cuenca del río La Encanada son bajas. Esto puede ser atribuído a la baja erosividad de las lluvias y a la baja erodabilidad de los varios tipos de suelo encontrados en la cuenca. Aunque sólo evento durante la estación de lluvia del 2003 produjo una concentración de sedimentos de of 50 g l^{-1} medido en el río. La conclusión es que esta carga de sedimento se originó de fuentes diferentes a las ocasionadas por la erosión entre surcos y dentro de los surcos en los campos agrícolas. Las fuentes de sedimento mencionadas en la literatura son campos abandonados o en descanso. La erosión en aquellos lugares puede ser alta debido a la baja capacidad de infiltración causado por la compactación del suelo y por la lenta recuperación de la vegetación (natural) debido al sobre pastoreo. Otras fuentes de sedimentos son las carreteras sin asfaltar así como muchos pequeños caminos rurales y zonas de construcción.

Curriculum Vitae

Consuelo Cecilia Romero was born on the 1st of May 1969 in Lima, Peru. After attending the private elementary and high school at Nuestra Señora del Pilar she entered the Universidad Nacional Agraria La Molina (UNALM) in 1986. In 1991 the International Potato Center (CIP) awarded her with a fellowship for her Bachelor thesis on non-symbiotic biological fixation of nitrogen by *Azospirillum* sp. in sweetpotato crop. She obtained her Bachelor degree in Sciences in 1992 and graduated as a Biologist in 1994. From 1992 to 1994 she continued studying at La Molina University obtaining her M.Sc. degree in Soil Science.

From 1994 till present she is a lecturer in the Soil Science Department at UNALM in the area of Soil and Water Conservation. In 1997 she attended a three-month training course entitled "Soil Analysis and Improvement" in Obihiro, Japan, organized by the Japan International Cooperation Agency. In December 1998, she was awarded with a fellowship for a sandwich Ph.D. position with the Erosion and Soil & Water Conservation Group of Wageningen University to carry out research on a multiscale assessment of soil erosion in La Encañada watershed, in northern Peru.
For carrying out the fieldwork (1999-2003) she got financial support for equipment from the International Foundation for Sciences, Sweden, and from the Soil Management Collaborative Research Program (SM-CRSP) through the Trade off project. Logistical support came from the International Potato Center. During her fieldwork she continued working as a lecturer at La Molina University.

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