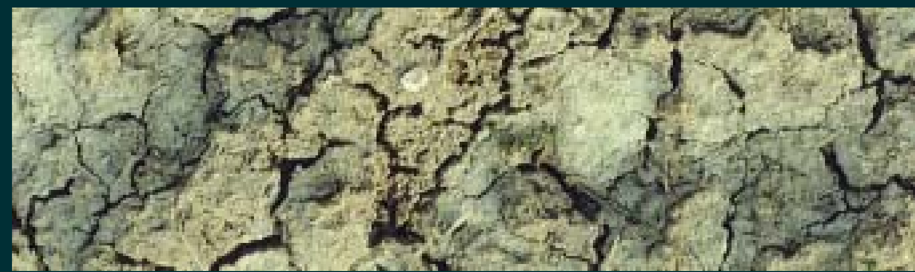
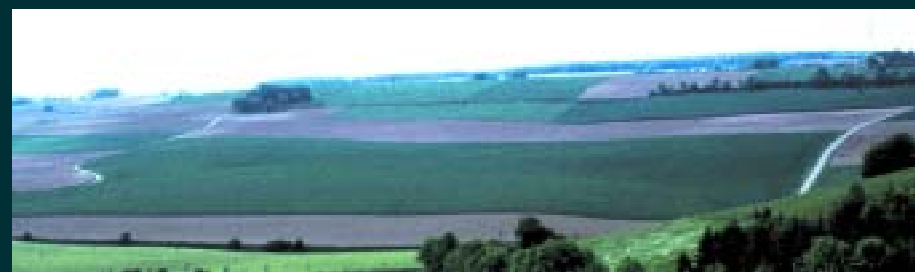
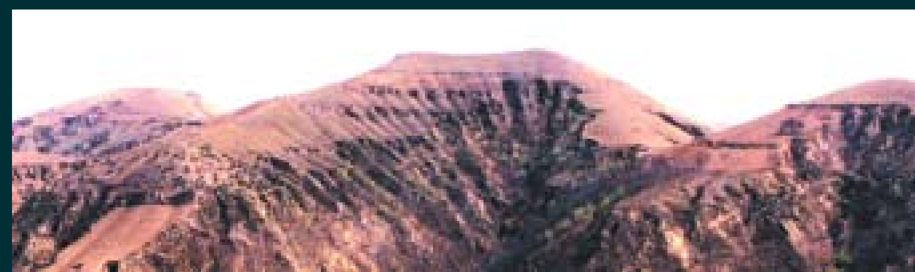
Effects of land use and infiltration behaviour on soil conservation strategies

Jannes Stolte







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EFFECTS OF LAND USE AND INFILTRATION BEHAVIOUR ON SOIL CONSERVATION STRATEGIES

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Jannes Stolte

Proefschrift

Ter verkrijging van de graad van doctor
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ABSTRACT

Soil erosion is a global problem because of its environmental consequences, including sedimentation and pollution in many areas of the world. Detachment of soil particles is mainly caused by rainsplash and the erosive force of overland flow. The main biophysical factor influencing the quantity of overland flow is the infiltration rate. Prediction of overland flow in catchments depends to a large extent on the characteristics of the infiltration process. Infiltration during a runoff-generating rainfall event is regulated by the hydraulic properties of the various soil layers, these are, the unsaturated or saturated conductivity and soil water retention characteristics, and the antecedent soil moisture conditions. This thesis deals with (i) the effects of spatial and temporal variability of soil physical properties, in particular the saturated hydraulic conductivity, on the generation and prevention of runoff in undulating loessial watersheds, and (ii) the application of an erosion model in the context of land-use planning and negotiation. Research for this thesis has been carried out in three small agricultural catchments in the southern loess area of the Netherlands (Limburg Province) and in an agricultural catchment on the Loess Plateau in China (Shaanxi Province).

Measurement of soil physical properties of soil horizons and land use units within the catchments was carried out, and the tendency of these soil layers to generate runoff was evaluated. Effects of heterogeneous saturated conductivity values on model outcome were evaluated using infiltration characteristics of both fully crusted and partially cracked crusted surfaces and were further examined by using a Simple Random Sampling approach to statistically identify different land use units. In loess areas, only differences in hydraulic properties of the surface layer caused differences in calculated discharge and soil loss, using the hydrological and soil erosion model LISEM. The China study showed that even if the soil type is the same, differences in land use and management may cause differences in hydraulic properties and, as a result of this, in calculated discharge and soil loss. If land treatment and soil type are the same, these land use units can be merged into the same soil physical unit, despite the fact that crops may differ. With this, a preliminary sampling scheme for comparable areas can be defined to reduce the number of samples needed to quantify K_s distributions.

To test the accuracy of the LISEM model on a small spatial scale, a single gully system was selected in the China catchment. It showed that measured and calculated hydrographs were in close agreement, but that the accuracy of the soil loss calculations decreased with smaller rainfall events. Alternative land use scenarios showed that reforestation of the gully floor significantly lowered water and sediment losses.

Effects of pre-defined land use scenarios on water and sediment losses were quantified for the China catchment, using the LISEM model and average and stochastic distributions of measured field K_s values. Use of stochastic K_s distributions and Monte Carlo analyses resulted in a range of model outcomes reflecting the effect of spatial heterogeneity upon simulated discharge and soil loss. In this way, probabilities of occurrence of the effects of alternative land-use strategies can be generated. Once a database has been compiled for a specific region, containing all necessary parameters of current and alternative land-use systems, on-the-spot simulations can be performed, allowing interactive negotiation with stakeholders. This database allows risk analyses to be performed for comparable areas to be conducted with relatively little additional effort.

The major challenge is to realise the on-the-spot use of the LISEM model to provide instant input into the negotiation process, which serves to stimulate the debate in defining conservation strategies.

VOORWOORD

Het idee voor dit proefschrift is ontstaan op een gezellig terrasje in Valkenburg. Daar zat ik samen met mijn co-promotor, Coen Ritsema, tijdens een van onze vele meetcampagnes in Zuid-Limburg. Het samenstellen van een proefschrift blijkt een terugkerend onderwerp van gesprek te zijn. Met name tijdens de vele gezamenlijke reizen met Coen, hebben we hier veelvuldig en intensief over gesproken. Eerst ging dat in Coens aftandse Peugeot (schakelen met een schroevendraaier!) op weg naar Limburg, later in het vliegtuig naar verdere bestemmingen. Uiteindelijk hebben al die gesprekken geleid tot dit boekje. Tijdens het erosienormeringsproject in Limburg werd het onderzoeksplan duidelijk. Ik heb dit verder kunnen uitwerken en realiseren tijdens het EROCHINA-project in China. Ik ben Coen erg dankbaar voor zijn enthousiasme en inhoudelijke bijdragen én voor de vele biertjes die we samen gedronken hebben. Mijn promotor, Johan Bouma, wil ik bedanken voor zijn vertrouwen in mij. Johan, je enthousiasme en relativeringsvermogen werken erg inspirerend en hebben zeer zeker bijgedragen tot het afronden van dit proefschrift.

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I'm also very grateful for the support of my Chinese colleagues in the EROCHINA project. I thank Dr. Guobin Liu, Institute for Soil and Water Conservation in Yangling, for his hospitality at Ansai station. We were always very welcome in Ansai. Prof. Baoyuan Liu, Beijing Normal University, I like to thank for his very enthusiastic input in the EROCHINA project, and his contributions to the discussions leading to this thesis. I also thank his students for their great efforts undertaken in Danangou catchment to keep on track with the field measurement programme. Baoyuan, I'm looking forward to have a joint diner again somewhere in Beijing, gǕnbǛ!

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CONTENT

CHAPTER 1

INTRODUCTION

1. INTRODUCTION

1.1 BACKGROUND AND PROBLEM DEFINITION

Soil erosion is a global problem because of its environmental consequences, including sedimentation and pollution in many areas of the world (Morgan, 1995). The world's population is growing rapidly: it currently stands at about 6 billion and is expected to rise to about 7.5 - 11 billion in 2050 (United Nations, 1998). To feed all these people, less than 4000 million hectares of land is available for agriculture, and nearly all of the most productive land is being used. An estimated 400 million hectares of land have been abandoned due to soil erosion over the past 50 years (Flanagan, 2001). Brown et al. (1997) reported that an estimated 40% of the world's cultivated area has been damaged by mismanagement since 1950. These figures have to be interpreted with some caution, however, as was pointed out by Lal (1988). Similarly, Morgan (1995) indicated that erosion rate data should also be interpreted cautiously, because rates vary with the size of the area being considered. Nevertheless, as was recognised by Kohnke and Bertrand as early as 1959, while the exact levels of erosion are not known, the seriousness of the problem is evident.

Effects of soil erosion can be divided into on-site and off-site effects (e.g. Boardman et al., 1990; Lal, 1990). On-site effects are important for agricultural fields, and cause phenomena like the breakdown of soil structure, loss of fertile soil, loss of seedlings and reduction of soil depth. Off-site effects include sedimentation downstream, siltation of reservoirs, floods, contamination of drinking water supplies, etc. Sfeir-Younis and Dragun (1993) divided the effects into upstream and downstream effects. Upstream effects include on-farm losses in productivity and inter-farm damages to irrigation terraces, roads, bridges etc., while downstream effects are comparable to the off-site effects defined above.

The process of water-induced soil erosion involves the detachment of individual soil particles and their transport by overland flow. Detachment of soil particles is mainly caused by rainsplash and the erosive force of overland flow. The main biophysical factor influencing the quantity of overland flow is the infiltration rate. Most rainwater falls on the soil, either directly or indirectly through stem flow or leaf drainage. A small part remains on the leaves (interception) and eventually evaporates. The water that reaches the soil surface is stored in micro-depressions, infiltrates into the soil profile or moves downhill as overland flow. The amount of infiltration and the infiltration rate depend on the characteristics of the soil (Morgan, 1995).

Many studies have tried to predict the rate of water-induced soil erosion, and to evaluate possible measures to reduce its negative effects. These studies can be roughly divided into empirical field studies and studies using models to predict the level of erosion, although many studies have combined the two, using field tests to generate model parameters (e.g. Mutchler et al., 1988; Van Dijk et al., 1996; Wu, 2000).

Soil erosion models can be divided into stochastic, empirical and physically based models (Gregory and Walling, 1973). Stochastic analyses are used to generate synthetic sequences of existing sample data. This approach is useful in generating input sequences for empirical and physically based models (Morgan, 1995). Empirical models are based on identifying statistically significant relationships between input (e.g. rainfall) and output (e.g. soil loss) while physically based models use the laws of nature to describe the processes, with the help of mathematical equations. Empirical models are generally site-specific, while the results of physically based models can be extrapolated to other regions if the appropriate parameters are measured independently. Empirical models do not need much data generation, while physically based models often need a long measurement campaign to retrieve all necessary parameters. Despite the never-ending debate about the use, abuse and non-use of models, it is generally accepted that empirical or physical models are the only instrument for generalising and predicting future environments (Boardman et al., 1990).

1.2 INFILTRATION

Prediction of overland flow in catchments depends to a large extent on the characteristics of the infiltration process. Infiltration during a runoff-generating rainfall event is regulated by the hydraulic properties of the various soil layers, these are, the unsaturated or saturated conductivity and soil water retention characteristics, and the antecedent soil moisture conditions. The hydraulic properties depend on the granular composition (texture) of the soil and on the spatial arrangement of the particles and voids in the soil (structure). Although texture may be considered a static property, structure may change dynamically, which may vary in space as well as in time, depending on soil type and soil management (e.g. Cassel and Nelson, 1985; Kutilek et al., 1993; Mallants et al., 1996; Fohrer et al., 1999). This dynamic behaviour of the soil structure means that the prediction of infiltration is a very complex matter.

Many publications have dealt with temporal and/or spatial heterogeneity of the infiltration rate or related parameters. Sharma et al. (1983) and Cassel and Nelson (1985) found significant differences in bulk density, cone index and soil water characteristic due to tillage treatment, with the greatest spatial variation in the 0-14 cm layer. They also found that the saturated conductivity varied significantly in space and time, but were unable to establish a relation with treatment. Messing and Jarvis (1993) found significant changes in soil physical properties in the course of one growing season. Mapa et al. (1986) showed that four soil-water properties (i.e. sorptivity with positive head, sorptivity with negative head, soil hydraulic conductivity and the soil-water retention characteristic) undergo significant temporal changes due to wetting and drying subsequent to tillage, with the first wetting and drying cycle being responsible for most of the temporal variability. Moreover, they found major differences in calculated water content profiles between simulations using parameters measured before irrigation events and those using parameters measured after such events.

Despite the commonly expressed view that infiltration determines the generation of overland flow, few studies have addressed the effects of the heterogeneity of soil hydraulic properties in space and time on the outcome of soil erosion models. De Roo and Riezebos (1992) concluded that stochastic methods, combined with a distributed hydrological model, could be valuable in evaluating the consequences of the large spatial variability of infiltration. From their study of concentrated flow erosion, Auzet et al. (1995) concluded that, though predicting the soil surface state in each part of a catchment is a very complex task, qualitative typologies of soil surface state and rough empirical models of its evolution constitute a considerable improvement over approaches ignoring the variability of soil surface state in space and time. Jetten et al. (1999) concluded from their evaluation of runoff and erosion models that the spatial variability of infiltration-related variables is difficult to handle, due to differences in scale between observations on small soil samples and the application of models on entire watersheds.

Overland flow is caused by (i) high intensity rainfall exceeding the infiltration capacity of the soil or (ii) lack of storage in the soil due to saturation. Both effects are strongly influenced and regulated by the saturated conductivity of the soil surface layers. Runoff and soil erosion studies should therefore also take into account the spatial and temporal heterogeneity of soil physical properties. So far, few studies have tried to quantify the effects of the spatial heterogeneity of saturated conductivity on model outcome (e.g. De Roo et al., 1992). Even fewer studies have tried to define proper sampling schemes to determine the spatial and/or temporal variability of saturated conductivity for application in soil erosion modelling studies (e.g. Jetten et al., 1996). Thus, one of the challenges in runoff and soil erosion studies is to determine the spatial and temporal variability of regulating soil physical properties and to evaluate its effect on the generation of runoff, while taking into consideration the various land-use types within the area under study. Furthermore, physically based runoff and soil erosion models have so far only sporadically been used for land-use and soil and water conservation planning purposes. The present thesis reports on an attempt to develop a system using model uncertainty as a negotiation tool in land-use planning.

1.3 OBJECTIVES

This thesis deals with (i) the effects of spatial and temporal variability of soil physical properties, in particular the saturated hydraulic conductivity, on the generation and prevention of runoff in undulating loessial watersheds, and (ii) the application of an erosion model in the context of land-use planning and negotiation.

Specific objectives are to:

- quantify the spatial variability of saturated conductivity within selected watersheds in China and the Netherlands;
- develop a soil physical schematisation procedure, taking into account spatial differences in soil layers and land use;
- investigate the relation between land-use type and saturated hydraulic conductivity distributions;
- quantify the effects of the spatial variability of saturated conductivity on computed water and soil losses;
- use models as a negotiation tool to explore promising land-use and soil and water conservation measures aiming to reduce runoff and water losses in a region, based on related distributions of soil hydraulic properties.

1.4 OUTLINE

Research for this thesis has been carried out in three catchments in the southern loess area of the Netherlands (Fig. 1.1) and in a catchment on the Loess Plateau in China (Fig 1.2). The research has been performed in the framework of two

Figure 1.1 Location of the three catchments in the southern loess area of the Netherlands.

multidisciplinary projects. The 'Erosienormeringsonderzoek' was carried out in Limburg, and results were published in Volume 10 issue No. 8 (1996) of Hydrological Processes. In China, the research was part of the 'EROCHINA' project (www.erochina.alterra.nl). Results of this project will be published in Volume 53 (2003) of Catena.

This thesis comprises 8 chapters. Chapter 2 focuses on measuring soil physical properties of various soil horizons within selected catchments in the southern loess area in the Netherlands, and evaluating the tendency of these soil layers to generate runoff in a variety of characteristic rainfall events. A functional criterion was used to compare the soil layers in this respect. The final result is a soil physical schematisation of the watershed.

Chapter 3 discusses two extreme soil surface conditions, one crusted and one with a partially cracked surface, and the effects of these conditions upon water

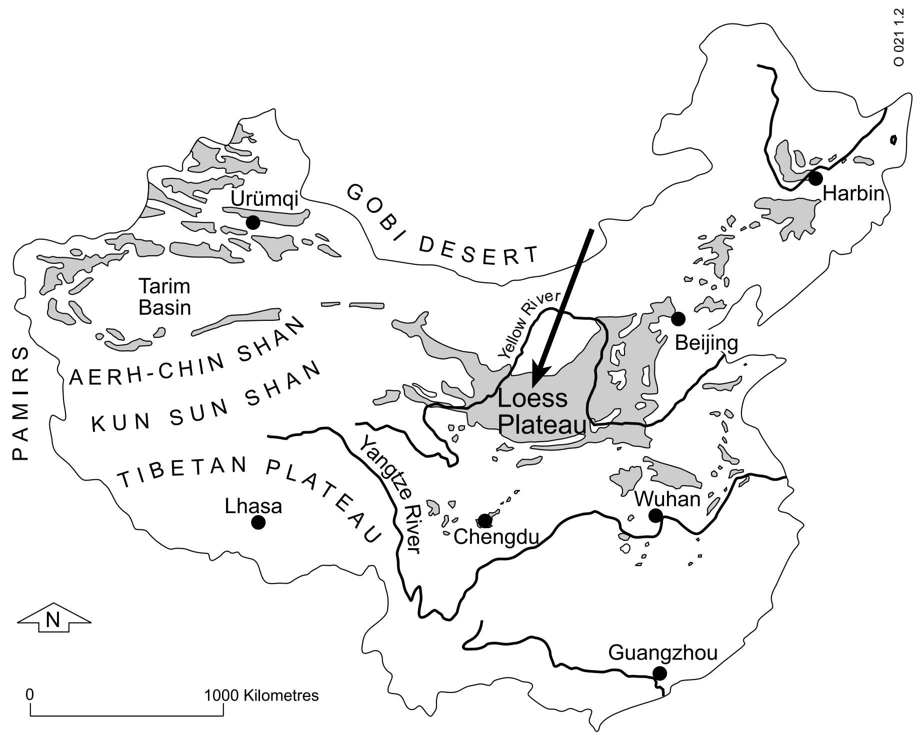

Figure 1.2 Location of the study area on the Loess Plateau in China (after Ritsema et al., 2003).

infiltration and the generation of runoff during typical rainstorm events. The study used the catchment-based, GIS-incorporated hydrological and soil erosion model LISEM to evaluate the influence of these two contrasting soil surface conditions on runoff and catchment discharge.

Chapter 4 deals with the spatial heterogeneity of soil physical properties within individual land-use units in the Danangou catchment in China. A statistically based measurement scheme was applied to quantify this 'internal' heterogeneity. Results for various land uses on the same soil type were compared statistically, and land-use units were merged for modelling purposes. Effects of the variability of individual soil and land-use types upon runoff and discharge generation were evaluated numerically using the LISEM model.

Chapter 5 describes a study using the LISEM model for a single-gully system on the Loess Plateau in China. Calibration was carried out for a single rain event by adjusting the saturated conductivity values. Validation was performed for two additional runoff events. Alternative land use options were defined, using soil hydraulic properties as regulating parameters to optimise the land use. Effects of alternative land-use options on runoff and soil loss were calculated using the LISEM model.

Chapter 6 attempts to develop a negotiation procedure for defining land-use scenarios to reduce soil and water losses. It focuses on ways to present potential effects of land-use changes to stakeholders in a negotiation process, emphasising risk analyses and economic impacts. The study quantified the effect of various land-use scenarios on the expected rate of discharge and sediment loss during a single rain event in a small agricultural watershed on the Loess Plateau in China, using geometric mean and stochastic distributions of K_s values measured in the field. The land-use scenarios used in this study are based on physical, economic and agricultural interests, and their effects on farmers' incomes were evaluated using empirically derived equations.

Summary, conclusions and recommendations for future research are given in Chapters 7 and 8.

CHAPTER 2

ESTABLISHING TEMPORALLY AND SPATIALLY VARIABLE SOIL HYDRAULIC DATA FOR USE IN RUNOFF SIMULATION IN A LOESS REGION IN THE NETHERLANDS

Adapted from:
Stolte, J. C.J. Ritsema, G.J. Veerman and W. Hamminga. 1996. Establishing temporally and spatially variable soil hydraulic data for use in a runoff simulation in a loess region of the Netherlands. Hydr. Processes 10, 1027-1034.

2. ESTABLISHING TEMPORALLY AND SPATIALLY VARIABLE SOIL HYDRAULIC DATA FOR USE IN RUNOFF SIMULATION IN A LOESS REGION OF THE NETHERLANDS

2.1 ABSTRACT

Soil hydraulic functions for runoff simulation were collected in three catchments in the southern loess area in the Netherlands, by sampling each soil horizon and determining water retention and hydraulic conductivity characteristics. A simulation with the SWMS_2D computer program was used to quantify runoff generation during standard rain events. The simulation outcome was used to merge soil horizons. This resulted in a database of 25 soil hydraulic functions, each representing a soil horizon or a specific condition of the top layer. Maps showing the soil physical composition of the area were constructed using these soil hydraulic functions. The maps can be used as input for soil and water erosion models to be applied at a catchment scale. Comparison of potential runoff figures with measured data showed that the soil physical schematisation appeared to be appropriate. The soil physical schematisation in the areas studied was based on structural rather than on textural differences of the top-soil.

2.2 INTRODUCTION

Spatial and temporal variability of hydraulic conductivity and initial moisture content are important parameters in soil-erosion studies (Springer and Cundy, 1988), and are generally difficult to obtain. So far, studies have been carried out to determine the spatial or temporal variability in soil physical properties themselves (e.g. Cassel and Nelson, 1985; Mapa et al., 1986) and their possible effects on model outcome (De Roo et al., 1992). In addition, geostatistical methods have been developed to describe variability in soil physical properties (Warrick et al., 1986).

The present chapter evaluates the effect of spatial and temporal variability in soil hydraulic functions on runoff by quantifying and comparing the effects of individual soil hydraulic functions on the generation of runoff during predefined rain events. The objective of the study was to obtain spatially and temporally variable soil physical building blocks for use as input data in soil erosion modelling. Using an appropriate functional criterion (Wösten et al., 1986), individual soil physical functions can be clustered into blocks with similar physical properties. In the case of changing physical properties due to, for example, soil tillage, measurements need to be repeated several times during a growing season or year to allow these units to be clustered into appropriate blocks. This procedure results in a soil physical schematisation in time and space for the area under consideration. The schematised physical maps provide useful basic input data for modelling hydrological processes in catchments.

The result of the soil physical schematisation has been evaluated by comparing simulation results with actual runoff data measured on experimental fields at the Wijnandsrade Experimental Farm. The procedure was carried out in 1992 and 1993 for three catchments in the southern loess area in the Netherlands (Fig. 1.1). The study was part of a project which aimed to develop a physically based hydrological and soil erosion model (Limburg Soil Erosion Model (LISEM), De Roo et al., 1996a). This model can predict soil erosion rates and the effects of conservation strategies in catchments under different land use and tillage systems.

2.3 MATERIALS AND METHODS

2.3.1 Study area and maps

In the southern loess area in the Netherlands, three catchments (Catsop, St.Gillisstraat, Etzenrade) were selected, with sizes of 0.42, 0.43 and 2.24 km^2 respectively. The main land-use types are shown in Table 2.1.

Soil maps at a 1:5000 scale were constructed for the three catchments that were monitored. Using these maps, representative soil profiles for each mapping unit were selected. The representative profiles are presented in Figure 2.1. The mapping unit represented by profile A covered 44% of the total area of the three catchments, profile B 13%, profile C 32%, profile D 4% and profile E 7%.

2.3.2 Sampling

Assuming that differences in runoff are caused by differences in the texture of the soil horizons and by structural differences in the top layers due to different crops and/or tillage systems, samples were taken from these land-use units. All horizons were sampled using cores with a diameter of 10 cm and a height of 8 cm. Samples were also taken from the top 8 cm of each of the soils used for the various crops and tillage systems in these three areas (Fig. 2.2).

Table 2.1 Main crops of the three catchments during the summer and winter period of 1992.

Land use	Area (%)					
	Catsop		St.Gillisstraat		Etzenrade	
	winter	summer	winter	summer	winter	summer
Orchard			28	28	1	1
Grass	25	17	16	7	25	19
Fallow	21		35		49	
Green manure	20		9		3	
Winter wheat	33	33	12	12	18	18
Sugar beet		30		19		25
Potatoes		17		13		10
Maize		2		21		23
Other	1	1			4	4

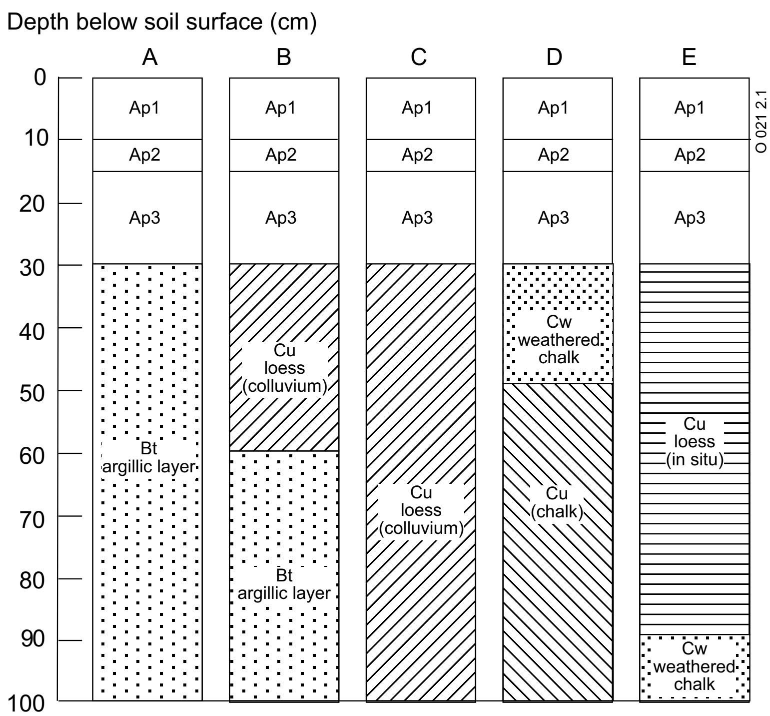

Figure 2.1 Representative soil profiles of the three catchments studied in the southern loess area in the Netherlands. A is a fine-silty, mixed, mesic, Typic Hapludalf, B is a fine-silty, mixed, mesic Typic Udorthent (fine-silty (loess) colluvial deposit less than 100 cm thick over fine-silty material (loess)), C is a fine-silty, mixed, mesic Typic Udorthent (fine-silty (loess) colluvial deposit), D is fine-silty over loamy-skeletal, mixed mesic Lithic Udorthent, E is a fine-silty, mixed, mesic Typic Udorthent (loess in situ).

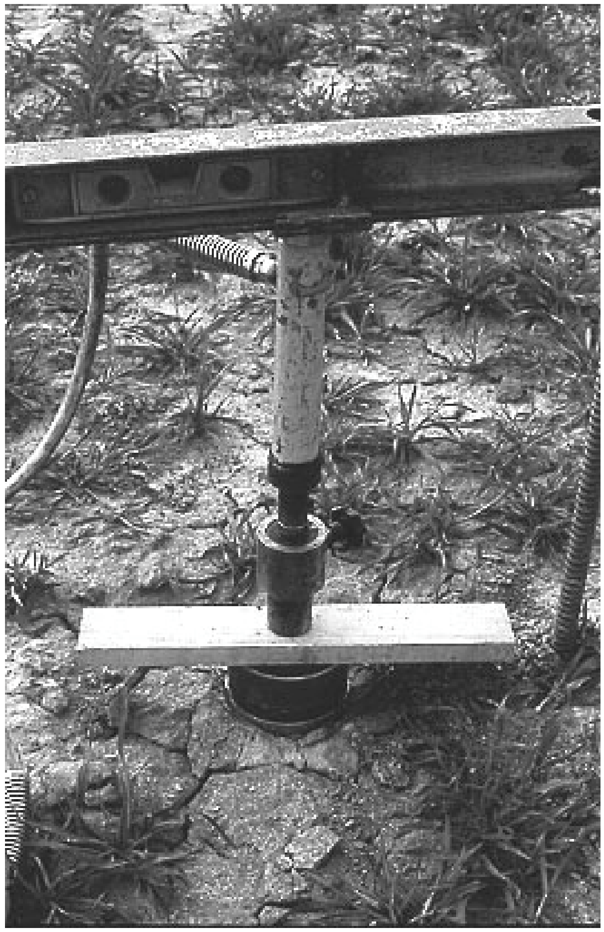

Figure 2.2 Taking samples of the top layer of a winter-wheat field, using hydraulic sampling equipment.

In view of the structural variations in the top layer that can be expected during the year, this layer was sampled five times: just before sowing in spring, just after sowing, during the growing season, just after harvesting and during the winter. The following crops were included: winter wheat, maize, orchard, sugar beet, green manure and grass. Six different tillage systems were sampled in maize on experimental fields. The treatments applied to these fields have been described in Wijnandsrade (1993), and are summarised in Table 2.2. The various crops were sampled on farm fields.

Table 2.2 Tillage systems of the maize experimental fields (after Wijnandsrade, 1993)

Code	Tillage system maize experimental fields
A	Rye in winter, no tillage in spring
B	Rye in winter, paraplow in spring
C	Rye in winter, mulching in spring
D	Rye in winter, row-cultivator in spring
E	Plough and rotary-cultivator in spring (common practice)
F	Plough and rotary-cultivator in spring, straw on seedbed

Table 2.3 lists the numbers of samples taken from the various soil horizons for hydraulic functions and texture measurement and the texture ranges of these horizons. Note that the texture of the layers are comparable, except for the chalk layer. The number of samples taken was determined by the occurrence and accessibility of the specific layer in the catchments.

Table 2.3 Number of samples taken from the different soil horizons for measurement of the hydraulic functions and the texture ranges of these horizons.

Horizon	Particle size				Number of samples	
	< 2		*2 - 50*		*texture*	*hydraulic*
	%	*S.D.*†	*%*	*S.D.*†		*functions*
Ap (0-8 cm below ss*)	14.5	2.5	76.6	2.6	12	67
Ap (6-14 cm below ss)	14.9	2.7	76.4	3.6	12	22
Ap (16-24 cm below	15.1	2.2	76.4	8.2	12	23
Bt (argillic horizon)	20.9	1.7	75.3	1.9	5	10
Cu (loess, colluvium)	16.8	1.8	75.3	1.7	13	34
Cu (loess, in situ)	20.2	1.7	75.6	1.9	6	4
Cw (weathered chalk)	23.3		64.8		1	4
Cu (chalk)	58.4		34.6		1	2

† *S.D. = standard deviation* * *ss = soil surface*

2.3.3 Calculation procedure

The water retention and hydraulic conductivity characteristics of the samples were measured in the laboratory using the evaporation method (Wind, 1968; Halbertsma and Veerman, 1994) and the constant-head method (Klute and Dirksen, 1986). A fit procedure (Van Genuchten et al., 1991) was used to describe the hydraulic functions with a set of Mualem-Van Genuchten parameters (Mualem, 1976; Van Genuchten, 1980). These hydraulic functions were used as input for the SWMS_2D computer program (Šimùnek et al., 1992), which evaluated them in terms of their contribution to the potential runoff, defined as precipitation minus infiltration. The SWMS_2D computer program considers two-dimensional Darcian flow described by a modified form of the Richards equation. Evaluation was done for standard rain events, as shown in Figure 2.3. The four artificial rain events were based on events measured over a 30-year period (Heidemij, 1988). The effect of the hydraulic functions on the potential runoff was evaluated using the standard rain events with a frequency of occurrence of once per two years (Fig 2.3 a and c).

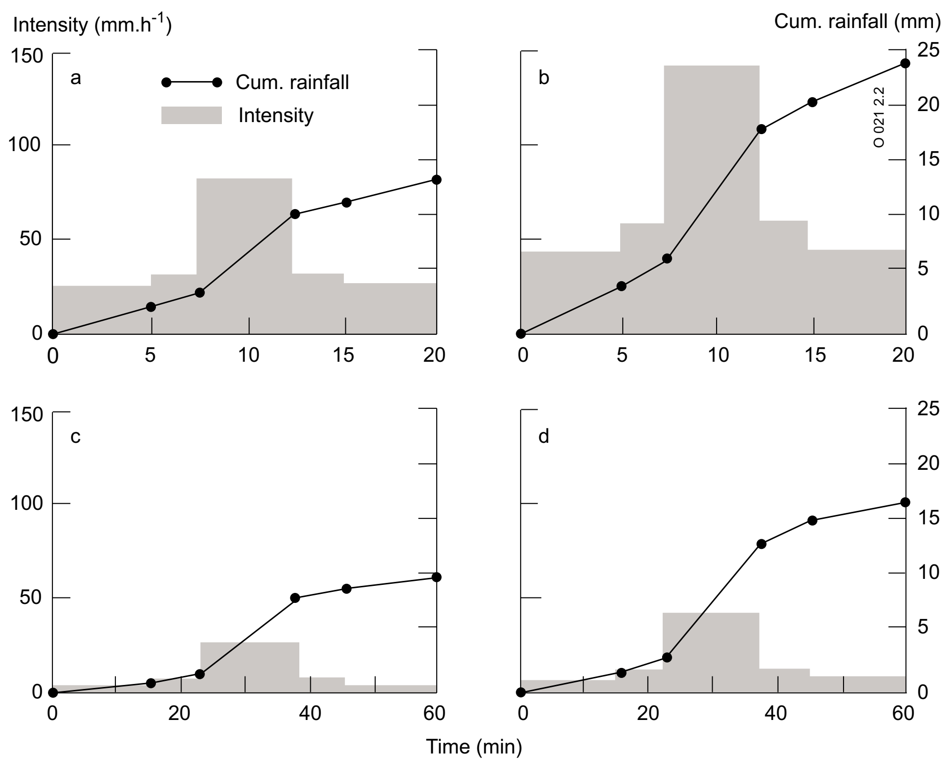

Figure 2.3 Standard rain events used to calculate the potential runoff of individual samples (a and c) and entire soil profiles (a, b, c and d). Summer shower a: two-year frequency; b: twenty-five year frequency. Winter shower c: two-year frequency; d: twenty-five year frequency.

2.3.4 Selection procedure

To investigate the influence of the individual subsoil horizons on runoff generation, we selected those hydraulic functions of each horizon that corresponded with the average, minimum and maximum potential runoff. These sets were subsequently used to calculate the potential runoff of the total representative profiles of Figure 2.1. In this session, the hydraulic functions of the A-horizon were kept constant. A potential runoff per profile was calculated for all four standard rain events presented.

The next step was to evaluate the SWMS_2D model outcomes using the hydraulic functions of the individual samples of the A_p2 (10-15 cm below soil surface) and A_p3 (15-30 cm below soil surface) layers. The outcomes were statistically analysed to detect any significant differences between the layers under different crops and/or tillage systems.

The final step was to investigate the influence on the potential runoff of the hydraulic functions of the top 10 cm under different crops and tillage systems. The simulation started with the representative profiles, using constant hydraulic functions for the subsoil and for the A_p2 and A_p3 layers, while the functions for the A_p1 layer (0-10 cm below soil surface) were varied. The procedure once again used the four standard rain events. If comparison of simulated potential runoff of the total profile showed no significant difference, the corresponding hydraulic functions of the A_p1 layers were grouped into soil physical building blocks.

2.4 RESULTS AND DISCUSSION

Figure 2.4 shows an example of calculated potential runoff. Such graph lines were constructed from the results of measurements for every sample. The potential runoff at the end of the rain event was used to distinguish different soil physical functions.

In terms of the influence of the hydraulic functions of the subsoil horizons, calculating the potential runoff while keeping the hydraulic functions of the A-horizon constant resulted in almost identical runoff figures for the five representative profiles. Therefore, soil physical properties of the subsoil in these catchments could be described by a single soil hydraulic function, as is illustrated in Table 2.4. This only shows a minor difference in the result for the 25-year winter shower, while the other results are identical for every shower.

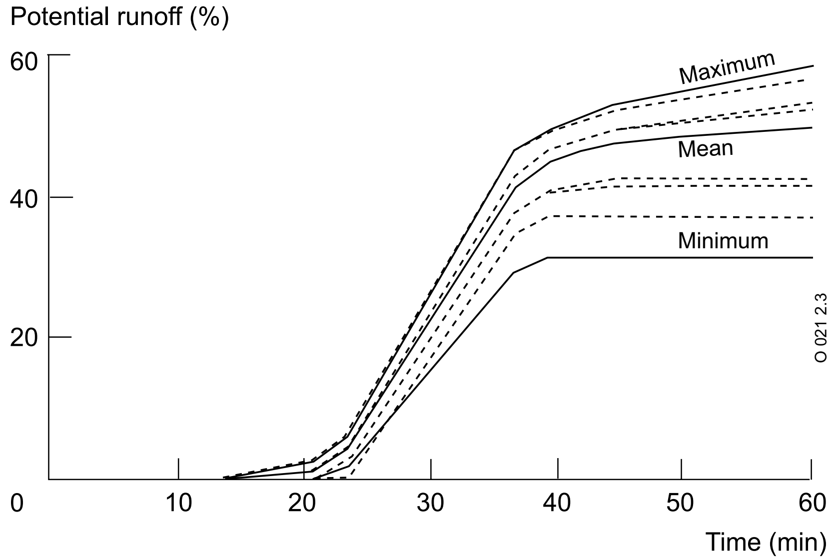

Figure 2.4 Potential runoff (in percentage of the precipitation), calculated with the SWMS_2D computer model, using the hydraulic functions of the ten individual samples taken from the argillic horizon. Calculations were done for a standard winter shower with a two-year occurrence frequency, with a precipitation of 10 mm in 60 min. The solid lines correspond to those samples that generated the maximum, mean and minimum potential runoff.

The calculation of the potential runoff, using the hydraulic functions of the individual samples of the A_p2 and A_p3 layers, resulted in a variety of runoff figures. Statistical analyses of these figures, using one-factor analysis of variance followed by Student t-tests (least significant difference method), showed that, in summer, a distinction must be made between orchards and arable land for these layers (Table 2.5). This is probably caused by a higher density of the layers at the orchard, due to frequent field traffic, whereas the layers of the arable land are loosened every year by ploughing.

Changing the hydraulic functions of the A_p1 layer and keeping the hydraulic functions of the other horizons constant resulted in a clear influence of the top layer conditions on runoff. Merging the potential runoff figures was only possible for results from the same moment and the same tillage system or crop. This resulted in 22 different soil physical building blocks, reflecting the effect of different top layer conditions on runoff. For example, a soil physical building block for maize in spring had to be distinguished, while a building block for wheel-tracks was also found to be significantly different from other clustered units (Stolte et al., 1994a).

Table 2.4 Calculated potential runoff (mm) of representative profiles for four standard rain events with constant hydraulic functions of the A-horizon. For the subsoil layers the hydraulic functions that generate the maximum, average and minimum potential runoff, as been calculated on individual basis, were used.

Profile	Winter shower						Summer shower					
	2-year frequency			*25-year frequency*			*2-year frequency*			*25-year frequency*		
	max	min	mean	max	min	mean	max	min	mean	max	min	mean
A	5.4	5.4	5.4	12.7	12.6	12.7	8.3	8.3	8.3	12.0	12.0	12.0
B	5.4	5.4	5.4	12.7	12.6	12.6	8.3	8.3	8.3	12.0	12.0	12.0
C	5.4	5.4	5.4	12.7	12.6	12.6	8.3	8.3	8.3	12.0	12.0	12.0
D	5.4	5.4	5.4	12.8	12.6	12.7	8.3	8.3	8.3	12.0	12.0	12.0
E	5.4	5.4	5.4	12.8	12.7	12.8	8.3	8.3	8.3	12.0	12.0	12.0

Table 2.5 Calculated mean potential runoff for a summer and winter shower with a two-year frequency, using the measured hydraulic functions of the A_p2 and A_p3 layers. Least significant difference method is used to analyse the figures.

	Mean potential runoff (cm)				Least significant difference
	orchard	*maize*	*sugar beet*	*winter wheat*	
A_p2 layer					
Summer shower	0.61	0.23	0.30	0.12	0.0916
Winter shower	0.85	0.52	0.81	0.68	0.1203
A_p3 layer					
Summer shower	0.55	0.31	0.12	0.17	0.1170
Winter shower	0.83	0.59	0.71	0.77	0.0940

The soil physical schematisation of the three catchment areas resulted in a total of 25 soil physical building blocks: one for the horizons below a depth of 30 cm, two for the layers at 10 - 30 cm below the soil surface and 22 for the conditions of the top layer. For this top layer, a temporal distinction had to be made. The building blocks were used to compose soil physical profiles. In view of the seasonal changes in the top layer conditions, five maps of soil physical profiles were distinguished during the year, consisting of soil physical profiles for the situations just after sowing, in spring, in summer, just after harvesting and in winter. The maps can be used as input in, for instance, the LISEM model (De Roo et al, 1996a). Two examples are shown in Figure 2.5. Each soil physical profile consists of three soil physical building blocks, described by a set of Mualem-Van Genuchten parameters. Areas with permanent crops, such as orchards and grassland, were found to include the same numbers (3 and 4) in the summer and winter periods, indicating that the top layer in these areas remains unchanged during the year.

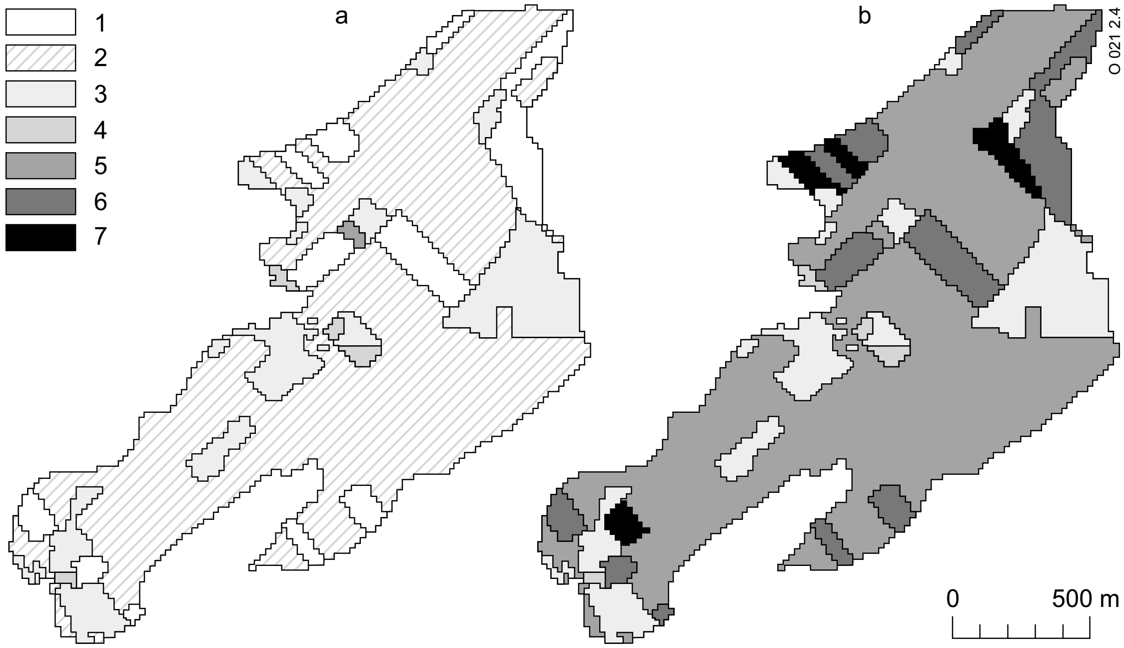

Figure 2.5 Maps of soil physical profiles at the 'Etzenrade' catchment area. 'a' refers to the summer period, 'b' to the winter period. The numbers 1-7 refer to soil physical profiles. These consist of several soil physical building blocks, which are composed of soil hydraulic functions representing the specific soil horizon or specific condition of the top layer.

2.5 COMPARISON OF MEASURED AND CALCULATED RESULTS

The reliability of the physical schematisation could be verified by comparing simulation results with measured data. However, the SWMS_2D model calculates a potential runoff, which is not measurable in the field. Normally, actual runoff is measured, which may be less than the calculated potential runoff due to storage in microdepressions, ponding etc. However, still an attempt has been made to compare calculated potential runoff with measured actual runoff for experimental fields with various tillage systems at the Wijnandsrade Experimental Farm. The plots we used had a length of 10 m and a width of 1.5 m. Rainfall simulations were performed on three replicates of six tillage systems. The rainfall simulator covered the entire plot. A rain intensity of about 80 mm/h was used for 45 min. Rainfall and runoff amounts were measured.

Calculated and measured results are shown in Figure 2.6. Although, as expected, measured runoff was always less than the calculated potential runoff, the observed trends in absolute values were more or less comparable for both, suggesting that the soil physical schematisation we applied was appropriate. For a detailed description of measured results and interpretation, see Wijnandsrade (1993).

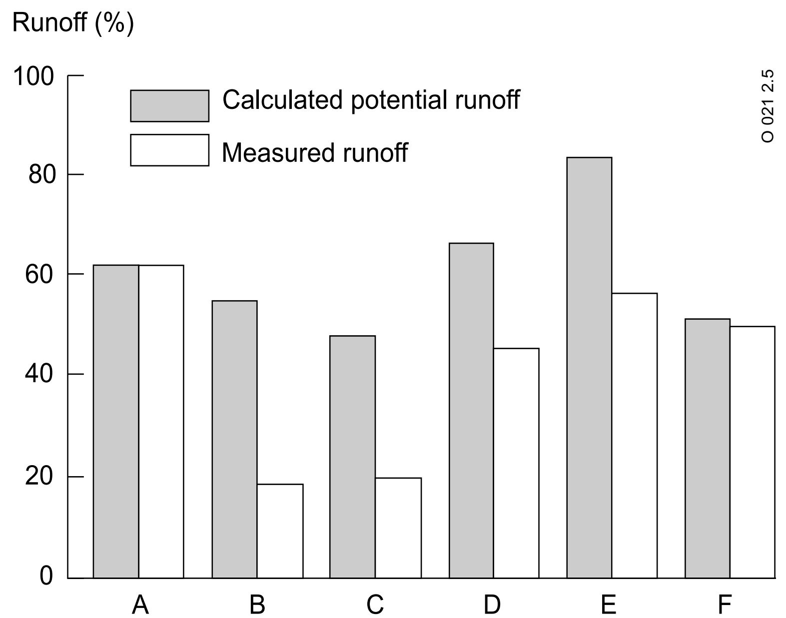

Figure 2.6 Measured runoff and calculated potential runoff (in percentage of the precipitation) of six experimental fields at the Wijnandsrade Experimental Farm. A to F correspond to fields with different tillage systems. Measurements took place at maize fields and were carried out using a rainfall simulator. Calculations were done using the SWMS_2D computer program. The simulation was carried out for 1m thick profiles, using soil physical building blocks corresponding the specific horizons and the condition of the top layer.

2.6 CONCLUSIONS

Simulation of soil loss and water discharge at catchment level requires data on soil hydraulic properties for each soil horizon and for each specific condition of the top layer. The large volume of measured data can be made manageable by clustering them into appropriate soil physical building blocks, using model simulations and potential runoff as the discriminating functional criterion. Such a soil physical schematisation provides reliable input data on temporal and spatial variability for soil erosion models. Comparison of potential runoff figures with measured data showed that the soil physical schematisation appeared to be appropriate.

In the southern loess area in the Netherlands, only differences in the hydraulic properties of the top layer caused differences in potential runoff. Thus, the soil physical schematisation was based on structural differences rather than textural differences.

CHAPTER 3

EFFECTS OF CRUSTS AND CRACKS ON SIMULATED CATCHMENT DISCHARGE AND SOIL LOSS

Adapted from:

Stolte, J. C.J. Ritsema and A.P.J. de Roo. 1997. Effects of crust and cracks on simulated catchment discharge and soil loss. J. of Hydrol. 195, 279-290.

3. EFFECTS OF CRUSTS AND CRACKS ON SIMULATED CATCHMENT DISCHARGE AND SOIL LOSS

3.1 ABSTRACT

Sealing, crust formation and cracking of crusts at the soil surface have been observed in many parts of the world in areas with sandy, silty and loamy soils. Sealing and crust formation occur under the influence of rainstorms followed by dry weather. After prolonged desiccation, surface crusts may crack, leading to complex situations in terms of infiltration and runoff generation. Cracking of crusted loamy soils appears to be a common process. This study aimed to measure the hydraulic properties of areas with intact crusts and those with cracked crusts, and to evaluate the effects of these properties on catchment discharge and soil loss in a loess region in the Netherlands, using the LISEM soil erosion model. Samples with minimum infiltration rates (on surfaces with intact crust) and with maximum infiltration rates (on surfaces with cracked crusts) were taken from fields with bare soil or winter wheat, after which their soil hydraulic functions were measured. The results of these measurements were used as input in the LISEM soil erosion model. Discharge and soil loss were simulated for each of these two types of land use and for two rain events. Additionally, simulated discharge and soil loss were calculated for the current, recorded land use. In all cases, soils without any surface cracks yielded higher discharge and soil loss values than those where 10% of the surface crust was cracked. A reliable interpretation of the results in terms of soil loss requires detailed examination of the spatial distribution of areas with intact crusts and those with cracked crusts. In dealing with these two types of area in modelling, the soil physical functions representing the maximum and minimum infiltration rates have to be measured very accurately. These functions then have to be assigned to calculation grids. As the LISEM model is capable of assigning various soil physical functions to each grid cell, it allows better predictions of the soil physical behaviour of the catchment.

3.2 INTRODUCTION

Sealing, crusting and cracking of crusts at the soil surface are phenomena that have been observed in many parts of the world in areas with sandy, silty and loamy soils (Valentin and Bresson, 1992). These processes may dramatically affect the local hydrological regime, especially in agricultural environments.

Surface sealing is (following the definition of Römkens et al., 1990) the structural degradation of a thin layer in the soil surface during a rain storm or irrigation event. Sealing of soil surface has been ascribed to disintegration of structural elements by slaking or dispersion leading to silt infillings in vertical inter-aggregate pores, or by coalescence or welding of aggregates into larger units (McIntyre, 1958; Bresson and Boiffin, 1990; Bresson and Cadot, 1992; Kwaad and Mücher, 1994). Crusting of a seal refers to (again following the definition of Römkens et al., 1990) the hardening and strength increase of the surface seal, in the dry period following the rain storm or irrigation event.

In agricultural fields, sealing and crust formation are most likely to occur during periods in which the soil surface is bare or sparsely vegetated. Sealing can take place during a single or during multiple rain events. Luk and Cai (1990), Luk et al. (1990) and Wessolek et al. (1994) indicated that a total of around 20 mm of rain might be sufficient for surface seal formation on loess soils in hilly, agricultural regions. The thickness of surface seals is usually no more than several mm (Römkens et al., 1986). However, Kwaad and Mücher (1994) showed that in very wet months, a complete collapse of the soil structure occurred in Dutch agricultural loess soils, leading to a 7 cm thick soil seal. The effect of the formation of surface seals is a local increase in bulk density, and a subsequent decrease in porosity as well as saturated and unsaturated hydraulic conductivity (Gimenez et al., 1992). During dry weather, surface seals may be converted into surface crusts. Both surface seals and surface crusts promote runoff compared with non-sealed and non-crusted areas. The effect on soil loss might be the opposite, as soil strength increases during crust formation (Luk et al., 1993). After prolonged desiccation, surface crusts may crack, leading to an even more complex situation in terms of infiltration and runoff generation.

The effect of soil crusts on runoff generation and soil loss in catchments may vary, depending on the spatial distribution of crusted and non-crusted areas and on the possible occurrence of shrinkage cracks within the crusted layer. Govers (1991) recognised the influence of cracked crusts on discharge, finding crack widths ranging from 2 - 3 mm (on the plateau) to 10 mm (on hill slopes). The difference was attributed to differences in the rate at which the soil dries out. Cracked surface crusts were found to have a larger storage capacity and infiltration rates, due to direct connection with soil macropores, allowing bypass flow and internal catchment (Van Stiphout et al*.,* 1987, Bronswijk, 1988). Govers (1991) found extended open crack networks in tilled fields on the silty, loamy soils of central Belgium, especially in springtime. The majority of these cracks remained open from March until the end of July, despite the precipitation during this period. We also recognised and observed this phenomenon in the loess region of the Netherlands. After the soil surface has become sealed during a rainstorm, crust formation and distinct crack patterns have been found to develop after a few days of dry weather (Fig. 3.1).

As cracking of crusted loamy soils appears to be a common process, there is an urgent need to quantify the effects of cracked-crust areas on total catchment

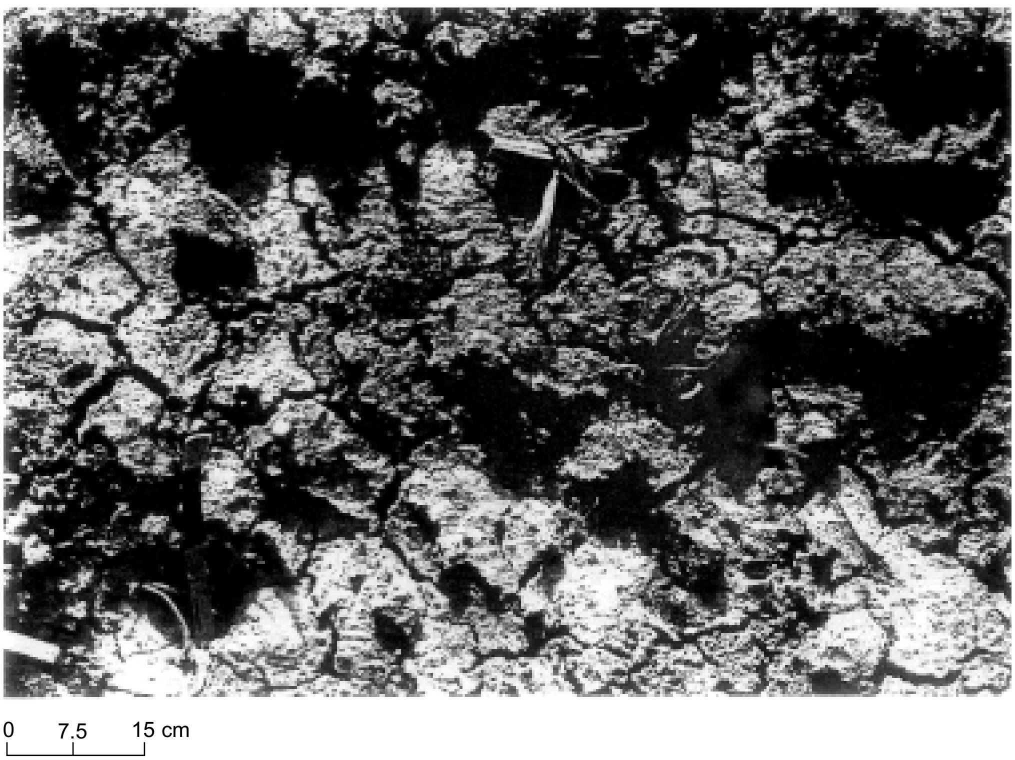

Figure 3.1 Surface crust with a distinct crack pattern in a bare soil field.

runoff and soil loss. Therefore, this study aimed (i) to measure the soil physical properties of cracked and non-cracked surface crusts commonly found in the loess region of the Netherlands, and (ii) to evaluate the effect of these soil physical functions on calculated catchment runoff and soil loss using the recently developed physically based hydrological and soil erosion model LISEM (De Roo et al., 1996a).

3.3 MATERIALS AND METHODS

3.3.1 Study site

The 'St. Gillisstraat' catchment in the southern loess region of the Netherlands covers 0.43 km^2 (Fig. 3.2).

Figure 3.2 'St. Gillisstraat' catchment in the southern loess area in the Netherlands.

During the winter period of 1992-1993, the catchment comprised 8% grassland, 28% orchards, 60% bare soil and 1% winter wheat (Fig. 3.3). The main soil types found in the catchment were a fine-silty, mixed, mesic, Typic Hapludalf (42%); a fine-silty, mixed, mesic Typic Udorthent (loess colluvial deposit) (41%); a fine-silty, mixed, mesic Typic Udorthent (loess colluvial deposit less than 100 cm thick over loess) (5%); a fine-silty over loamy-skeletal, mixed mesic Lithic Udorthent (6%) and a fine-silty, mixed, mesic Typic Udorthent (loess in situ) (6%).

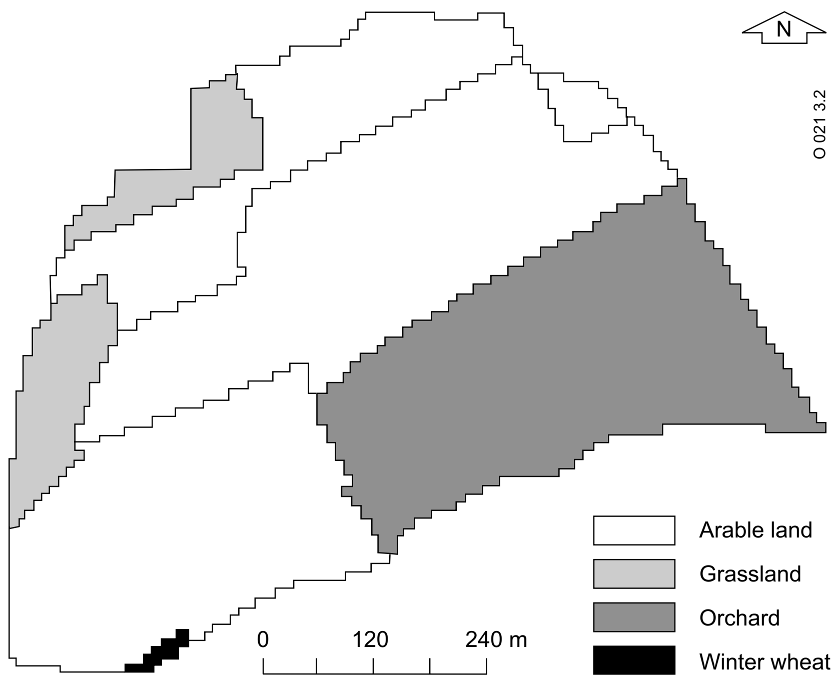

Figure 3.3 Land use at the 'St. Gillisstraat' catchment during the winter of 1992 - 1993.

3.3.2 Sample collection

Samples were taken in the 'St. Gillisstraat' catchment, at sites with bare soil and with winter wheat. The winter wheat had been sown in the autumn of 1992 and no subsequent tillage activities had taken place. At the bare soil site, no tillage activities had taken place since the 1992 harvest. Residues of a maize crop from 1992 were still on the field (Fig. 3.1). Samples were taken on 15 April 1993, prior to any tillage activities. At the time of sampling, a distinct crust was present. The soil at the sampling locations was a fine-silty, mixed, mesic Typic Udorthent (fine-silty (loess) colluvial deposit).

Soil cores with a diameter of 10 cm and a length of 8 cm were taken in duplicate from a site with an intact surface crust and from a site with surface cracks. Crack widths varied from 1 to 2 cm at the surface, with depths of 2 to 3 cm. The surface area of the cracks comprised about 10% of the total surface area of the sample, a percentage estimated from the sample surface using a ruler. The saturated conductivity of the samples was measured using the constant-head method (Klute and Dirksen, 1986), while the unsaturated conductivity and water retention characteristics were measured using the evaporation method (Halbertsma and Veerman, 1994). The samples were carefully transported to the laboratory and put in a tray with a shallow layer of water (2 cm). The samples were left to saturate, while the layer of water in the tray was increased by 2 cm a day, up to 8 cm. During this saturation process, the cracks remained open, which is in agreement with field observations. The edge of the sample surface was covered with a strip of grease (approx. 0.5 cm wide) to avoid any influence of possible damage to the crust at the edge of the sample surface. The evaporation method measured the water retention in the hydraulic head range from 0 (saturation) to about -800 cm and the hydraulic conductivity characteristic from about -80 to -600 cm (Fig. 3.4). To this end, a

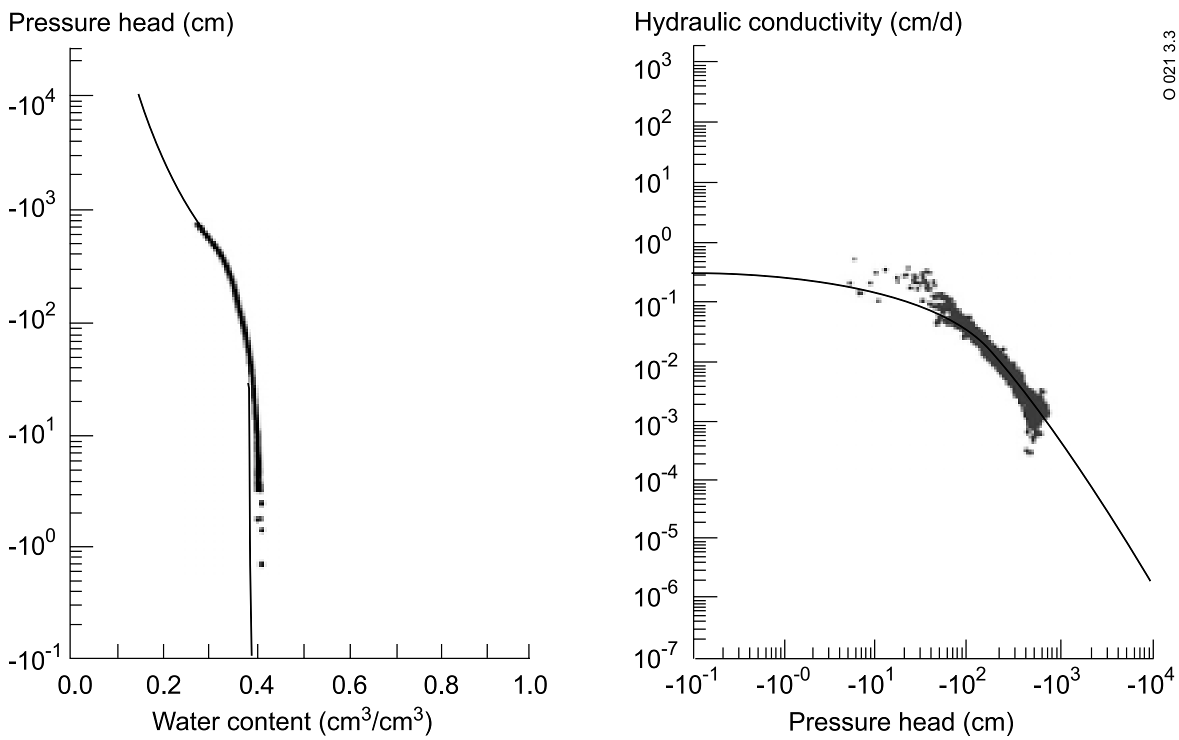

Figure 3.4 Example of measurement results of the evaporation method. On the left is the water retention characteristic, on the right the hydraulic conductivity characteristic. The points are the measured data and the line has been fitted using the RETC computer program; it is described by the Mualem-Van Genuchten equations.

saturated sample was placed on a balance and tensiometers were installed. The sample was exposed to evaporation and weight and hydraulic head values were recorded periodically. These data were then used to calculate the hydraulic properties of the sample. A comparison of this method with other laboratory methods for measuring unsaturated conductivity has been presented in Stolte et al. (1994b). A set of Mualem-Van Genuchten parameters (Mualem, 1976; Van Genuchten, 1980) was fitted to the data using the RETC computer program (Van Genuchten et al., 1991).

3.3.3 Runoff simulations

The influence of crusts and cracks on runoff and soil loss at the 'St. Gillisstraat' catchment was investigated using the LISEM computer model. The LISEM model is a physically based hydrological and soil erosion model. The measured hydraulic functions of a sample without cracks and one with 10% surface cracks were used as input for the top layer (0-10 cm). All other input parameters (surface roughness, structure stability, plant density, etc.) remained constant during the various simulations. Soil physical functions of the top layers of areas with a land use other than bare soil or winter wheat, and of the soil horizons, were established on the basis of a spatial and temporal physical schematisation (Stolte et al. 1996). To this end, the soil and land-use map was converted into a soil physical map using the calculated potential runoff (defined as precipitation minus infiltration) as the functional criterion to cluster physical functions of the soil layers. Samples were taken from the various land use systems and soil horizons, and functions were clustered on the basis of the calculated runoff rate from each soil profile. A detailed description of this procedure has been given in Chapter 2 of this thesis. Calculation grid cells were 10 x 10 m in size. Calculations were done for situations with bare soil and those with winter wheat. Additionally, a simulation was carried out for the 1992/1993 land use situation.

Simulations were done for two standard rain events during a summer period (Fig. 3.5). The artificial rain events had return periods of two years and 25 years, based on rainfall events recorded over a 30-year period. Input parameters (surface roughness, plant density, structure stability etc.) for the simulation were based on datasets relating to spring, just before tillage activities took place on the bare soils.

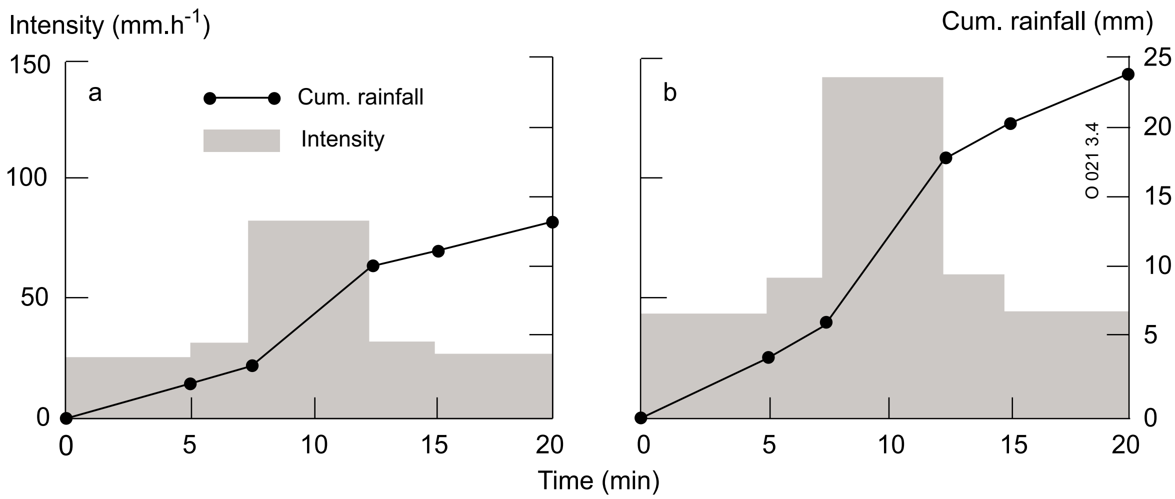

Figure 3.5 Standard rain events used to simulate discharge and soil loss. Storm a: 2-year frequency; storm b: 25-year frequency.

Per pixel, the LISEM model can use up to three different soil physical functions to calculate infiltration and vertical soil moisture transport at the soil surface. For every pixel, a surface area fraction can be assigned to each of these functions, for example crusted soils, areas with surface cracks and areas with tractor wheeling. Total infiltration amounts are calculated by multiplying the infiltration amounts of infiltrated water by the surface area of each contributing component within the pixel. This results in a 'weighted average' infiltration amount. Simulations can then be carried out using various combinations of, for instance, crusted areas and areas with surface cracks. This procedure was used for the rain event with a 25-year frequency. The contributions of the soil physical functions of the samples with cracks ranged from 0% to 100%, with step sizes of 12.5%, reflecting a proportion of cracks varying from 0% to 10%.

3.4 RESULTS AND DISCUSSION

3.4.1 Measurements

The evaporation method generated the data presented in Fig. 3.4, which shows the data points as well as the line fitted through them using the Mualem-Van Genuchten equations. The soil physical functions of the samples are presented as Mualem-Van Genuchten parameters in Table 3.1. This table also presents the soil physical functions of the subsoils that were used in the calculation procedure, together with the measured saturated conductivities (K_s). The measured K_s values of the samples with surface cracks were about 4 to 7 times as high as those of the samples with an intact surface crust, for all situations.

Table 3.1 Soil physical functions, represented by Mualem-Van Genuchten parameters, of duplicate samples taken at a bare soil and winter wheat field at 15 April 1995. Samples surfaces contained a complete crust or a cracked crust. The marked samples are used in the calculations. Also, the parameters of the subsoil used in the calculations are presented.

	θ_r† (m^3/m^3)	θ_s (m^3/m^3)	α (-)	n (-)	l (-)	K_s-fit (cm/d)	K_s-meas (cm/d)
Winter wheat crust 1*	0.01	0.310	0.0087	1.529	0	1.780	30.3
Winter wheat crust 2	0.01	0.300	0.0052	1.583	0	0.729	29.8
Winter wheat crack 1*	0.01	0.315	0.0064	1.586	0	3.010	118.8
Winter wheat crack 2	0.01	0.316	0.0067	1.424	0	2.671	118.7
Bare soil crust 1*	0.01	0.310	0.0253	1.274	0	14.446	31.8
Bare soil crust 2	0.01	0.310	0.0087	1.523	2	5.140	28.7
Bare soil crack 1*	0.01	0.374	0.0406	1.286	-1.872	41.401	206.2
Bare soil crack 2	0.01	0.296	0.0212	1.292	0	20.126	199.1
Layer 10 - 30	0.01	0.425	0.0060	1.185	-5	0.192	179.5
Layer 30 - 1000	0.01	0.420	0.0129	1.284	0	2.304	55.4

†θ_r = *residual water content;* θ_s = *saturated water content;* α, n, l = *shape parameters;* K_s-fit = *fitted saturated conductivity;* K_s-meas = *measured saturated conductivity*

Conductivity characteristics (K(h)) as shown in Fig. 3.6 were used as input for modelling. The K(h) relationship of a sample shows a sharp change in the characteristic in the wet range of the soil, reflecting the sudden increase in conductivity of the soil due to macropore flow. The inflexion point starts at a pressure head where the water content is 0.01 m^3/m^3 lower than the saturated water content and increases in linear fashion to the measured saturated conductivity. This is a pragmatic method of dealing with the effect of macropore flow, which induces a large drop in conductivity at near-saturation relative to measurements of saturated samples. This drop in conductivity is due to the emptying of macropores (Bouma, 1980/1981).

3.4.2 Simulation

To demonstrate the effect of areas with intact crusts and areas with cracked crusts on runoff generation in a catchment, the LISEM model was used to simulate the St.Gillisstraat area. Results of the simulation for areas with 0% and 10% open

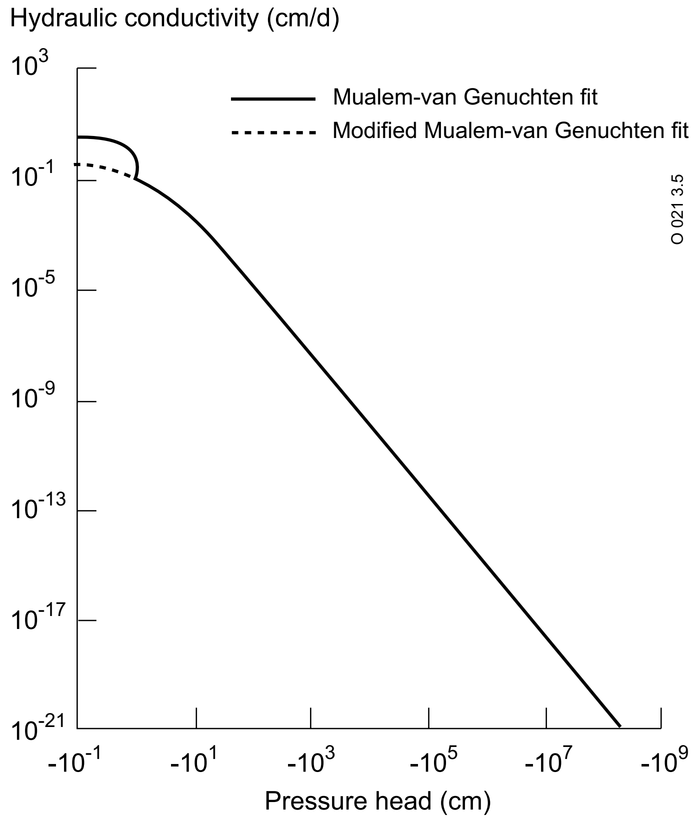

Figure 3.6 Example of hydraulic conductivity used in the simulation of discharge and soil loss. From a pressure head where the corresponding water content is 0.01 times lower than the saturated water content, the hydraulic conductivity increases in linear fashion to the measured saturated hydraulic conductivity.

cracks are shown in Fig. 3.7, providing the calculated average discharge, peak discharge and average soil loss of the catchment. The situation with 0% cracks leads to higher values for all units than the situation with 10% cracks; this was true for all three scenarios: actual land use, winter wheat and bare soil.

3.4.3 Discharge

The differences between the two situations (0% versus 10% cracks) for the scenario with only winter wheat are largest for the total discharge, whereas the difference is smallest for the actual land-use scenario. This is due to the grass and orchard areas included in the catchment. The characteristics of these areas do not differ between the two calculated situations, so infiltration rates are the same. The absolute influence of intact crust or 10% cracked crust areas is similar for both rain events. However, the relative influence is larger for the 2-year frequency storm than

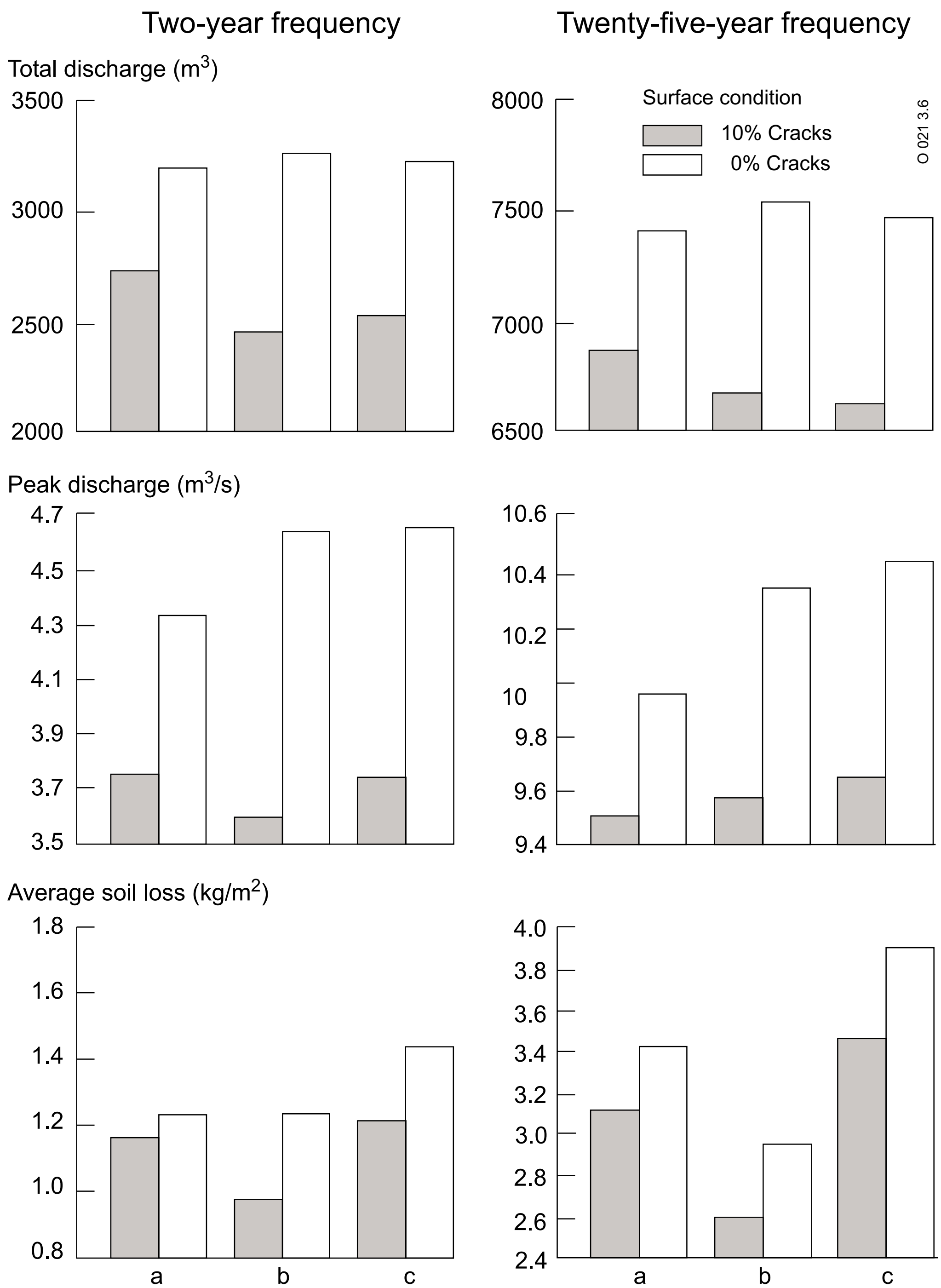

Figure 3.7 Simulation results for total discharge, peak discharge and average soil loss for three scenarios, (a) actual land use, (b) winter wheat and (c) bare soil, with 0% cracks and 10% cracks in the surface crust.

for the 25-year frequency storm (14.4, 24.9 and 21.4% versus 7.3, 11.6 and 11.4% for the actual land-use, winter wheat and bare soil scenarios, respectively).

The differences in peak discharge show a similar behaviour as those in total discharge. The difference is largest for the winter wheat scenario and smallest for the actual land-use scenario. The absolute difference in peak discharge is slightly larger for the 2-year frequency rainstorm. However, the relative difference is considerable larger for the 2-year frequency than for the 25-year frequency (13.6, 22.7 and 19.9% versus 4.7, 7.5 and 7.6% for the actual land-use, winter wheat and bare soil scenarios, respectively).

3.4.4 Soil loss

From Fig. 3.7 it can be concluded that soil loss also decreases with an increasing proportion of cracks, although not spectacularly. Because soil physical functions were the only parameters that changed, this decreased soil loss is explained by an increased infiltration rate when the soil physical functions of the cracked crust sample is used. A higher infiltration rate causes a lower discharge and hence a lower water velocity. In the model, water velocity influences the soil loss by (i) deposition and (ii) detachment. Note that the winter wheat scenario produces a smaller average soil loss in all situations. This is explained by the plant density factor: the winter wheat has already developed a vegetation cover by spring (soil cover in April is 13%).

A more detailed examination of the influence of the proportion of cracks on discharge and average soil loss is shown in Figure 3.8. Calculations were carried out for various distributions of surface areas, varying from 0% cracks (i.e. with intact crust) to 10% cracks, with step sizes of 1.25% for the current land-use situation. Figure 3.8 shows a small change in the rate of decrease of the discharge and average soil loss at almost 6% cracks. This is caused by the fact that the sieve function of the grass area near the outlet of the catchment depends on the total upstream water and sediment input. Relatively low discharges lead to a lower overland flow rate. As flow rate determines the sediment transport capacity of overland flow, it influences the net soil loss. However, the general trend is clear: an increase in the cracked crust areas decreases total water and soil loss compared with situations with a surface layer with intact crust.

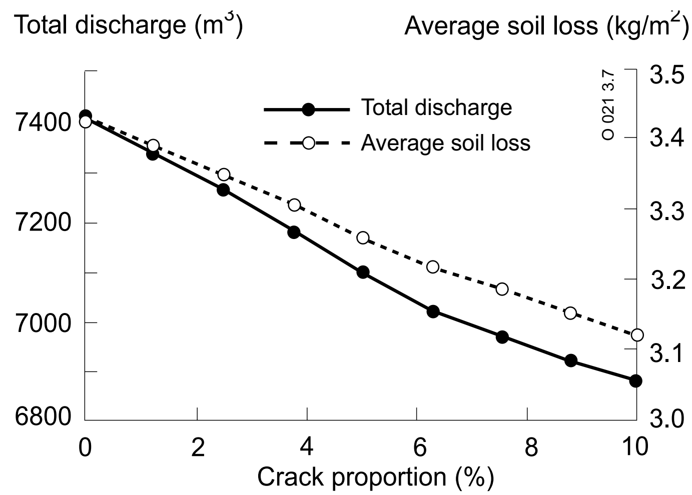

Figure 3.8 Influence of the proportion of cracks in the surface crust on the calculated discharge and average soil loss at the 'St. Gillisstraat' catchment, based on actual land use.

3.4.5 Validation

We conducted a sensitivity analysis of the use of the LISEM model on the soil physical functions of the top layer. Validation of the LISEM model itself has been presented by De Roo et al (1996b). Although the quantitative validation showed it to be far from perfect, LISEM produces reliable qualitative results. Thus, the results obtained in the present study provide a useful indication of the influence of crusts and cracks. An uncertain factor is the scale effect of the procedure, in which an attempt was made to establish soil physical functions of a tillage system using relatively small samples. Stolte et al. (1996) introduced this method of soil physical schematisation in a soil erosion study, in which they found results to be sufficiently reliable for the purpose of characterising experimental fields. The method of soil physical schematisation, which was originally introduced by Wösten et al. (1985), assumes that samples are taken from spots with the lowest infiltration rate (areas with intact crusts) and from spots with the highest infiltration rate (with 10% of the surface cracked). Using these two extreme values provides an indication of the range of the model results. The procedure presented here assumes that the actual field heterogeneity lies between the two extreme values.

3.5 CONCLUSIONS

Soil physical functions of samples with an intact crust and samples with cracked crusts can be measured and used for input in the physically based soil erosion model

LISEM. Differences were simulated for total and peak discharges on areas with intact crusts compared to areas with cracks, especially for high frequency rainstorms. Soil loss values calculated for the various soil physical functions were also found to decrease with increasing proportions of cracks, because the simulations generated runoff only on the soil areas with intact crusts, and hardly on the areas with cracked crusts. A decrease in the surface area of soil with intact crust therefore directly results in a decrease in water runoff and total soil loss. This effect might be less pronounced in situations in which runoff is generated on both types of area. The total effect might then be more complicated than that presented here.

Simulating runoff generation on cracked areas requires an accurate estimate of the proportion of cracks. Soil physical functions should be determined for spots with the highest infiltration rates (cracks) and for those with the lowest infiltration rates (intact crusts). The various soil physical functions will then have to be assigned to calculation grids, corresponding to the proportions of crusted areas and areas with cracked crusts. The exact spatial distribution of areas with intact crusts and those with cracked crusts might affect the computed total discharge of water and soil, especially in grid cells over which the surface runoff passes. Future studies should focus on this aspect. A major advantage of the LISEM model is that a ratio of various soil physical functions can be assigned to each calculation grid. This allows the model to produce better predictions of catchment discharge and soil loss than other distributed hydrological and soil erosion models. If spots with the most distinct crust and the largest proportion of cracks are sampled, calculating the discharge will yield the limits of the model for the specific area. The real discharge will be situated in between these limits.

CHAPTER 4

LAND-USE INDUCED SPATIAL HETEROGENEITY OF SOIL HYDRAULIC PROPERTIES ON THE LOESS PLATEAU IN CHINA

Adapted from:
Stolte, J., B. van Venrooij, G. Zhang, K.O. Trouwborst, G. Liu, C.J. Ritsema and R. Hessel, 2003. Land-use induced spatial heterogeneity of soil hydraulic properties on the Loess Plateau, China. Catena, In Press.

4. LAND-USE INDUCED SPATIAL HETEROGENEITY OF SOIL HYDRAULIC PROPERTIES ON THE LOESS PLATEAU IN CHINA

4.1 ABSTRACT

On the Loess Plateau in China, soil erosion amounts to between 10 000 and 25 000 tons/km^2 per year. The EROCHINA project, aimed to develop alternative land-use and soil and water conservation strategies for the Loess Plateau, using the LISEM soil erosion model. In order to provide the model with accurate input on soil hydraulic properties of the catchment, the present study tried to quantify these properties for major land-use units and to examine the effects of the statistically detected in-field heterogeneity on model outcome. The study area (Danangou catchment) is located in the central part of the Loess Plateau in the northern part of Shaanxi Province. The catchment is about 3.5 km^2 in size. To determine the hydraulic properties of the soil, a sampling scheme was implemented to measure unsaturated conductivity and water retention characteristics. The saturated conductivity (K_s) measurements were performed on land-use clusters, based on treatment and plant and soil differences. A 100 m x 100 m sampling grid was laid out on 14 fields, with 1 m x 1 m grid squares. On each field, ten sampling spots were randomly selected, using Simple Random Sampling. The sensitivity of the LISEM model to the measured heterogeneity of K_s was analysed using the geometric mean and standard deviation of the K_s values for the various land-use units to calculate discharge and soil loss during a single rain event. Using the 30 – 50% standard deviation of the K_s, it was found that the calculated discharge and total sediment losses varied by ~ 80%. Using the standard deviation had a minor effect on the calculated sediment concentration. As regards the on-site effects, the use of the geometric mean of K_s *minus* the SD resulted in an *increase* in the calculated level of erosion, while the use of the geometric mean of K_s *plus* the SD value resulted in a significant *decrease* in erosion level relative to that obtained using the geometric mean of K_s itself. Using randomly selected sampling spots and a calibration procedure, as was done in the present study, makes detailed information on K_s available, which can be used to compare alternative land-use options for their effectiveness in reducing discharge and sediment losses.

4.2 INTRODUCTION

Spatial and temporal variability of soil hydraulic conductivity are important parameters in soil erosion studies (Springer and Cundy, 1988), and are generally difficult to measure. So far, studies have been carried out to determine the spatial or temporal variability in soil physical properties themselves (e.g. Cassel and Nelson, 1985; Mapa et al., 1986, Mallants et al., 1996). Kim and Stricker (1996) concluded that one set of equivalent soil hydraulic characteristics does not accurately capture the effects of (field-scale) spatial heterogeneity on the presence of surface runoff. Sharma et al. (1980) concluded from their experiments at watershed level that there was no obvious pattern in the distribution of infiltration parameters with respect to soil type or position in the watershed. De Roo and Riezebos (1992) used infiltration experiments to show that within-unit variability was greater than between-unit variability, so no statistically significant differences in infiltration characteristics could be detected between the experimental fields they used. Studies on the effects of the variability of soil hydraulic properties, or related parameters such as infiltration rate, show that these properties are key factors in predicting runoff rates (e.g. Singh and Woolhiser, 1976, De Roo et al., 1992). Trends in infiltration properties are crucially important in understanding and predicting Hortonian runoff (Woolhiser et al., 1996). De Roo et al. (1996b) showed that saturated hydraulic conductivity is the most sensitive parameter for a physically based soil erosion model. In-field variation in conductivity characteristics of crusted areas was found to have major effects on calculated runoff (Stolte et al., 1997).

On the Loess Plateau in China, soil erosion amounts to between 10 000 and 25 000 tons/km^2 per year (Zhang et al., 1998). Of this quantity, 73% ends up in the Huang He (Yellow River), causing huge sedimentation problems, as well as flood risks, in downstream areas. In 1998, the EROCHINA project was started, with the major objective of developing alternative land-use and soil and water conservation strategies for the Loess Plateau (Ritsema et al., 2003). To evaluate alternative land-use options, model simulation has been carried out using the physically based LISEM soil erosion model (De Roo et al., 1996a). The model is highly sensitive to saturated hydraulic conductivity (De Roo et al., 1996b). In order to provide the model with accurate input on soil hydraulic properties of the catchment, the present study aimed at (i) quantifying the soil hydraulic properties of major land-use units, (ii) quantifying the within-unit heterogeneity of saturated conductivity, (iii) detecting statistically significant differences between land-use units, and (iv) examining the effects of on-field heterogeneity on model outcome.

4.3 MATERIALS AND METHODS

4.3.1 Study area

The study area (Danangou catchment) is located in the central part of the Loess Plateau in the northern part of Shaanxi Province (Fig 4.1). The catchment is about

Figure 4.1 The Danangou catchment, with view on Leipingta village.

3.5 km^2 in size, and drains directly into the Yanhe river. The elevation of the catchment ranges from 1085 to 1370 m above sea level (Fig. 4.2).

A soil survey (Messing et al., 2003) found Calcaric Regosols in the WRB (1998) reference system and Typic Ustorthents according to the Soil Survey Staff (1992) for the stratified loessial soils above 1200-1225 m altitude. The stratified loessial soils below 1200-1225 m were found to be Calcaric/Chromic Cambisols (WRB) and Calcic Ustochrepts/Umbric Fragiochrepts (SSS); the alluvial soils were Calcaric Fluvosols (WRB) and Typic Ustifluvents (SSS); soils with the bedrock at a depth of less than 25 cm or containing little fine earth (skeleton soils) belonged to the Calcaric/Lithic Leptosols (WRB) and Lithic Ustorthents (SSS). The soil map is shown in Figure 4.3.

At Ansai City, 5 km from the Danangou catchment, average annual rainfall was 513 mm over the 1971-1998 period (Ansai County Meteorological Station), of which 72% fell in the period June-September, with an average of 3 – 4 storms each year causing discharge.

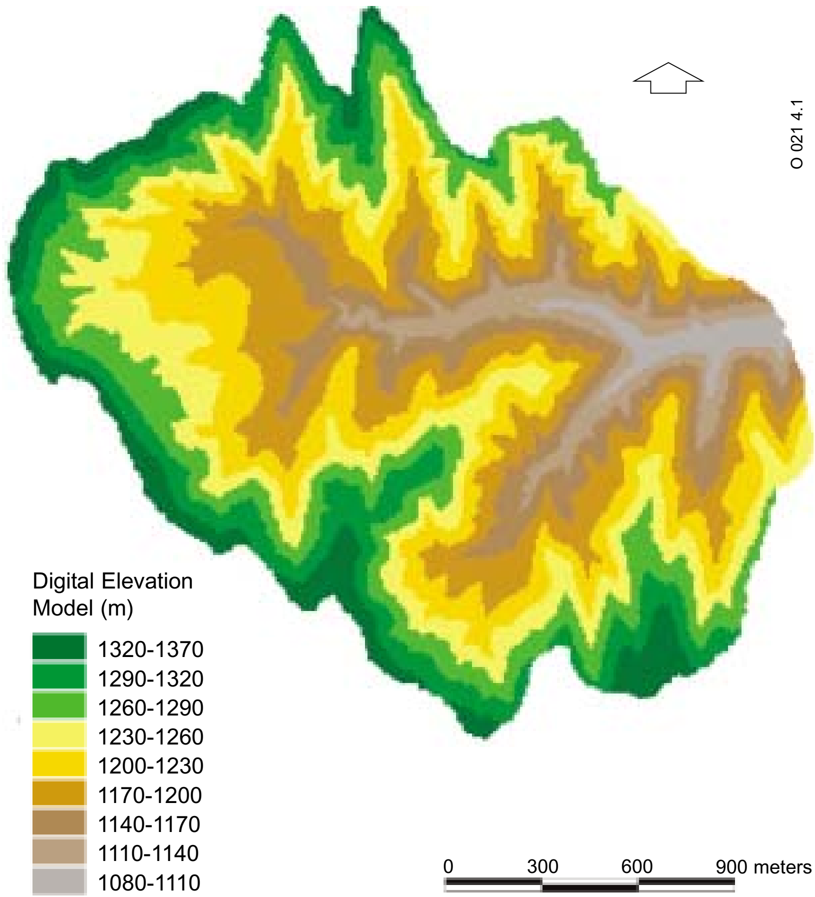

Figure 4 2 Digital elevation map of the study area.

In 1999, land use of the Danangou catchment consisted of 41.4% wasteland/wild grassland, 35.4% cropland (mainly maize, millet, potato and soybean), 13.4% forest/scrub, 7.3% fallow, 2.4% orchard/cash tree and 0.1% vegetables (Hessel et al., 2003a). Average crop coverage was less than 50%, while the wasteland and fallow areas had a vegetation coverage of 33%, the scrub one of 42% and the forest one of 49% (Wu et al., 2003). The farmers treat fallow areas as cropland in spring, but no crop is planted during the season, while wasteland is not subjected to any treatment.

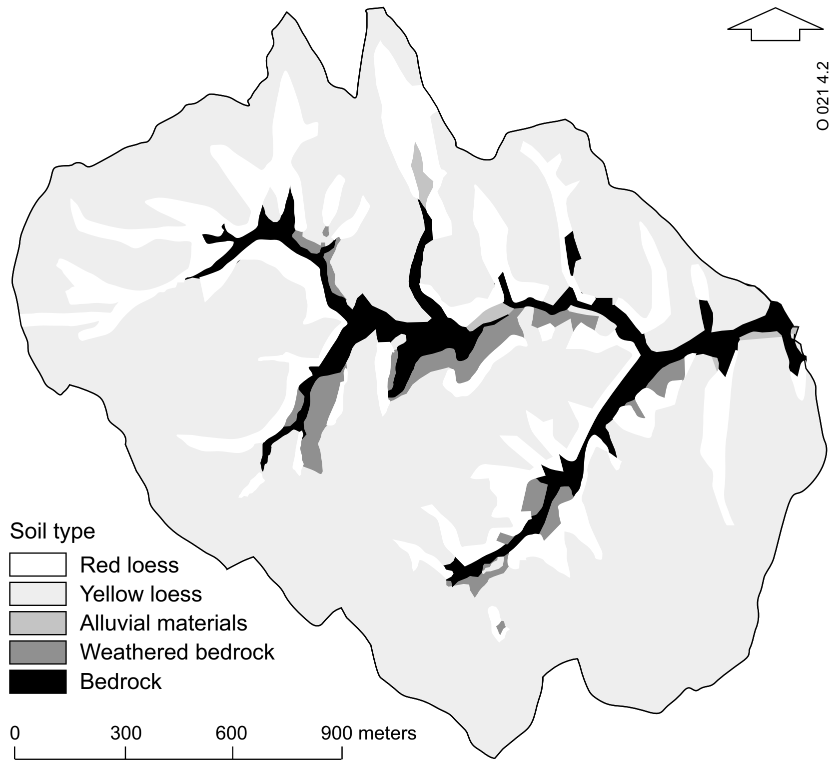

Figure 4.3 Soil map of the study area. The Red loess belongs to the Calcaric/Chromic Cambisols (WRB) and Calcic Ustochrepts/Umbric Fragiochrepts (SSS); the Yellow loess belongs to the Calcaric Regosols (WRB) and Typic Ustorthents (SSS); Alluvial material belongs to Calcaric Fluvosols (WRB) and Typic Ustifluvents (SSS); the (weathered) bedrock belongs to the Calcaric/Lithic Leptosols (WRB) and Lithic Ustorthents (SSS).

4.3.2 Measurements of hydraulic properties

To determine the hydraulic properties of the soil, samples were taken to measure unsaturated conductivity and water retention characteristics, as well as saturated conductivity. Unsaturated conductivity and water retention characteristics were assessed by taking samples from the top soil layer (0- 10 cm) at fields representing the various major types of land use in the catchment, on the assumption that these land-use differences would cause differences in overland flow. The major land use types were cropland (4 samples), orchard (2 samples), wasteland (2 samples), scrub (2 samples) and forest (2 samples). Deeper soil horizons (10 – 20 cm: 4 samples, 20 – 100 cm: 6 samples, taken at 30 cm depth) were measured as well, to provide the model with the necessary input data to solve the Richards equation for flow in unsaturated soils. Sampling was done in duplicate at each field, taking samples 10 cm in diameter and 8 cm high. The sampling cores were carefully closed, sealed and transported to the field station in Ansai City to be measured using the evaporation method (Halbertsma and Veerman, 1994). In this method (Fig. 4.4), the weight of the sample and the pressure head at four depths (1, 3, 5 and 7 cm from top of sample) are measured simultaneously and automatically while the sample is left to evaporate soil water. These measurements were used to calculate each sample's water retention and unsaturated hydraulic conductivity characteristics (Wind, 1968).

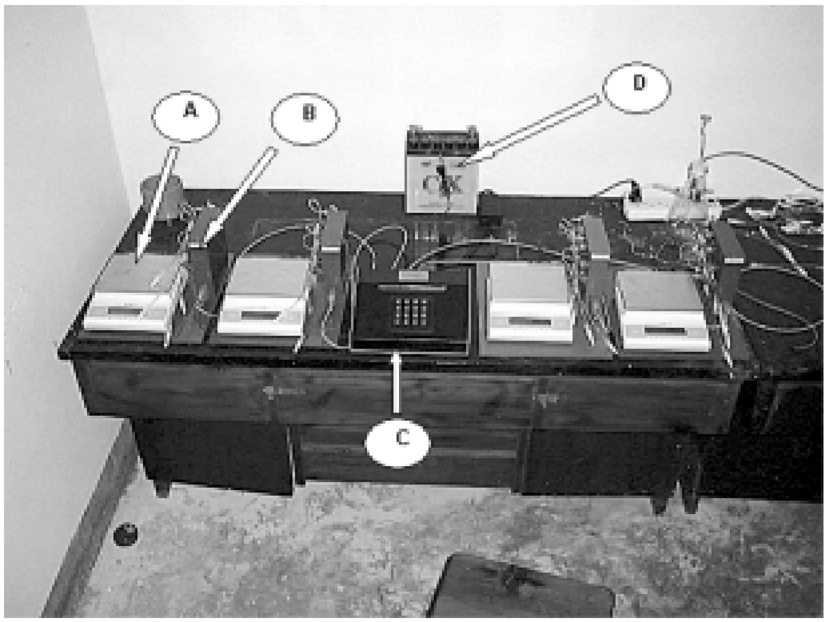

Figure 4.4 Set-up of the evaporation method
A = Balance
B = Pressure transducers module
C = Data logging and control unit
D = Back-up battery

The evaporation equipment allowed four samples to be measured at a time, with a total measurement period per cycle (i.e. four samples) of about two weeks. A fit procedure (Van Genuchten et al., 1991) was used to describe the hydraulic functions with a set of Mualem-Van Genuchten equation parameters (Mualem, 1976; van Genuchten, 1980).

The saturated conductivity measurement was based on a sampling scheme using Simple Random Sampling. Together with other types of probability sampling, this approach to sampling is referred to as the design-based approach (De Gruijter, 1999). In the Simple Random Sampling design, all sample points are selected with equal probability and independently from each other. Sampling was performed on the soil surface of land-use types identified on an overlay of land treatment and plant and soil differences. It was expected that land treatment and plant and soil differences would cause differences in overland flow, as has been shown by Stolte et al. (1996). The land-use types identified in the catchment area and sampled as such included cereal, potato, bean on red and yellow loess; orchards on red and yellow loess; forest on red and yellow loess and wasteland and scrub. The latter were present only on yellow loess. On each of 14 selected fields (each field representing one of the land use types), a 100 m x 100 m square was laid out with 1 m x 1 m grid squares. This sampling grid encompassed most of the field area. Ten sampling spots were selected, using randomly selected x and y coordinates for the grid identification. Soil samples were taken carefully from the surface, causing as little disturbance to the top layer as possible. The samples were transported to a shed owned by a local farmer, where equipment for measuring saturated conductivity had been installed (Fig. 4.5). The samples were saturated, and the constant head method was used to measure saturated conductivity (Stolte, 1997).

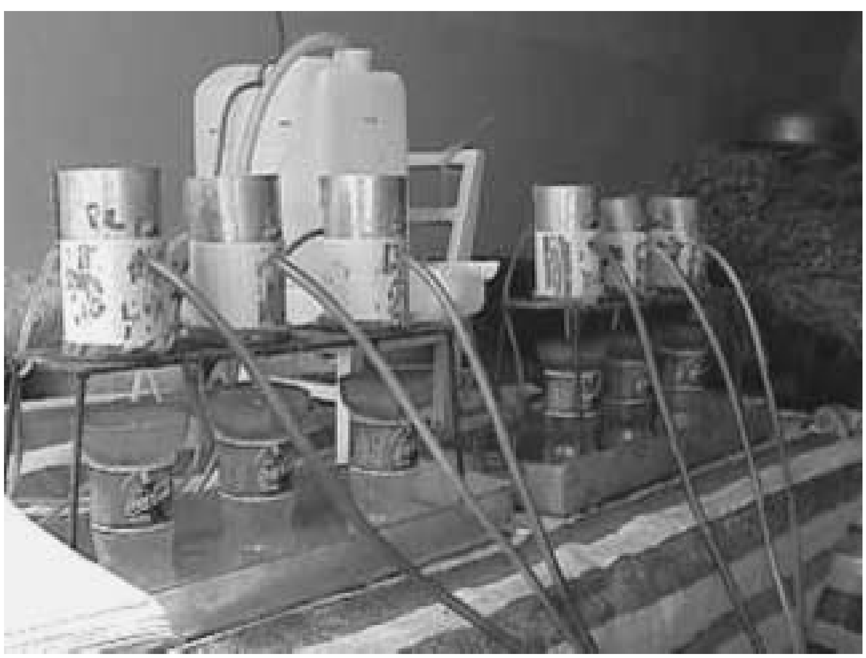

Figure 4.5 Set-up of saturated conductivity measurements.

4.3.3 Calibration on saturated conductivity

A one-factor analysis of variance, followed by Student t-tests (least significant difference method), was used to evaluate the results of the measurements in terms of significant differences between land-use types. Land-use types were merged into physical units if no significant differences were found. For each of the physical units, the geometric mean of the saturated conductivity was calculated, together with the standard deviation. We used a calibration procedure (Hessel et al., 2003c) to optimise the LISEM model results, using fitted saturated conductivity (resulting from the Mualem-van Genuchten fitting procedure on the data from the evaporation method), as well as measured saturated conductivity. Theoretically, the fitted K_s value is too low (since the Mualem-Van Genuchten equations do not take the influence of macro-pore flow into account) while the measured K_s is too high (as a result of soil sample disturbance and cutting through dead-end pores). The 'actual' value of the saturated conductivity (K_s-optimised) lies between these values. Ciollaro and Romano (1995) also recognised that the K factor resulting from the Van Genuchten equation is a model parameter rather than an estimate of the saturated conductivity, and proved it to be smaller than measured K_s. The calibration took place for a single rain event and was based on optimising the calculated hydrograph and sedigraph on the basis of the measured hydrograph and sedigraph (Fig 4.6). Validation was done for four other rain events (Hessel et al., 2003c).

4.3.4 LISEM model

Discharge and sediment losses from the Danangou catchment were simulated using the physically based LISEM soil erosion model (De Roo et al., 1996a). Basic processes incorporated in the model are rainfall, interception, surface storage in micro-depressions, infiltration, vertical movement of water in the soil, overland flow, channel flow, detachment by rainfall and throughfall, transport capacity and detachment by overland flow. The model is one of the first examples of a physically based model that is completely integrated in a raster Geographical Information System. The catchment under study is divided into grid cells of equal sizes. Rainfall and interception by plants are calculated for each grid cell and for every time step, after which infiltration and surface storage are subtracted to give net runoff. Subsequently, splash and flow erosion and deposition are calculated using the stream power principle, and the water and sediment are routed to the outlet with a kinematic wave procedure. Infiltration can be calculated with various sub-models, according to available data. The present study used a finite difference solution of the Richards equation, which included vertical soil water transport and the change

Figure 4.6 Weir at the outlet of the Danangou catchment to measure discharge and sediment concentration. Discharge is measured using an ultra-soon sensor, and sediment concentration using an automatic sampler.

in matrix potential in the soil during a rainfall event. For a detailed background description of the model, the reader is referred to the web page www.geog.uu.nl/lisem/. The sensitivity of the LISEM model to the measured heterogeneity of the saturated conductivity was analysed using the geometric mean and standard deviation of K_s-optimised as input for the various physical units to calculate effects on discharge and soil loss during a single rain event. This rain event took place on July 20, 1999, and produced a total rainfall of 21 mm in 65 min, with a peak intensity of 180 mm/h. This event was also used to calibrate the model (Hessel at al., 2003c). The saturated conductivity measurements took place in the first week of August 1999.

4.4 RESULTS

4.4.1 Hydraulic properties

An example of the results of the evaporation method and the fit procedure is shown in Figure 3.4. The results of the measurements of water retention and unsaturated hydraulic conductivity characteristics are presented in Table 4.1, in the form of Mualem-Van Genuchten equation parameters. In Table 4.1, results of measurements have been assigned to soil layers. It presents the results of the samples that were selected as input in the model. Selection was based on the results of the evaporation method, selecting samples with the largest range of data and the best fit.

Table 4.1 Mualem-Van Genuchten equation parameters of land-use systems and soil layers in the Danangou catchment.

	Layer 0-10 cm					10-20 cm layer	20-100 cm layer
	Cropland	Orchard	Wasteland	Scrub	Forest		
ɗ$_r$†	0.12	0.1	0.1	0.1	0.1	0	0.1
ɗ$_s$	0.425	0.459	0.391	0.35	0.45	0.396	0.35
Ŭ	0.0075	0.0052	0.0067	0.0062	0.0036	0.0059	0.0044
n	1.925	2.7	2.331	3.207	3.058	2.137	2.595
l	0.1	0.5	0.5	0.5	0.5	0.5	0.5
m	0.481	0.63	0.571	0.688	0.673	0.532	0.615
K_s-fit	1	25	0.587	10	13.164	0.922	20

†ɗ$_r$ = residual water content (cm^3/ cm^3); ɗ$_s$ = saturated water content(cm^3/ cm^3); Ŭ, n, l = shape parameters (-); K_s-fit = fitted saturated conductivity (cm/d).

The results of the saturated conductivity measurements are presented in Table 4.2, showing the geometric mean and standard deviation (SD) of the saturated conductivity for each field. The data shown in Table 4.2 indicate that the permanent land-use systems (forest, orchard, wasteland, scrub) showed higher geometric mean K_s values and greater heterogeneity within the system (high SD values) than the arable areas. This is probably due to the presence of more macro-pores (e.g. insect burrows or roots) in the permanent systems than in the arable land, a phenomenon that was also noticed during sampling.

Table 4.2 Geometric means of measured saturated conductivity for several land-use/soil-type combinations in the Danangou catchment. Measurements used the constant head method; sampling sites for each field were selected using Simple Random Sampling.

Soil type	Land use	Crop	Geometric mean K_s-measured (cm/d)	S.D[†] (cm/d)	n[‡]
Red loess	Arable land	Cereal	76.0	34.7	10
		Potato	72.0	20.4	9
		Bean	60.5	16.3	9
		Cereal	60.1	28.2	9
	Orchard		219.0	91.3	10
	Forest		287.5	158.2	10
Yellow loess	Arable land	Cereal	51.5	18.9	10
		Potato	43.4	12.1	5
		Bean	86.4	16.2	9
		Cereal	60.3	12.2	10
	Scrub		163.7	48.6	10
	Orchard		96.9	30.9	10
	Forest		122.1	45.6	10
	Wasteland		153.4	98.7	9

† S.D. = Standard Deviation, ‡ n = number of samples

4.4.2 Land use units

The measured K_s data showed that differences between the geometric means of K_s for a number of field combinations were smaller than the Least Square Difference (Table 4.3). Using this table, it was possible to merge land-use groups into groups that were similar in terms of soil type and land management, as shown in Table 4.4. The statistical analysis of the saturated conductivity resulted in the identification of six physical units within the catchment. These units were forest & orchard on red loess cropland and cereal and potato, bean, orchard, and wasteland, scrub and forest on yellow loess.

Table 4.3 Geometric mean of measured K_s for each field and significant differences between fields at a Least Significant Difference (at 5% level) of 0.3415. X indicates the fields which are significantly different ($|lnK_{si} - lnK_{sj}|$ > l.s.d.).

Soil Type			Red loess				Yellow loess				Red loess		Yellow loess			
	Land use		Cereal 1	Potato	Bean	Cereal 2	Cereal 1	Potato	Bean	Cereal 2	Orchard	Forest	Forest	Waste	Orchard	Scrub
		Mean lnK_s	*4.23*	*4.25*	*4.07*	*4.00*	*3.88*	*3.74*	*4.45*	*4.08*	*5.31*	*5.51*	*4.74*	*4.91*	*4.52*	*5.05*
Red Loess	Cereal 1	*4.23*	-------				X	X			X	X	X	X		X
	Potato	*4.25*		-------			X	X			X	X	X	X		X
	Bean	*4.07*			-------				X		X	X	X	X	X	X
	Cereal 2	*4.00*				-------			X		X	X	X	X	X	X
Yellow Loess	Cereal 1	*3.88*	X	X			-------		X		X	X	X	X	X	X
	Potato	*3.74*	X	X				-------	X		X	X	X	X	X	X
	Bean	*4.45*			X	X	X	X	-------	X	X	X		X		X
	Cereal 2	*4.08*							X	-------	X	X	X	X	X	X
Red Loess	Orchard	*5.31*	X	X	X	X	X	X	X	X	-------		X	X	X	
	Forest	*5.51*	X	X	X	X	X	X	X	X		-------	X	X	X	X
Yellow Loess	Forest	*4.74*	X	X	X	X	X	X		X	X	X	-------			
	Waste	*4.91*	X	X	X	X	X	X	X	X	X	X		-------	X	
	Orchard	*4.52*			X	X	X	X		X	X	X		X	-------	X
	Scrub	*5.05*	X	X	X	X	X	X	X	X		X			X	-------

Table 4.4 Geometric mean of K_s and Standard Deviation for land-use groups that showed no significant differences according to analysis of variance on the measured K_s values.

Soil type	Land use	Geometric mean K_s-measured (cm/d)	S.D[†] (cm/d)
Red loess	Cropland	62.8	26.1
	Orchard and forest	223.7	89.5
Yellow loess	Cereal and potatoes	51.0	16.0
	Bean	86.4	16.2
	Orchard	96.9	30.9
	Wasteland, scrub, forest	134.2	67.4

† S.D. = *Standard Deviation*

4.4.3 Simulations

For the July 20, 1999, event, the calibration procedure proposed by Hessel et al. (2003c) resulted in a ratio between measured and fitted K_s values of 0.15 and 0.85 respectively, calibrating on peak discharge. The same ratio was used in the sensitivity analysis, resulting in a value for K_s-optimised that was considerable lower than that of K_s-measured. The K_s fit was based on the results of the evaporation method, as shown in Table 4.1. The geometric mean of K_s-optimised and its standard deviation were used to calculate discharge and soil loss, to be used as input for the LISEM model. These values are shown in Table 4.5. The spatially varying input data for saturated conductivity given in Figure 4.7 correspond to Table 4.5. The 1999 land-use map is shown in Figure 4.7, together with the derived map of the physical unit groups for the saturated conductivity data.

Figure 4.8 shows the calculated and measured values of discharge, sediment concentration and calculated cumulative sediment load in the Danangou catchment, for the rain event on July 20, 1999, calculated on the basis of the geometric mean of K_s-optimised, plus or minus the standard deviation.

*Table 4.5 Geometric mean of K_s-optimized (= 0.15 * K_s-measured + 0.85 * K_s-fitted) and Standard Deviation of land-use groups*

Soil type	Land use	Geometric mean K_s-optimised (cm/d)	S.D.[†] (cm/d)
Red loess	Cropland	10.3	3.9
	Forest	49.8	18.5
	Orchard	54.8	13.4
Yellow loess	Cereal and potatoes	8.5	2.4
	Bean	13.6	2.4
	Orchard	35.0	4.6
	Forest, Scrub, Wasteland	28.6	10.1

[†] S.D. = *Standard Deviation*

The figure shows that using the 30 – 50% standard deviation of saturated conductivity, led to calculated discharge and total sediment losses varying by ~ 80%. By contrast, using the standard deviation had a minor effect on the calculated sediment concentration. Figure 4.9 shows the on-site effects of the calculated erosion patterns, in terms of the absolute erosion value resulting from the use of the mean value of K_s-optimised, and the differences resulting from the use of the standard deviation. It is clear that using the K_s value minus the SD results in an increase in the level of erosion, while using the K_s value plus the SD results in a significant decrease relative to that obtained using the mean K_s value.

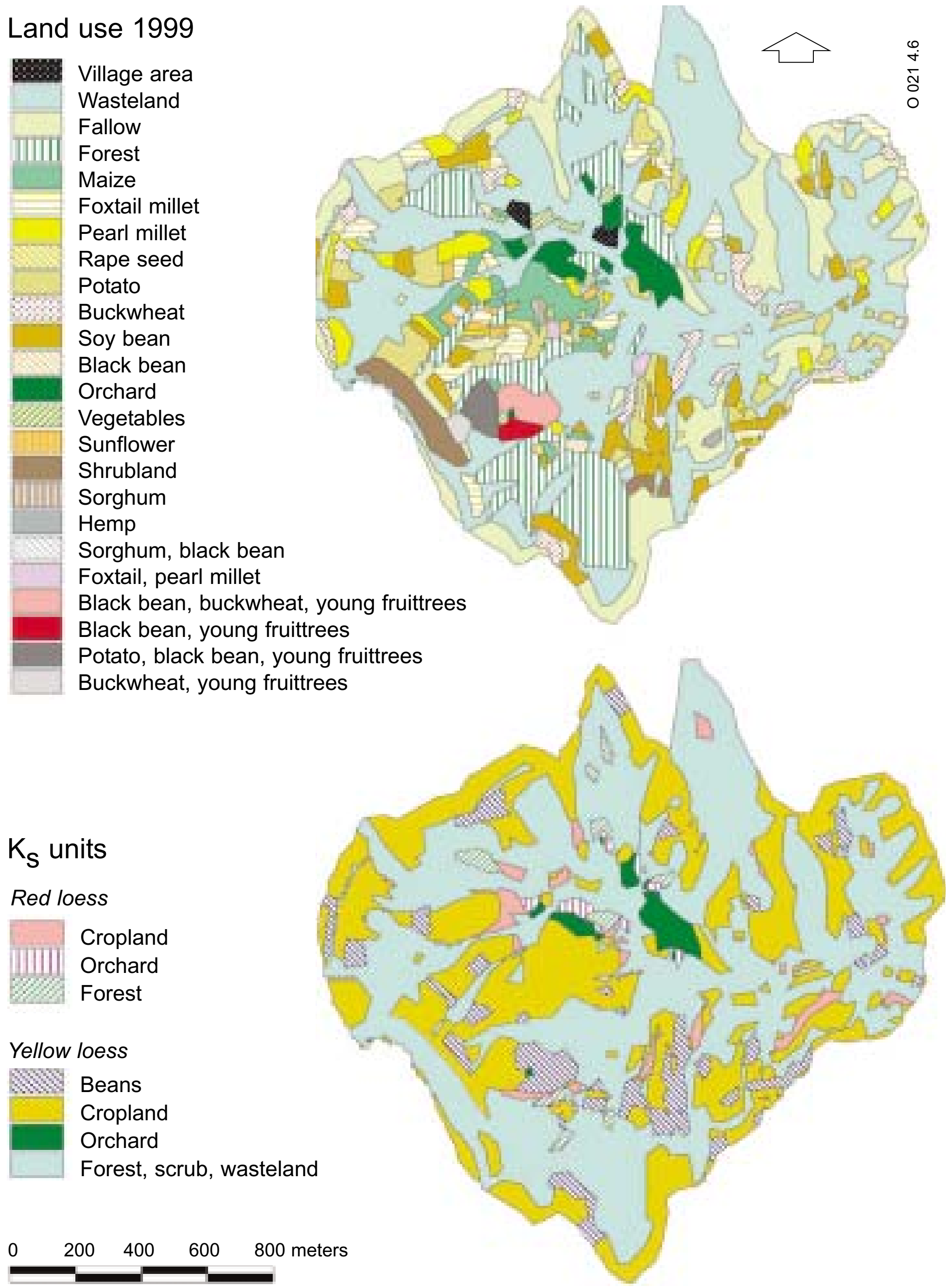

Figure 4.7 Land-use map of the Danangou catchment for 1999 (top) and derived land-unit map for saturated conductivity (bottom).

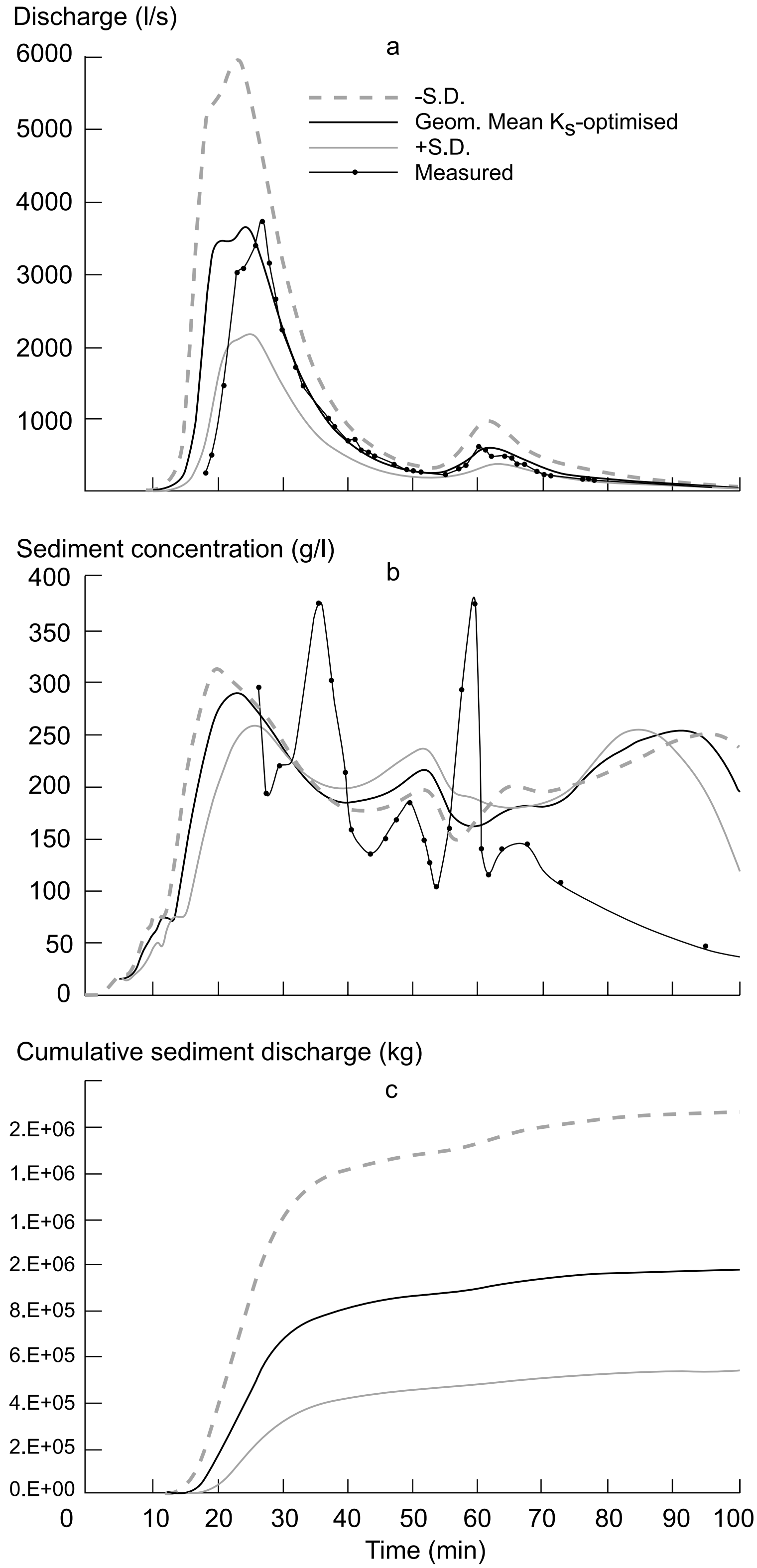

Figure 4.8 Calculated and measured discharge (a), sediment concentration (b) and calculated cumulative sediment load (c) in the Danangou catchment for a rain event on July 20, 1999. Calculation was based on the geometric mean of K_s-optimised, plus or minus the standard deviation.

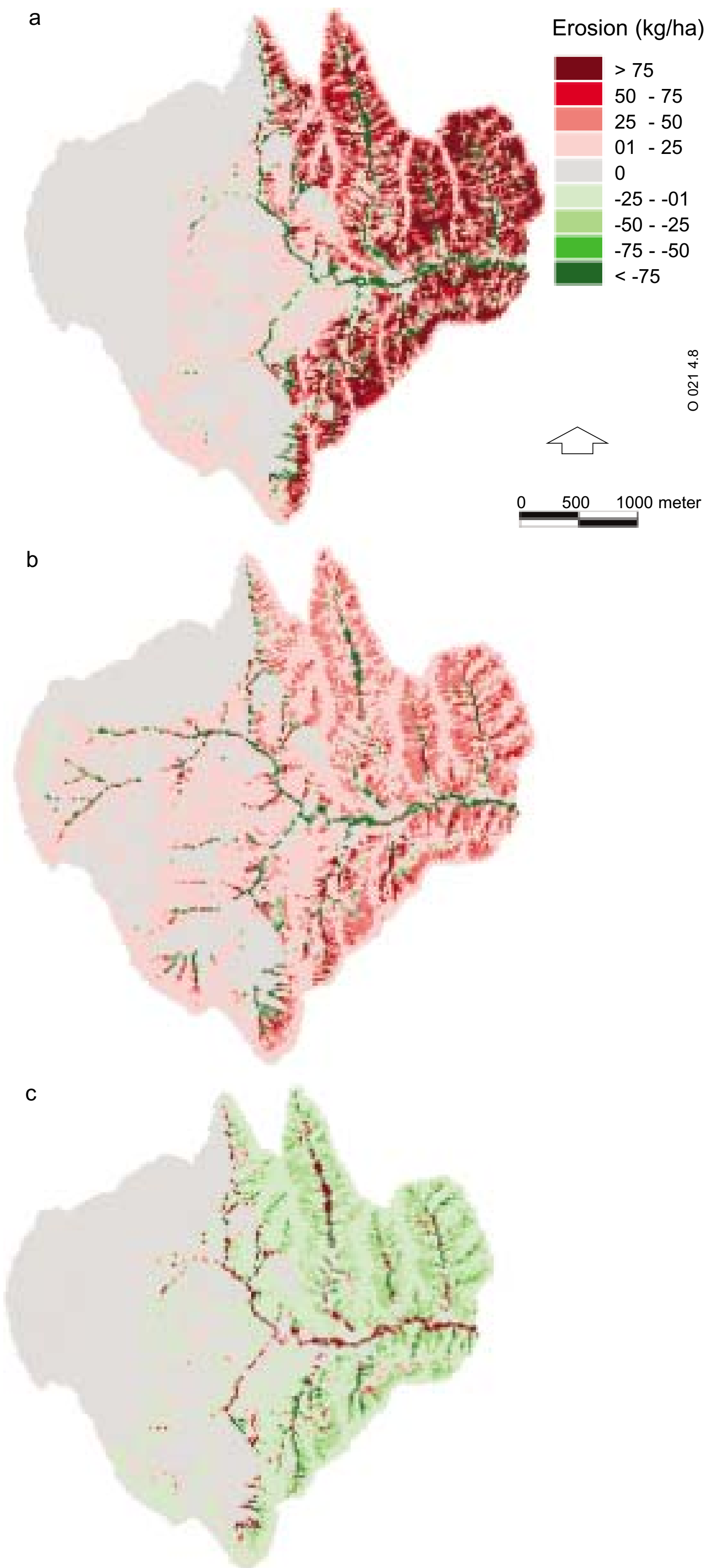

Figure 4.9 Calculated erosion/deposition pattern in the Danangou catchment for a rain event on July 20, 1999, using the mean value of K_s-optimised (a) (green = deposition, red = erosion); difference in erosion/deposition using K_s – S.D. (b) (green = less deposition, red = more erosion) and K_s + S.D. (c) (green = less erosion, red = more deposition).

4.5 DISCUSSION AND CONCLUSION

Saturated hydraulic conductivity proved to be very heterogeneous. Although this had previously been recognised by several other authors (e.g. Russo et al., 1997, Mallants et al, 1997, Mohanty et al., 1994, Lauren et al., 1988), the effect of this spatial variability on soil erosion predictions has rarely been quantified. The procedure carried out in the present study provides a sensitivity analysis of the LISEM model, using the standard deviation of the optimised saturated conductivity. Although the SD of K_s-optimised was much lower than that of K_s-measured, there was nevertheless a considerable effect on calculated discharge and sediment loss. This indicates that considerable effort is required to estimate the saturated conductivity in order to predict the discharge of a catchment. Using randomly selected sampling spots and a calibration procedure, as was done in the present study, makes detailed information on K_s available, which can be used to compare alternative land-use options for their effectiveness in reducing discharge and sediment losses.

There is no indication that the results would have been different if other rainfall events had been used. As is shown in the calibration results by Hessel et al (2003c), the ratio between K_s measured and K_s fitted shows minor differences for different events. That means that differences between the soil physical units remain the same, and hence the outcome of the sensitivity analysis also remains the same. It is only the magnitude of the differences due to different rainfall amounts and intensities which changes.

The present study has shown that saturated conductivity depends on both soil type and land use. This indicates that this value is determined by the texture and structure of the soil. Apart from the bean-field, none of the crop fields on a specific soil type differed significantly from the others. This could be explained from the fact that the same tillage techniques are used for all fields in this area. It is not clear why the bean field on yellow soil showed aberrant values. The fact that orchard and forest are in the same physical unit for the red loess, in contrast to the yellow loess where the orchard is a separate unit, can be explained by the way the field is being used. The orchard on red loess was not tilled, whereas the orchard in the yellow loess area was used for growing vegetables. The finding that every field with the same treatment on a particular soil type generally had the same K_s value shows that a preliminary sampling scheme can be defined to reduce the number of samples.

CHAPTER 5

MODELLING WATER FLOW AND SEDIMENT PROCESSES IN A SMALL GULLY SYSTEM ON THE LOESS PLATEAU IN CHINA

Adapted from:
Stolte, J., Liu, B., Ritsema, C.J., Van den Elsen, H.G.M., Hessel, R. 2003. Modelling water flow and sediment processes in a small gully system on the Loess Plateau of China. Catena, In Press.

5. MODELLING WATER FLOW AND SEDIMENT PROCESSES IN A SMALL GULLY SYSTEM ON THE LOESS PLATEAU IN CHINA

5.1 ABSTRACT

A single gully system was selected in a small agricultural watershed on the Loess Plateau in China with the objective of measuring and then simulating water and sediment transport and defining alternative land uses to reduce discharge and soil loss. The gully had a total length of about 40 m and was about 30 m wide. The watershed feeding the gully covered about 1950 m^2 (including the gully itself). The gully floor sloped by about 32 – 40 degrees, while the gully walls had slopes of 40 to over 60 degrees. Soil water content and water and sediment discharge were measured automatically. The physically based hydrological and soil erosion model LISEM was used to calculate water and sediment discharge. Calibration was carried out for one event, by adjusting the saturated conductivity values. Validation was performed for two additional runoff events. Calibration results showed reasonably comparable hydrographs for measured and calculated discharges. LISEM could be calibrated on the hydrograph quite satisfactorily using saturated conductivity as a calibration factor. Validation of LISEM for two other runoff events also showed reasonably good results, as did the calibration on total soil loss. Results of the validation runs for soil loss were poor, probably due to limitations of the measuring equipment and the incapability of the model to simulate small events. Scenario analyses showed that forest as an alternative land-use option for the gully floor will result in significantly smaller water and sediment losses. This strongly supports the implementation of the reforestation policy recently suggested and implemented by the central government of the People's Republic of China.

5.2 INTRODUCTION

On the Loess Plateau in China, soil erosion totals between 10 000 and 25 000 tons/km^2 per year (Zhang et al., 1998). Of this quantity, 73% enters the Huang He (Yellow River), causing huge sedimentation problems and flooding risks downstream. The numerous gullies and gully systems on the Loess Plateau are important sediment sources. Zhang et al. (1998) showed that ~ 8000 – 10 000 tons/km^2 per year are lost from cultivated areas, indicating that much of the sediment originates from gully slopes.

Based on aerial photographs, Vandaele et al. (1996a) concluded that ephemeral gully erosion is an important and dominant sediment source in cultivated catchments in central Belgium and Portugal. From published data and their own research, Poesen et al. (1996) concluded that gully erosion contributes significantly to sediment yield in small agricultural catchments in Europe and North America. As most soil loss equations do not explicitly include gully erosion rates (Vandaele et al., 1996b), there is a need for a critical review of the use and accuracy of current soil erosion models for gullied areas. Ongoing studies are examining the modelling of gully head initiation (e.g. Dietrich et al., 1993). Additionally, attempts are ongoing to include gully and rill erosion processes in soil erosion models (e.g. Huang and Bradford, 1993; Vandaele et al., 1996b; Desmet and Govers, 1997; Bryan et al., 1998).

The EROCHINA project aimed to develop alternative land use and soil and water conservation strategies for the Loess Plateau, by combined use of land evaluation and soil erosion modelling techniques (Ritsema, 2003). The present study specifically aimed at (i) calibrating and validating a hydrological and soil erosion model for a typical gully area on the Loess Plateau in China, (ii) identifying the applicability of the model, and (iii) defining and evaluating effects of alternative land-use options for such a gully area in reducing losses of water and soil.

5.3 MATERIALS AND METHODS

5.3.1 Gully description

The study area (Danangou Catchment) is located in the central part of the Loess Plateau in northern Shaanxi Province (Fig. 1.2). A typical gully was selected within the chosen watershed (Fig. 5.1). The gully had a total length of ~40 m and was ~30 m wide. The watershed feeding the gully covered an area of ~1950 m^2 (including the gully itself). The gully floor sloped by ~32 – 40 degrees, while the gully walls had slopes of 40 to > 60 degrees. Land use at the gully's watershed consisted of arable land above the gully, and bare land with some grass and small shrubs in the gully. The gully was situated at the upper part of a steep slope. Soil type was a soft-yellowish silty loess, locally called Huangtu (Messing et al. 2003), and classified as a Typic Ustorthents in the Soil Survey Staff (1992) system and as a Calcaric Regosols in the WRB (1998) reference system. The gully seems to be inactive, with some development of small (ephemeral) gullies (Poesen and Govers, 1990) in the gully floor. Farmers are not tilling the gully floor, and it seems most likely that these ephemeral gullies will progressively enlarge, as was observed over the two years of the field survey. Furthermore, some small incisions occur near the gully head and its immediate surroundings, and there is evidence of piping in one of the gully walls.

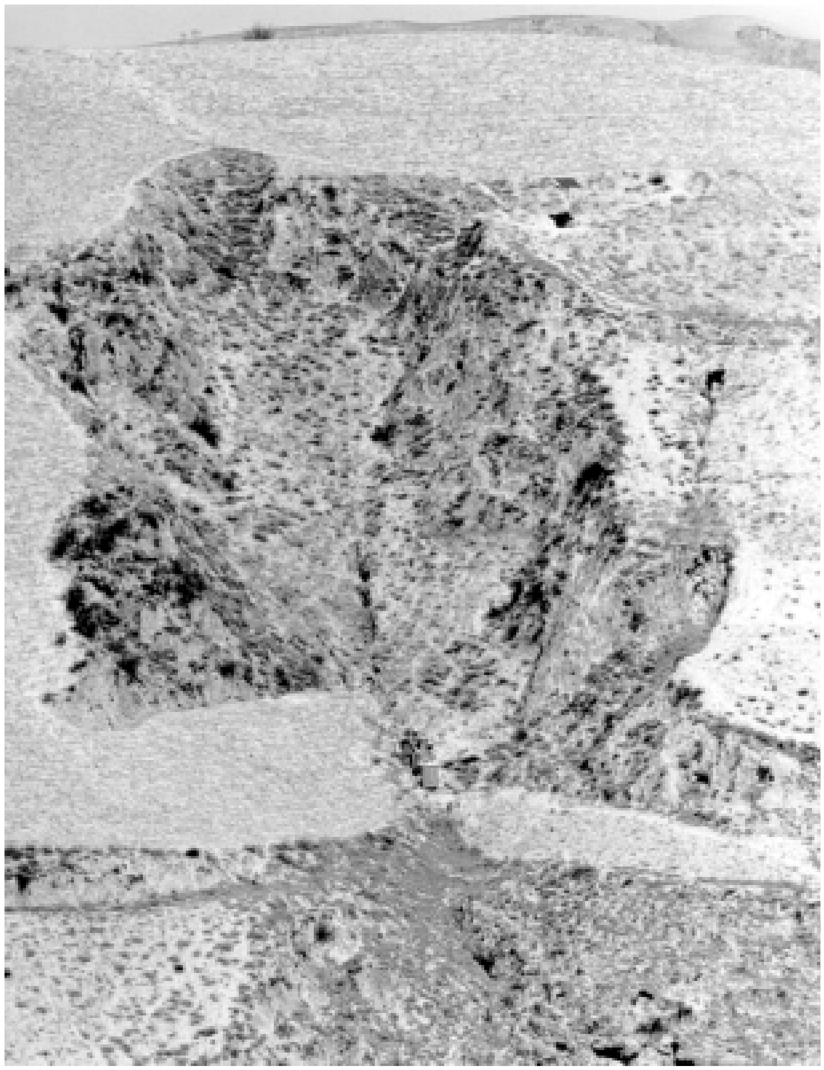

Figure 5.1 Gully system used to measure and calculate water and sediment discharge

5.3.2 Field measurements

In the entire gully system, 29 TDR sensors were installed at various positions and depths to monitor soil water content changes over time, and a flume was constructed at the outlet for automatic measurement of the water and sediment discharges (Van den Elsen et al., 2003a). The flume consisted of an ultra-sonic sensor to measure water height, and a turbidity sensor to measure sediment concentrations (Fig. 5.2).

Figure 5.2 Flume at the outlet of the gully catchment to measure discharge and soil loss

During the three years of measurements, maximum sediment concentrations were > 100 g/l (the upper limit of detection). The maximum rain intensity was 180 mm/h, and the maximum peak discharge was 65 l/s, a discharge which occurred on July 20, 1999. During the three years, soil surface and plant parameters were measured on a two-weekly basis at representative fields in the Danangou Catchment (Wu et al., 2003, Liu et al., 2003). One of these representative fields was the field above the gully. Soil hydraulic data (Stolte et al., 2003) were also collected from the representative fields and from a comparable gully system. Other soil physical data has been presented by Messing et al. (2003) and is summarised in Table 5.1. These field measurement activities resulted in a database containing time-dependent information on soil and plant characteristics.

Table 5.1. Soil data of the top- and subsoil in the Danangou catchment (after Messing et al., 2003)

	Topsoil	Subsoil
Sand (%)	16.5	14.4
Silt (%)	65.6	68.9
Clay (%)	17.8	16.8
pH	8.84	8.92
OM (%)	0.52	0.27
Available P ($mg.kg^{-1}$)	1.4	0.7
Total P (%)	0.056	0.056
Available N ($mg.kg^{-1}$)	22.6	13.5
Total N (%)	0.034	0.020

5.3.3 LISEM model and input

This data served as input for the physically based hydrological and soil erosion model LISEM (De Roo et al., 1996a), which was used to calculate water and sediment fluxes from the gully system. The model calculates water and sediment transport processes during a single rain event within a catchment, on a grid cell basis. Figure 5.3 shows the flow diagram for the model, including processes and parameters. Basic processes incorporated in the model are rainfall, interception, surface storage in micro-depressions, infiltration, vertical movement of water in the soil, overland flow, channel flow, detachment by rainfall and throughfall, transport capacity and detachment by overland flow. A more detailed description of the LISEM model is given in 4.3.4.

Elevation measurements at the gully were carried out using GPS, and the resulting data was used to construct a Digital Elevation Model with a grid cell size of 0.25 m (Figure 5.4). This map, together with the land-use and soil maps and the database with time-dependent information on soil and plant characteristics, formed the basis for the model input. The initial soil water contents before a rain event were derived from the automated TDR sensors, and from the two-weekly manual water content measurements on representative fields (Qiu et al., 2003).

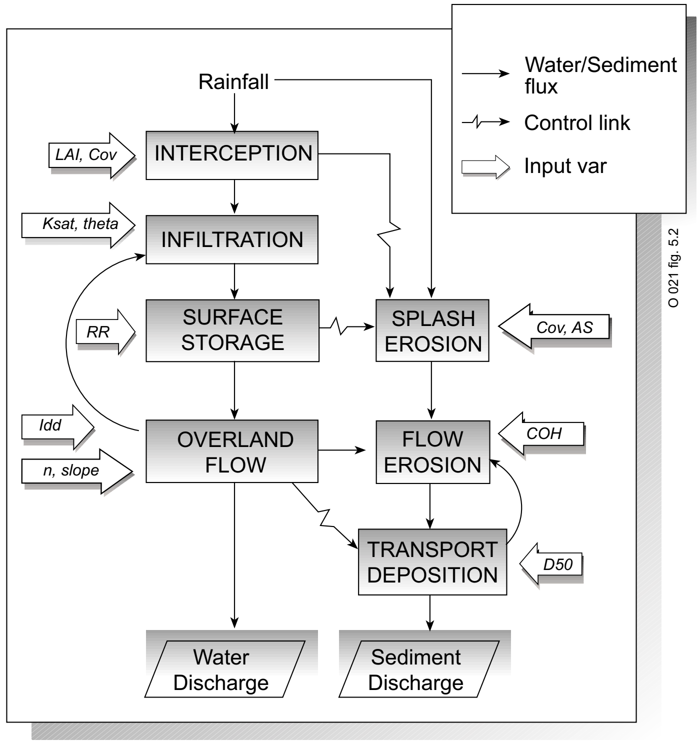

Figure 5.3 Diagram of the processes in the physically based hydrological and soil erosion model LISEM. LAI = Leaf Area Index; Cov = plant coverage; K_{sat} = soil hydraulic properties; theta = initial soil water content; RR = random roughness; ldd = drainage direction; n = Manning's n coefficient; slope = slope gradient; AS = aggregate stability; COH = cohesion of the soil; D50 = median texture of the sediment.

5.3.4 Model calibration, validation and application

The model was calibrated for a rain event on August 1, 1998 and validated for rain events on August 23, 1998 and July 20, 1999. These events differed in the total amount of precipitation (a total of 16.4 mm for the August 1, 1998 event, 17.1 mm for August 23, 1998 and 28 mm for July 20, 1999), in intensity (a maximum of 144 mm/h for August 1, 1998, a maximum of 111 mm/h for August 23, 1998 and a maximum of 160 mm/h for July 20, 1999) and in initial water content (the soil being dry at the start of the 1998 events and wet from the previous day's precipitation at the 1999 event).

A sensitivity analysis on the LISEM model (De Roo et al., 1996b) showed that the model is very sensitive to saturated conductivity. In this analysis, the values of several parameters were altered by 20% to assess the effect on peak discharge, total discharge and soil loss. These changes in saturated conductivity resulted in a change in the model outcome of ~ 50% for the total discharge calculations and > 60% for peak discharge calculations. A similar sensitivity was found by Stolte et al. (2003), who used the standard deviation of calibrated values to calculate the saturated conductivity and found differences in model outcome of ~ 80% for both total and peak discharge.

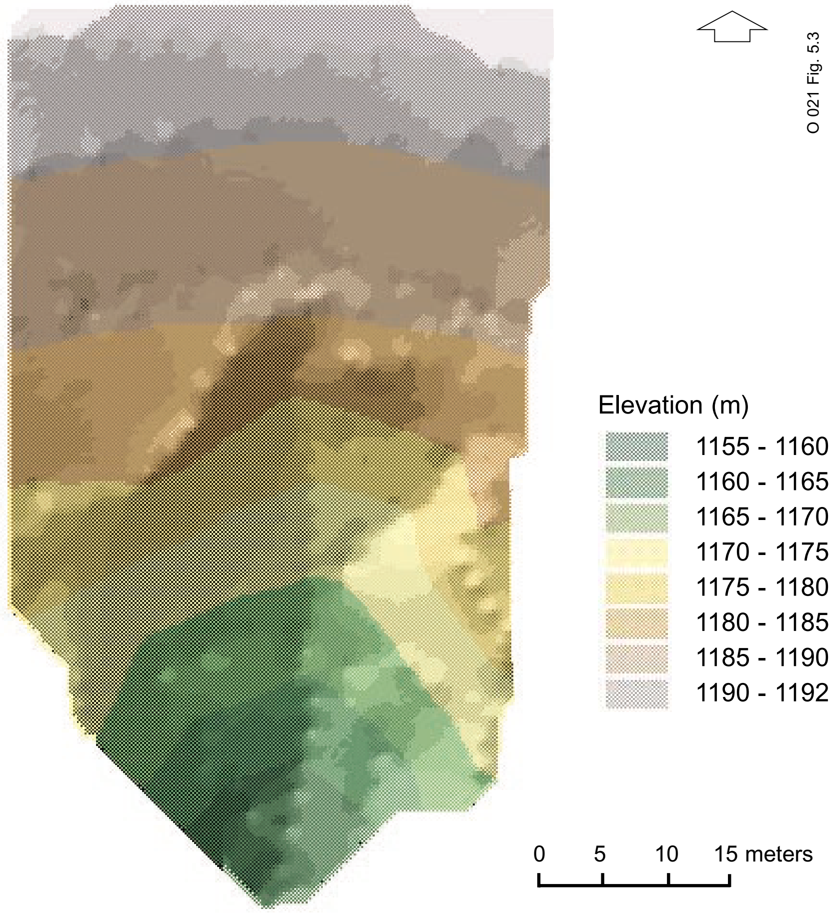

Figure 5.4 Digital Elevation Model of the watershed of the gully. Grid cell size is 0.25 m and relative relief is 40 m.

The model was calibrated for the gully system by optimising the saturated conductivity, using the measured results and the fitted value of saturated conductivity. The fitted value is an extrapolation of the measured data of unsaturated conductivity, which was obtained using the evaporation method (Halbertsma and Veerman, 1994). The evaporation method measures water retention and hydraulic conductivity simultaneously. The resulting data was used to calculate the hydraulic properties of the sample (Wind, 1968). A set of Mualem-Van Genuchten parameters (Mualem, 1976; Van Genuchten, 1980) was fitted to the data using the RETC computer program (Van Genuchten et al., 1991). One of the parameters is the fitted saturated hydraulic conductivity. Theoretically, the fitted value is too low, as it does not take macropore flow into account, while the measured value is too high because sampling causes dead-end pores to be cut and so to contribute to the flux. The calibrated saturated conductivity is within these two values (Stolte et al., 2003). The next step in the calibration procedure was the calibration on the sediment, using cohesion to optimise model outcome. Although cohesion was measured, the results showed great variability within land-use units and a strong temporal heterogeneity (Liu et al, 2003.).

The LISEM model was specifically developed to analyse effects of alternative land uses on discharge and soil losses. In the EROCHINA project, alternative land uses have been proposed and analysed for the entire Danangou Catchment (Hessel et al., 2003a, Chen et al., 2003). The most promising alternative thus defined has been implemented in the gully system to evaluate its possible effects on reducing discharge and soil losses. The scenario analyses for the entire Danangou Catchment showed forest to be the best solution in terms of soil conservation (Hessel et al., 2003a). The land-use option used for the gully system in the present study was therefore afforestation on the gully floor. Implementing forest on the gully floor will change the vegetation, soil surface and soil physical properties in the LISEM input maps. Forests in the loess area are characterised by a more structured surface soil, resulting in higher saturated conductivity values. All other land uses within the gully system (i.e. cropland above the gully) were kept unchanged. The events of August 1, 1998 and July 20, 1999 were used to evaluate the effects of the alternative land-use option, because these events differed most in their maximum intensity and initial soil moisture levels.

5.4 RESULTS

5.4.1 Model calibration and validation

The calibration of the model outcome on measured discharge resulted in optimised saturated conductivity values which showed that a ratio of 75% K_s-fitted and 25% K_s-measured had to be used to calibrate the model outcome (Table 5.2). Figure 5.5 shows results of measured and calculated water discharge, and Figure 5.6 shows the sediment load of the August 1, 1998 event, using the optimised K_s and cohesion values. The shape and height of the calculated hydrograph are in reasonable agreement with the measured hydrograph, except for the two peaks in the measured hydrograph. A similar conclusion can be drawn for the sediment load, with calculated sediment load approximating the measured load.

*Table 5.2. Measured, fitted and optimized saturated conductivity of soil layers for the gully system. The optimized saturated conductivity is calculated using 0.75 * K_s-fitted + 0.25 K_s-measured.*

Land use	Depth (cm)	K_s measured (cm/d)	K_s fitted (cm/d)	K_s optimized (cm/d)
Gully floor	0 – 20	15.0	0.9	4.4
Gully slope	0 – 20	76.5	0.9	19.8
Cropland	0 – 10	60.0	5.0	18.7
Cropland	10 – 20	60.0	0.9	15.7
Deeper layers	> 20	70.6	20	32.7

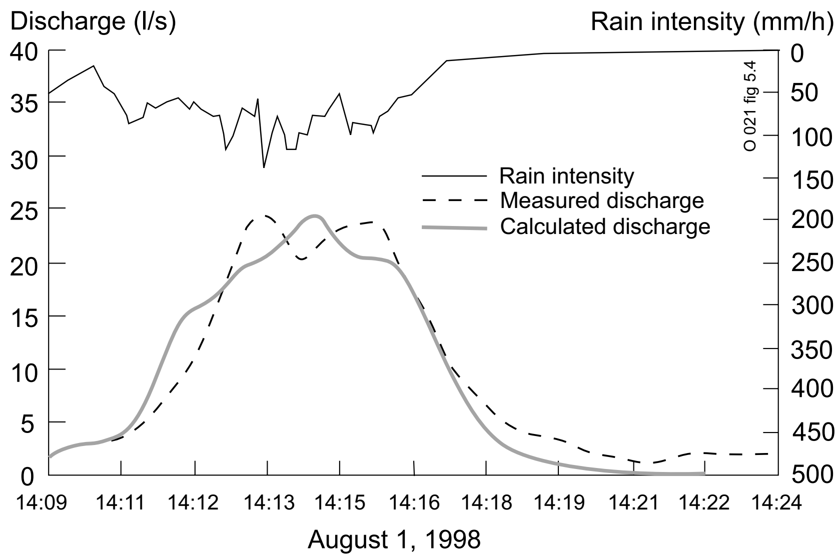

Figure 5.5 Measured and calculated water discharge in the gully watershed for the August 1, 1998 event.

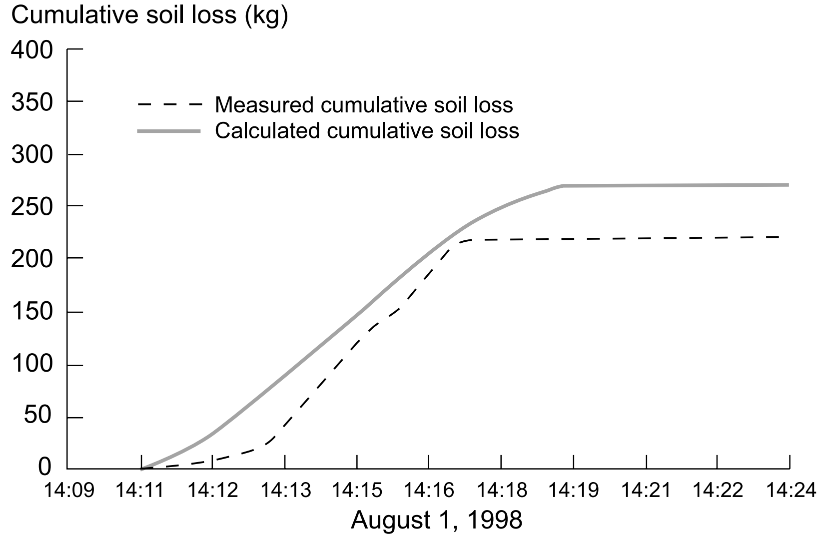

Figure 5.6 Measured and calculated soil loss in the gully watershed for the August 1, 1998 event.

Figures 5.7 and 5.8 show the results of the validation run for the July 20, 1999 event. All input data for plant and soil surface characteristics are derived from the measured data, and the calibration ratios between measured and fitted saturated conductivity and for cohesion were the same as those used for the calibration event. The general shape and timing of the hydrograph (Fig. 5.7) are reasonably comparable, except for the start of the event, where the model calculates a peak that was not measured. The sediment load shows poor validation results (Fig. 5.8),

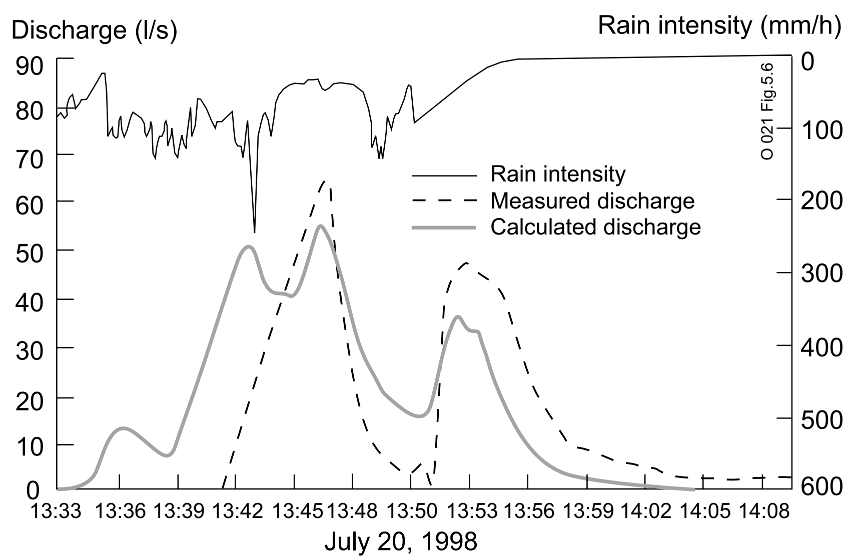

Figure 5.7 Measured and calculated water discharge in the gully watershed for the July 20, 1999 event.

probably because the real sediment concentration exceeded the measurement range of the turbidity sensor (100 g/l), making it difficult to calculate the total soil loss.

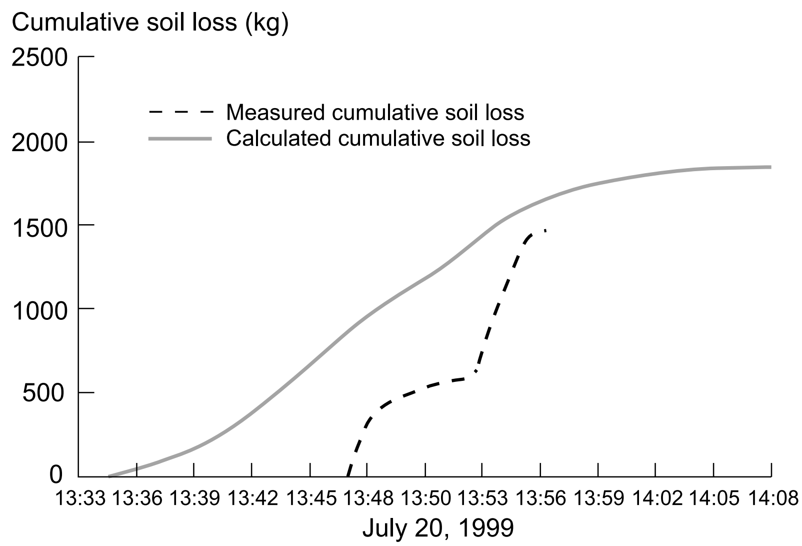

Figure 5.8 Measured and calculated soil loss in the gully watershed for the July 20, 1999 event.

Figures 5.9 and 5.10 show the results of the validation for the August 23, 1998 event. They show the same effect as seen in the July 20, 1999 event. The model calculates a peak discharge at the start of the event, while the measurement equipment does not detect any discharge at that moment. A major difference between this event and the other two events is the low discharge. Although the total rainfall exceeded that of the August 1, 1998 event, the measured peak discharge was only 25% of that in the August 1 event. This is explained by the lower rainfall intensity of the August 23 event (max. 111 mm/h versus 144 mm/h). The total soil loss calculation (Fig. 5.10) shows very poor results, probably because of the low discharge. The model tends to calculate high sediment loads at relatively low discharge, and decreases the sediment concentration when the discharge increases.

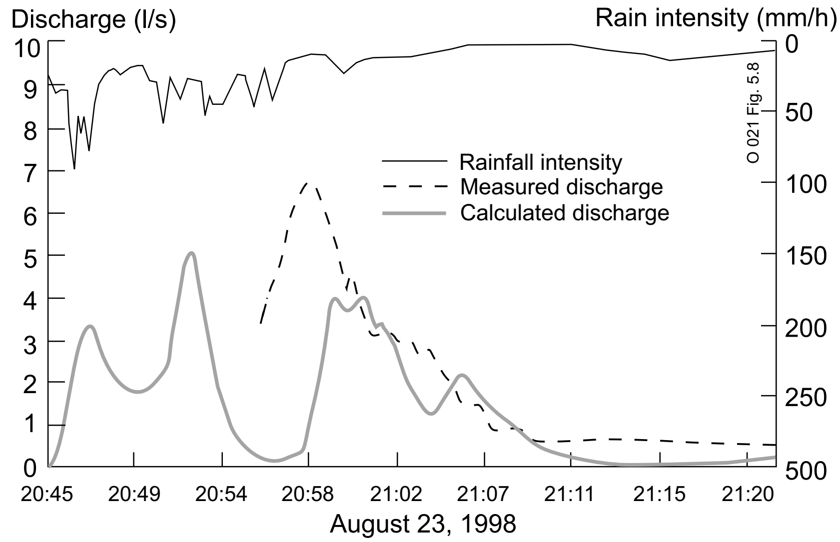

Figure 5.9 Measured and calculated water discharge in the gully watershed for the August 23, 1999 event.

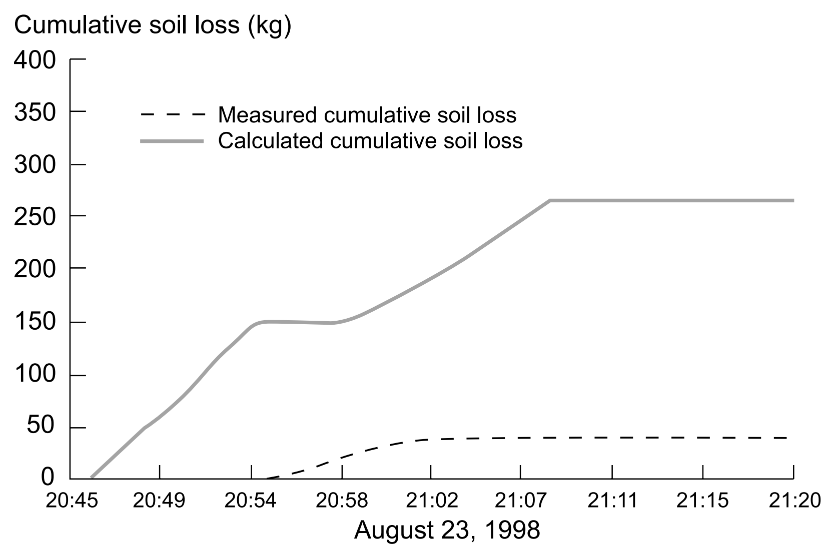

Figure 5.10 Measured and calculated soil loss in the gully watershed for the August 23, 1999 event.

5.4.2 Alternative land use

The results of the calibration and validation runs show that most sediment is generated at the gully floor (Figs. 5.11a and 5.12a). Alternative land use will thus be most effective in this area. Results of the calculations based on current land use and forest on the gully floor for the two rain events are given in Table 5.3, which shows that forest reduces the total soil loss considerably (from about 50 % for the 1999 event to almost 100 % for the 1998 event). The effect of the soil loss reduction is visualised in Figures 5.11 and 5.12, the erosion maps. These maps represent the net erosion of an event. The figures show that the main source of sediment (i.e. the

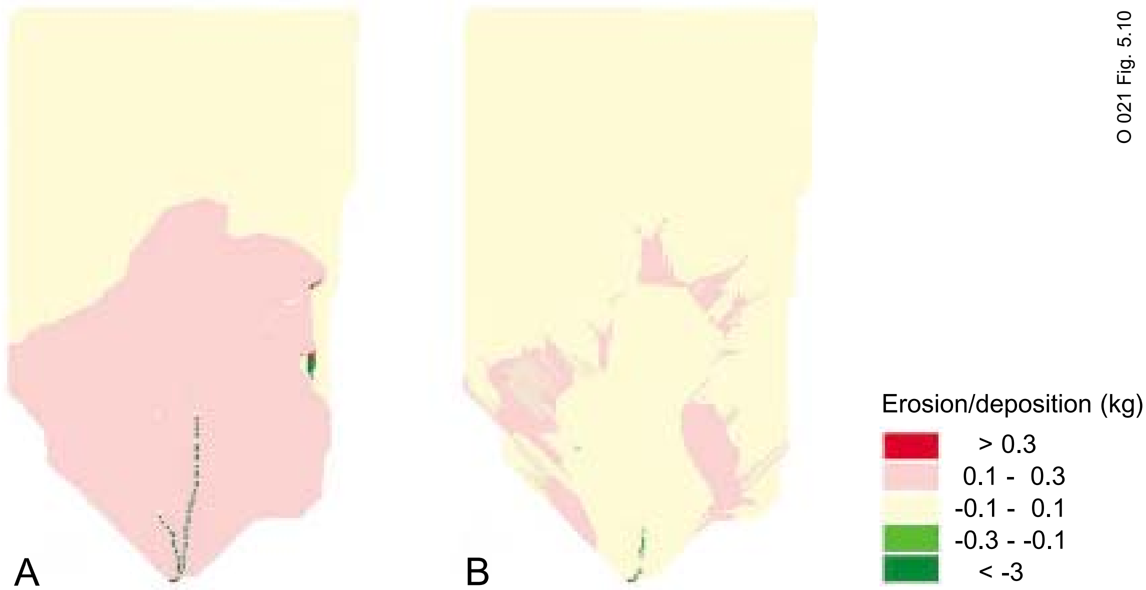

Figure 5.11 Computed erosion maps of the gully watershed for the August 1, 1998 event, for current land use (A) and with forest on the gully floor (B).

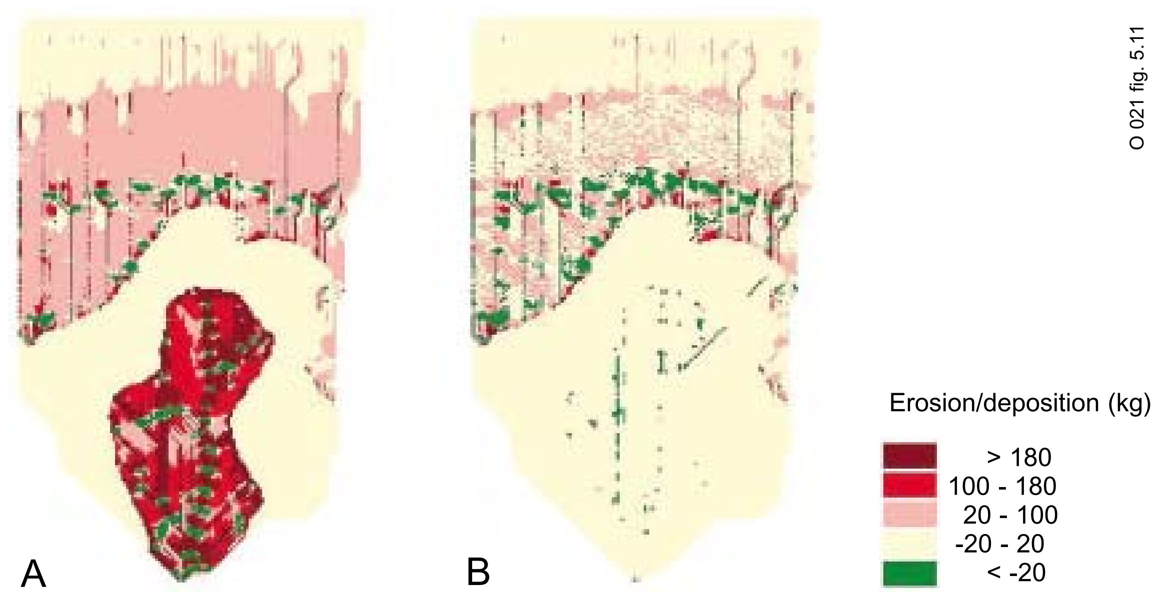

Figure 5.12 Computed erosion maps of the gully watershed for the July 20, 1999 event, for current land use (A) and with forest at the gully floor (B).

gully floor) is stabilised by trees. The erosion maps for the 1999 event show a heterogeneous pattern, probably caused by small differences in grid cell characteristics (i.e. by the accuracy of the Digital Eleveation Model). No such heterogeneous pattern can be seen for the 1998 event, because the area contributing to the soil loss in this event is very small (only the bottom part of the gully). The discharge is only reduced for the 1998 event. During the 1999 event, the soil profile was almost saturated prior to the rain event, so there were no differences in total infiltration between the current situation and forest scenarios at the gully floor.

Table 5.3. Calculated discharge and soil loss results, for current land use and forest at the gully floor, for two rain events.

Event	Land use	Peak discharge (l/s)	Discharge/rainfall (%)	Total discharge (m^3)	Total soil loss (tonnes)
August 1, 1998	Current	24.2	26.3	8.4	0.41
	Forest at gully floor	11.6	12.1	3.9	0.005
July 20, 1999	Current	55.0	58.5	50.9	5.6
	Forest at gully floor	40.0	53.1	34.8	3.4

5.5 DISCUSSION AND CONCLUSION

The shape of the gully, and especially its steep walls and sloping floor, make the use of standard physical equations uncertain, as most are only valid for gentler slopes. Despite this limitation, LISEM could be calibrated on the hydrograph quite satisfactorily, using the saturated conductivity as a calibration factor. The validation of LISEM for two other runoff events also yielded reasonably good results, as did the calibration on total soil loss. Results for the validation runs for total soil loss, however, were poor. This is partly due to the measuring equipment used. The turbidity sensor had an upper limit of 100 g/l, whereas the real concentration exceeded this value at least during the July 20, 1999 event. Another factor that might explain the difference between measured and calculated soil losses during the validation events is the use of automated equipment. The thresholds of the program controlling the equipment have to be defined in such a way that a limited number of measurements are done (since there would otherwise be too much data to handle), while at the same time all relevant data are captured. In the example of the July 20, 1999 event, the start of the event has apparently been missed by the equipment. A great deal of rain fell during the first five minutes (when measurements are made at a frequency of 5 min), and this probably produced considerable discharge, which has been missed by the measuring equipment. After a certain discharge has been measured, the measuring frequency is increased to every 30 sec (Van den Elsen et al., 2003a), so that more accurate measurements are performed. The third possible explanation of the difference between measured and calculated sediment loads is that the model calculates high concentrations at low discharge levels, which is particularly important at events with relatively low discharge and indicates that the model is not capable of simulating small discharges.

The number of replicates we used to test the LISEM model was limited, while the diversity of gullies on the Loess Plateau is considerable. Hessel & Van Asch (2003) describe the different typologies of gullies in the Danangou catchment (Fig 5.13).

In comparison with other gully typologies, the gully we studied is morphologically representative, but inactive, the only sediment source being a small rill in the gully floor. Taking these considerations into account, it can be concluded that the LISEM model is useful to calculate water movement in steep single gully systems, and sediment loss for inactive gully systems. The model starts producing unreliable results for sediment load at low discharges, as was shown for the August 23, 1998 event. This strengthens the conclusion that the model's results for both discharge and soil loss improve with higher discharge levels, which is in line with the conclusions of other studies (e.g. Hessel et al., 2003c).

With the current land-use situation in the gully system, most sediment originates from the floor of the gully. This means that soil and water conservation strategies should be designed mainly for this area. Scenario analyses showed that forest as an alternative land use for the gully floor would result in significantly smaller water and sediment losses compared with the current situation. This strongly supports the implementation of the reforestation policy, as recently suggested and implemented by the central government of the People's Republic of China.

Figure 5.13 Typical yellow loess gullies, according to the Hessel and Van Asch (2003) typology, in the Danangou catchment.

CHAPTER 6

DEVELOPING INTERACTIVE LAND-USE SCENARIOS IN CHINA AND PRESENTING RISK ANALYSES AS NEGOTIATION TOOLS

Adapted from:
J. Stolte, Ritsema, C.J., Bouma, J. Developing interactive land-use scenarios in China and presenting risk analyses as negotiation tools. Submitted for publication in Agriculture, Ecosystems & Environment

6. DEVELOPING INTERACTIVE LAND-USE SCENARIOS IN CHINA AND PRESENTING RISK ANALYSES AS NEGOTIATION TOOLS

6.1 ABSTRACT

This study aimed to develop a negotiation procedure for defining land-use scenarios to reduce soil and water losses. It focused on methods to present stakeholders with potential effects of land-use change to be used in a negotiation process, emphasising risk analysis and economic impacts. We quantified the effect of various land-use scenarios on the expected rate of discharge and sediment loss during a single rain event in a small agricultural watershed on the Loess Plateau in China, using the geometric mean and stochastic distributions of measured field K_s values. Land-use scenarios were based upon physical, economic and agricultural interests, and effects on farmers' incomes were evaluated using empirically derived equations. A physically-based hydrological and soil erosion model was used to quantify the effects of land use on discharge and soil loss. Using geometric mean values of K_s as the model input resulted in higher values for runoff coefficients and total soil loss compared with the use of stochastic K_s values. The use of stochastic K_s distributions resulted in a range of model outcomes reflecting the effect of spatial heterogeneity on simulated discharge and soil loss. The conservation-driven scenario was most effective in reducing water and sediment losses by runoff and erosion, followed by the soil-specific scenario and the agriculture-driven land-use scenario. Only the agriculture-driven scenario resulted in a small increase in household income, while a serious loss of income is predicted for the other scenarios. The form in which the results are presented provides policy-makers with information on plausible effects of various alternatives on conservation, and as such provides a powerful negotiation procedure for defining land-use alternatives.

6.2 INTRODUCTION

Erosion modelling as a tool to quantify effects of alternative land-use options requires knowledge of local biophysical parameters. These parameters have been found to have various effects on model outcomes. Spatial variability of soil hydraulic conductivity is important in soil erosion studies (e.g. Springer and Cundy, 1988). The adoption of physically based infiltration models as components of watershed models has been hampered by the problem of spatial variability of infiltration parameters (Woolhiser and Goodrich, 1988). Freeze (1980) concluded that the distribution of hydraulic conductivity in a watershed should be included in parametric representations of the unit hydrograph, in conceptual predictions of flood exceedance probabilities and in any physically based assessment of the autocorrelation structure of streamflows. De Roo et al. (1992) concluded that a combination of Monte Carlo procedures and hydrological model simulations provides useful information on the influence of the spatial variability of saturated infiltration rate on model outcome. Based on the results of their study, Séguis et al. (2002) concluded that it is desirable to describe K_s in semi-distributed models as a log-normal random variable by its means and variation coefficient over each spatial model unit, rather than by a single uniform value. Taking these recommendations and considerations into account, a detailed investigation of the heterogeneity of the saturated conductivity and the implications for model outcomes was carried out. So far, studies on this subject have concentrated on the effect of a hypothetical heterogeneity of infiltration parameters on model outcome (e.g. Smith and Hebbert, 1979; Woolhiser and Goodrich, 1988; Séguis et al., 2002), or on quantifying the field heterogeneity of the infiltration rate (e.g. Cassel and Nelson, 1985; Loague and Gander, 1990; Mallants et al., 1996). Few studies have tried to combine these two (e.g. De Roo et al., 1992).

On the Loess Plateau in China, soil erosion totals to between 10 000 and 25 000 tons/km^2 per year (Zhang et al., 1998). Of this quantity, 73% ends up in the Huang He (Yellow River), causing huge sedimentation problems, as well as flood risks, in downstream areas. The Chinese government acknowledges the erosion problem and promotes comprehensive erosion control. Erosion modelling can be a useful tool to understand and predict erosion and ultimately to find ways of preventing it by designing alternative land-use options (Hessel et al., 2003a). Such alternative land-use options have to be defined on the basis of various interests. If only environmental issues are considered, biophysical solutions are often proposed. But if the regional economic situation is taken into account, restrictions on land-use changes are determined by the possible yield change in cash terms. There is a growing awareness that successful research will also have to take into account the farmers' objectives and constraints, and that it can benefit from their knowledge of local conditions (Hoang Fagerström et al., 2003a). Farmers are more closely acquainted with the real local problems, and are therefore aware of factors that experts often fail to consider. Also, their objectives are more realistic for economic development (Stocking, 1996). Lu (2000) concluded in his study in Ansai county that successful policy interventions in terms of sustainable land use require participation by the local people. This means that if the environmental problems are used as the main point of departure for land-use change, farmers should be involved in defining alternatives, to quantify their social and economic impact.

At the decision-making level, there is a need to raise awareness of the importance of appropriate policies for successful implementation of integrated farming systems (Li, 2001). Effective environmental policy-making requires that policy-makers gather and disseminate adequate information on the consequences of soil erosion for both the farm's long-term productivity and the farmer's health (Troaré et al., 1998). This may have a positive effect on the adoption of conservation practices. Soil research should specifically emphasise interaction with stakeholders in the process of planning, executing and reporting research (Bouma, 1997). Land-use planning is increasingly becoming an interactive process with the stakeholders, and the term negotiation is therefore more appropriate than planning (Bouma, 2001). In this negotiating process, scientists are the facilitators of knowledge on land-use opportunities and of risk analyses of environmental and socio-economic parameters. In soil erosion research, many studies have been and are still being conducted into the modelling of erosion processes. While some of these studies quantify the effect of alternative land use on soil and water losses, uncertainty analyses combined with analyses of socio-economic effects are essential for stakeholders to gather and disseminate adequate information and to come to well-founded, feasible decisions.

Figure 6.1 shows a procedure on how to execute a participatory planning process. In this process, economical, social, cultural and technical input is needed to define land use strategies. Land use scenarios will be evaluated and refined, using an iterative process. This negotiation process will provide guidelines and recommendations. The present chapter aimed to develop methods of presenting the effects of land-use changes to stakeholders, to be used in a negotiating process emphasising risk analyses and economic impacts. Specific objectives were to:

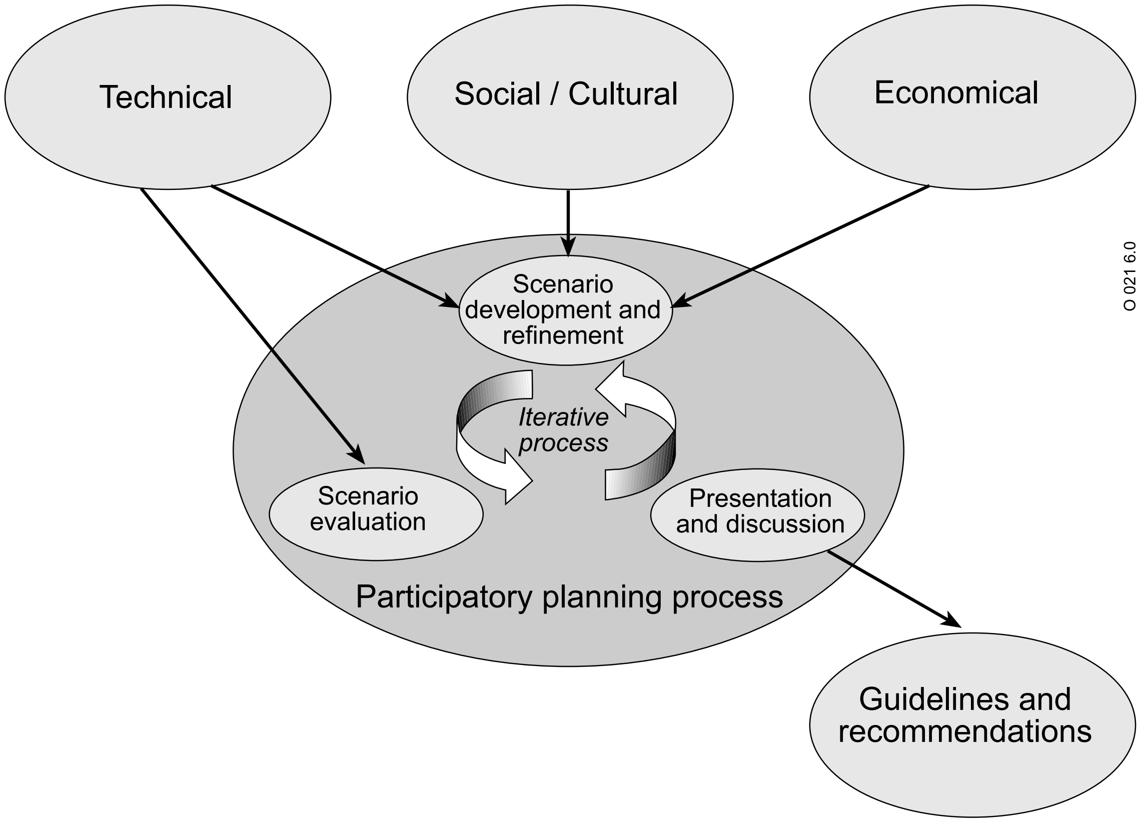

Figure 6.1 Scheme of a participatory planning process

- investigate the effect of measured spatial heterogeneity of saturated hydraulic conductivity (K_s) on computed water and sediment losses;
- compare model results using geometric mean values of K_s versus stochastic distributions;
- present a risk analysis of the effects of different land-use scenarios in terms of reducing soil and water losses, using a physically based hydrological and soil erosion model;
- quantify the expected changes in farmers' incomes for different land-use scenarios.

6.3 METHODS

6.3.1 Area description

The study area is the Danangou catchment in Shaanxi Province, China. Soil map of the area is given in Figure 4.3, and an area description 4.3.1 At Ansai City, close to the Danangou catchment, average annual rainfall was 513 mm over the period

1971-1998 (Ansai County Meteorological Station), of which 72% fell in the period June-September, with an average of 3 – 4 events per year causing discharge. Two villages, Leipingta and Danangou, are situated within the catchment studied. In 1998, the total population in the catchment was 206 individuals, belonging to 46 households. Average land area per household was about 1-2 ha, including small, scattered field plots (Hoang Fagerström et al., 2003a).

6.3.2 Land use scenarios

The Danangou catchment was a subject of study during the recently concluded Erochina project (Ritsema, 2003), in which various research disciplines surveyed the area. Using the project's results, several land-use scenarios have been developed to identify opportunities for land-use changes within the Danangou catchment to reduce soil and water losses, and to quantify effects on household incomes. The present study defined four land-use scenarios:

- the current situation (land use 1999);
- an agriculture-driven scenario;
- a soil-driven scenario;
- a conservation-driven scenario.

The land use distribution of each scenario is given in Fig. 6.2. In the 1999 situation, land use at the Danangou catchment consisted of 41.4% wasteland/wild grassland, 35.4 % cropland (mainly maize, millet, potato and soybean), 13.4% forest/scrub, 7.3% fallow, 2.4% orchards/cash tree and 0.1% vegetables (Hessel et al., 2003a). Average crop coverage was less than 50%, while the wasteland and fallow areas had a vegetation coverage of 33%, against 42% for the scrub and 49% for the forest (Wu et al., 2003). Land management on the fallow areas in spring is the same as on cropland, but no crop is planted during the season, while wasteland is not subjected to any treatment.

Scenario II was based on the results of a socio-economic survey (Hoang Fagerström et al., 2003b). This scenario aims to increase productivity, while decreasing the total area of agricultural land, resulting in the same household incomes as in the current situation. The expected yield increase is to be achieved by increasing fertiliser use and adapting related land management measures. In this scenario, cropland is allowed on slopes < 15 degrees, orchards between 15 – 30 degrees and a mixture of wild grassland and forest on slopes > 30 degrees. No fallow land was assumed in this scenario.

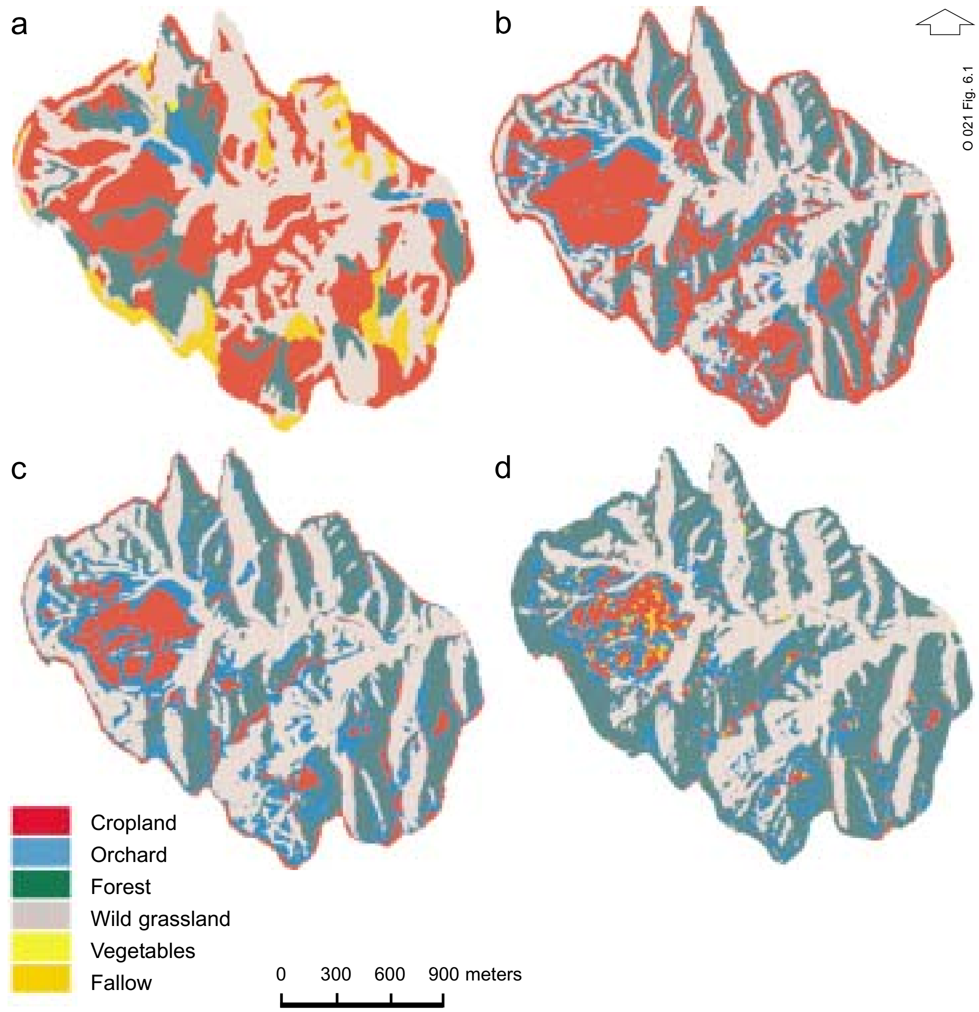

Figure 6.2 Land-use distribution maps of four land-use scenarios. a: Current land use; b: Agriculture-driven land use; c: Soil-driven land use; d: Conservation-driven land use.

For scenario III, land-use distribution was assigned on the basis of pedological information in order to reduce discharge and sediment losses. The stratification of the catchment was based on the soil map and on measurements of saturated conductivity. Land-use units with high potential infiltration rates are situated on steep areas in the catchment. On the yellow loess area, cropland is allowed on slopes < 15 degrees, orchards on slopes of 15 – 25 degrees and a mixture of forest and wild grassland on slopes > 25 degrees. On the red loess areas, orchards are allowed on slopes < 25 degrees and a mixture of forest and wild grassland on slopes > 25 degrees. This scenario does not include any fallow area.

Scenario IV is the result of a participatory study involving local farmers (Hoang Fagerström et al., 2003b). In this scenario, agricultural cropland is found only on soils with slopes <15 degrees. Land with slopes of 15-25 degrees is converted into orchards/cash trees and land with slopes >25 degrees and all land with shallow soils are converted into other uses (woodland/scrub/grassland) (Chen et al., 2003). Additional conservation measures include ridges and grass strips on orchards/cash tree land and cropland/fallow land. Fallow area is somewhat smaller than in the current situation (Hessel et al., 2003a).

The land-use distributions of the scenarios are shown in Figure 6.3. The cropland area decreases most in the conservation-driven scenario, which features the largest forest area. The agriculture-driven scenario shows a minor decrease in cropland, but a considerable increase in orchards. The soil-driven scenario shows a considerable decrease in cropland and a considerable increase in orchards. The land-use changes have a direct effect on farmers' incomes. The change in cropland area for each scenario is given in Table 6.1.

Table 6.1. Cropland area for each defined land use scenario

	Cropland area (km^2)	Cropland area (%)†
Current land use (I)	1.25	100
Agriculture-driven (II)	1.11	89
Soil-driven (III)	0.47	38
Conservation-driven (IV)	0.23	19

†*100% cropland = 35% of total area*

6.3.3 Model description and input

The present study used the physically based hydrological and soil erosion model LISEM (De Roo et al., 1996a) to quantify effects of land use on discharge and soil loss. All parameters necessary for LISEM were gathered during an intensive measurement campaign in 1998 and 1999 (Liu et al., 2003, Wu et al., 2003, Hessel et al., 2003b). In this campaign, 17 representative fields were selected and measurements of plant and soil characteristics were performed on a two-weekly basis. An elevation map was constructed using an existing topographical map, updated with GPS measurements. Rainfall data was gathered over the years by means of 5 rainfall gauges distributed over the catchment area. Discharge and sediment concentration were measured at a weir in the catchment (Van den Elsen et al., 2003b), and soil water content was measured in transects through the catchment (Qiu et al, 2003). Samples for the assessment of saturated conductivity were collected using a statistically designed Simple Random Sampling schedule (Stolte et

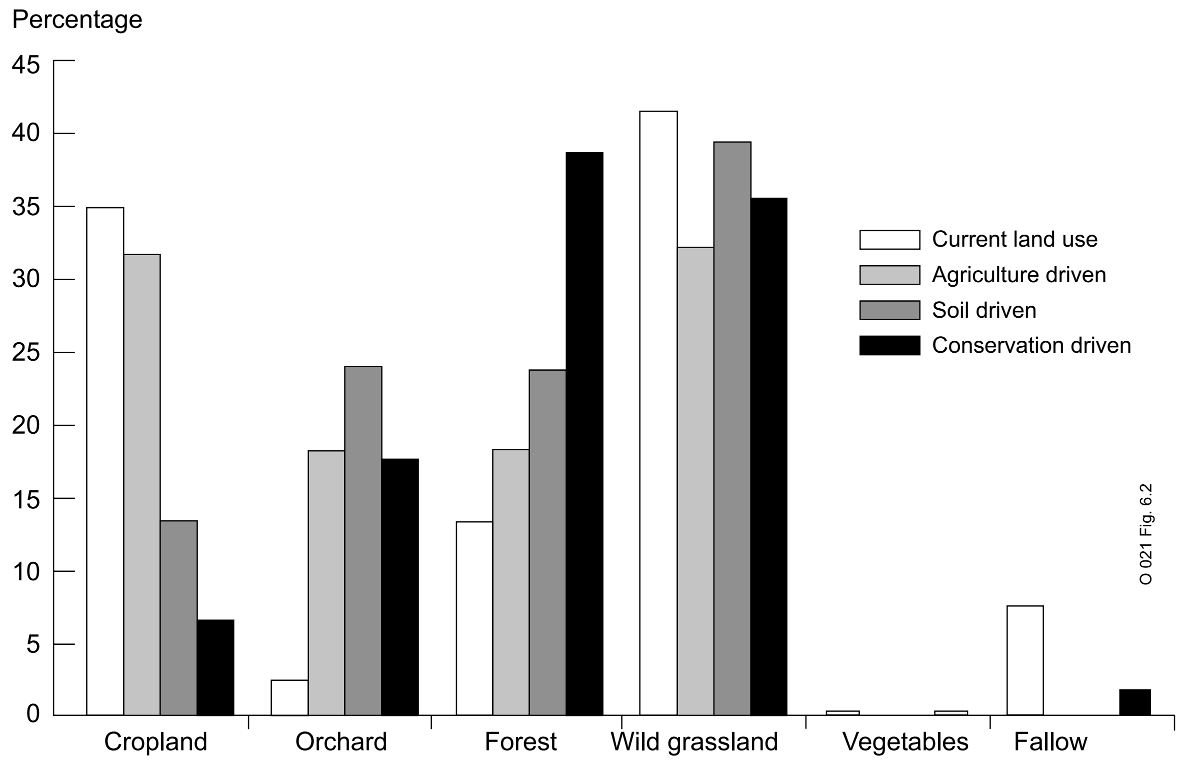

Figure 6.3 Land use in four land-use scenarios, in percentage of total area.

al., 2003). A combination of soil and land-use units were selected and used for sample collection. The surface layers were carefully sampled to prevent any disturbance. Samples were transported to a shed owned by a local farmer, where equipment to measure saturated conductivity had been installed. The samples were saturated, and the constant head method was used to measure saturated conductivity (Stolte, 1997).

To compare the effects of the four land-use scenarios on the generation of runoff and erosion, calculations were based on a single rain event. Most erosion can be expected to take place during large events, but smaller events also produce considerable amounts of discharge, especially taking the frequency of occurrence, and hence the cumulative volumes, into account. The present study used a measured event that took place on August 1, 1998. The total amount of rainfall during the event was 15.1 mm, while the maximum rainfall intensity measured was 96 mm/h. This event produced considerable discharge during the measurement period in comparison with other measured events (Van den Elsen et al., 2003b). Since this event was a 'normal' event, with an estimated recurrence of once a year in terms of intensity and amount, it is thus representative of events causing most of the discharge on a yearly basis.

Table 6.2 Parameters for the LISEM model for the August 1, 1998 event (after Hessel et al., 2003c)

	Crop[1]	Fallow	Orchards	Scrub	Waste	Forest
Aggregate Stability (drop no)	6	5	6	6	8	7.25
Cohesion (kg/cm^2)	0.08	0.10	0.10	0.09	0.11	0.11
Random roughness (cm)	1.75	1.11	1.28	1.03	1.66	0.88
Manning's n	SD[2]	0.079	0.092	0.153[3]	0.091	0.214
Leaf Area Index	0.06	0.12	1.46	1.25	0.54	1.63
Plant cover (fraction)	0.06	0.10	0.18	0.40	0.23	0.35
Plant height (m)	0.28	0.11	3.1	0.97	0.25	13.6

[1] *Cropland was subdivided into 5 types. The values given here are those for foxtail millet. The other types are pearl millet, potato, tall crops (maize, sorghum) and beans.*

[2] *SD = slope-dependent, Manning's n is calculated as a function of slope angle based on a series of 16 experiments, see Hessel et al (2003b).*

[3] *Average of wasteland and forest.*

Input parameters for the LISEM model for this event are given in Table 6.2. Saturated hydraulic conductivity has proved to be a sensitive parameter in the model. De Roo et al. (1996b) conducted a sensitivity analysis and found that this was the most sensitive of all parameters. Stolte et al. (2003) compared calculations using the geometric mean K_s values with calculations using the standard deviation of this value and proved that the resulting values for calculated discharge and total sediment losses varied by ~80%. The model was extensively calibrated for the event used, using measured discharge and sediment concentrations. The measurements were done at a weir located just upstream of Danangou village (Fig. 4.6). The calibration took place for a single rain event and was based on optimising the calculated hydrograph and sedigraph on the basis of the measured hydrograph and sedigraph. We used a calibration procedure (Hessel et al., 2003c) to optimise the LISEM model results, using fitted saturated conductivity as well as measured saturated conductivity. The fitted K_s is the result of an extrapolation of the measured unsaturated conductivity, using the Mualem-van Genuchten equations (Mualem, 1976; van Genuchten, 1980). Theoretically, this means that the fitted K_s value is too low, while the measured K_s is too high (Stolte et al., 2003). The 'actual' value of the saturated conductivity (K_s-optimised) is in between these values. Validation was done for four other rain events (Hessel et al., 2003c). The initial water content was estimated using equations with aspect and slope angle as variables. The validation showed that peak discharge calibration for the given event had been successful (measured 5125 l/s *vs.* calculated 4931 l/s), but that the total discharge had been overestimated (measured 5125 m^3 *vs.* calculated 7946 m^3).

6.3.4 Model computations

Using average K_s values

For model input of saturated conductivity values the geometric mean of the K_s-optimised values were used for the land-use groups identified (Table 6.3). These groups were merged based on a statistical comparison of the measured saturated conductivity values (Stolte et al., 2003).

Table 6.3 Geometric mean of K_s and Standard Deviation for land-use groups in the Danangou catchment (after Stolte et al., 2003)

Land use	Geometric mean K_s-optimised (cm/d)	S.D.† (cm/d)	n‡
Vegetables	10.3	4.0	37
Cropland & Fallow	8.5	2.4	34
Forest	31.3	10.1	10
Orchards	35.0	4.6	10
Wild grassland	20.6	10.1	19

† S.D. = *Standard Deviation*

‡ n = *number of samples*

Using a stochastic, Monte Carlo approach

Calculations using average K_s values ignore the existing field heterogeneity of this parameter. It is therefore to be expected that the outcome of the model using stochastic distributions of K_s will differ from the results obtained using the average K_s value. Randomly assigning values to each calculation grid cell can be expected to result in a more diverse outcome of the model, reflecting the reality more reliably. The present study used 50 randomly drawn K_s values for each land use scenario. A K_s value from the K_s-distribution of each land-use group (Table 6.3) was randomly assigned to each grid cell belonging to this specific land-use group. The lower limits of the K_s-distribution were defined as the maximum value of the unsaturated conductivity at near saturation for the specific land-use unit.

6.4 ECONOMIC IMPACT OF THE SCENARIOS

Changes in land use will directly influence the household incomes of those affected. Several methods to assess economic impacts have been identified in previous studies (e.g. Li, 2001). In the Erochina project, a Participatory Household Economy Analysis (PHEA method) was developed to predict potential changes in household economy (Hoang Fagerström et al., 2003a). The PHEA method involves (1) selecting representative farms using a formal interview and wealth ranking and (2) conducting an in-depth study of the selected households. Eight households were selected from among 19 surveyed in Danangou, and 7 households were selected from among 17 surveyed in Leipingta .

The criteria used to differentiate between the representative households were family composition, land-use characteristics and production, income and labour and qualitative wealth ranking by the village leader (Hoang Fagerström et al., 2003b). Figure 6.4 shows an example of farming practice in the Danangou catchment.

Changes in farm production resulting from land conversions in the various scenarios were calculated according to the empirically derived equations 1 and 2.

$$L = \text{Current Production} \cdot CC\ \% \qquad (1)$$

$$I = (CA \cdot CC\ \% \cdot P) \qquad (2)$$

Here, L (*yuan*) is the production after the land-use conversion; CC is the change in cropland area *(in % from current area*); I is the production change due to intensification (*yuan*); CA is the current cropland area (*Mu*); P is a crop-dependent parameter, estimating the increase in crop yield when certain improvement measures are taken, such as improved fallow, mulching and/or fertilisers (Hoang Fagerström et al., 2003a).

6.5 RESULTS AND DISCUSSION

6.5.1 Effects of land-use scenarios on runoff and erosion

Model calculations using average K_s values

The hydrographs for the simulations using the geometric mean of the K_s values are given in Fig. 6.5 for all scenarios.

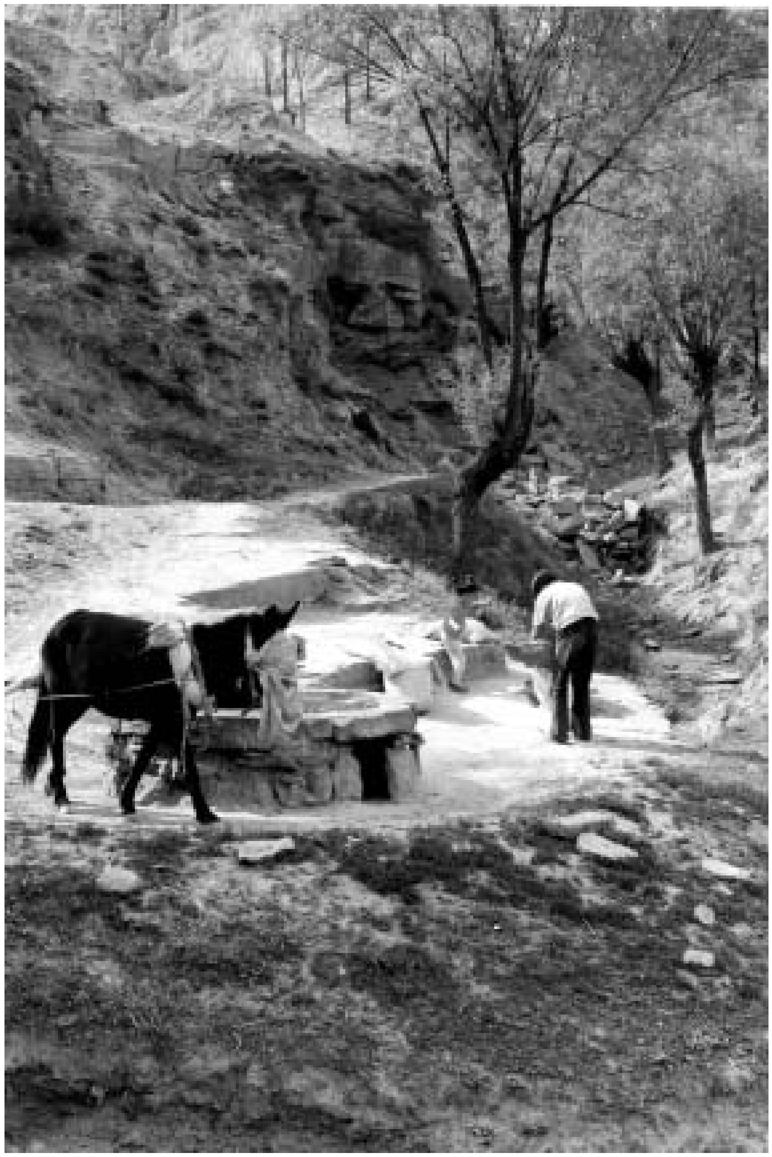

Figure 6.4 Mill in the Danangou catchment. The mill is operated by a mull, and used for grinding maize and millet.

The conservation-driven scenario was found to produce minimal discharge relative to that generated under the current land-use conditions. A comparison between Figs. 6.3 and 6.5 shows that discharge increases with increasing areas of cropland and decreasing areas of forest. The appearance of two discharge peaks in the various scenarios can be explained by the spatial land-use distribution in the watershed. The current cropland area within the catchment is largely concentrated in the flatter areas in the upstream and downstream parts of the catchment. This can be seen in Fig. 6.2, which shows the land-use distribution for the four scenarios. The first peak of water is produced close to the main outlet of the catchment and the

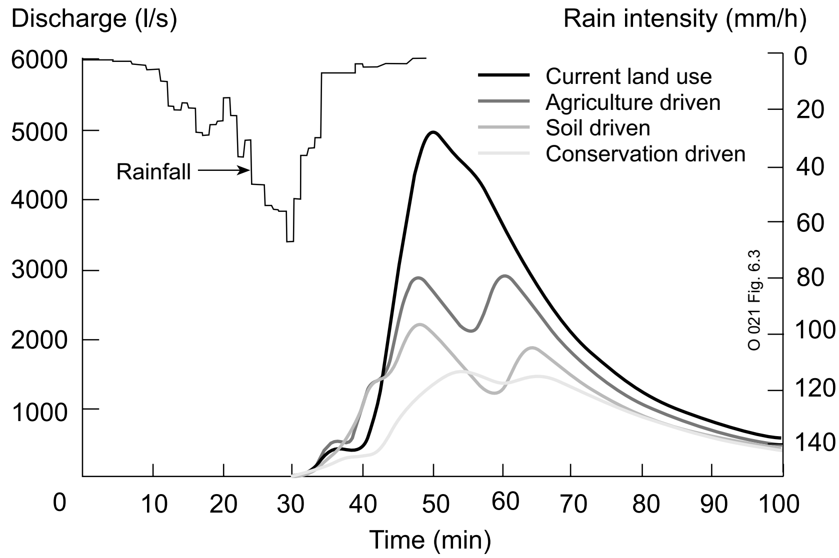

Figure 6.5 Computed hydrographs for four different land-use scenarios using the mean K_s value as input for an event on August 1, 1998.

second peak in the large cropland area in the upstream part of the catchment. This is visualised in Fig 6.6, which shows the velocity of the discharge one minute before the first discharge peak arrives at the main outlet of the watershed. Two waves can be seen in this figure, one at the outlet and a second one more upstream in the

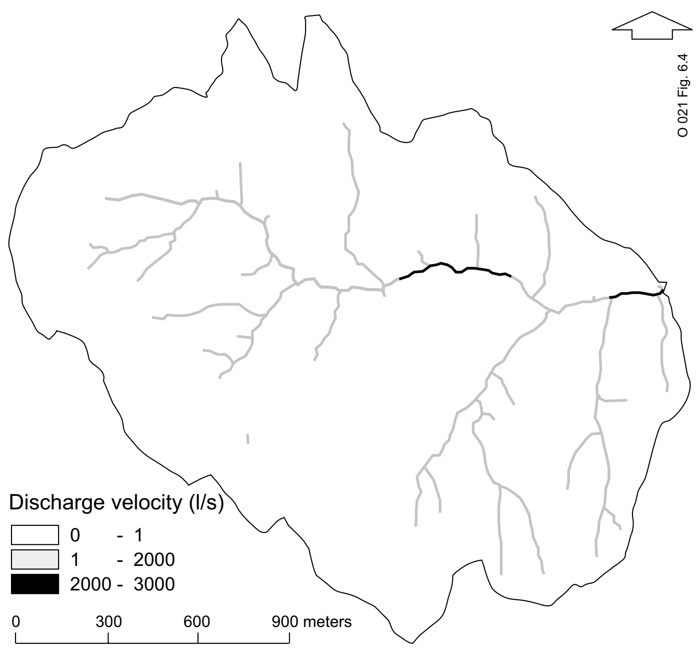

Figure 6.6 Computed discharge velocity in the Danangou catchment for the agriculture-driven scenario, 49 minutes after the start of the computations and just before the first peak has reached the outlet of the catchment.

catchment. The absence of the double peak in the current land-use simulations can be explained by the spatial distribution of the land use, which is more heterogeneous than in the defined alternative land-use scenarios (Fig. 6.2). The first peak in the conservation scenario is not very clear, which can be explained by the lack of cropland in the downstream part of the catchment.

Model calculation using Monte Carlo analysis

Figure 6.7 shows the effect of a stochastic distribution of saturated conductivity values for each grid cell on the calculated hydrograph for the current land-use scenario. The figure presents the hydrographs of 50 LISEM runs using random K_s-values for each grid cell. For the sake of comparison, the calculation result of the

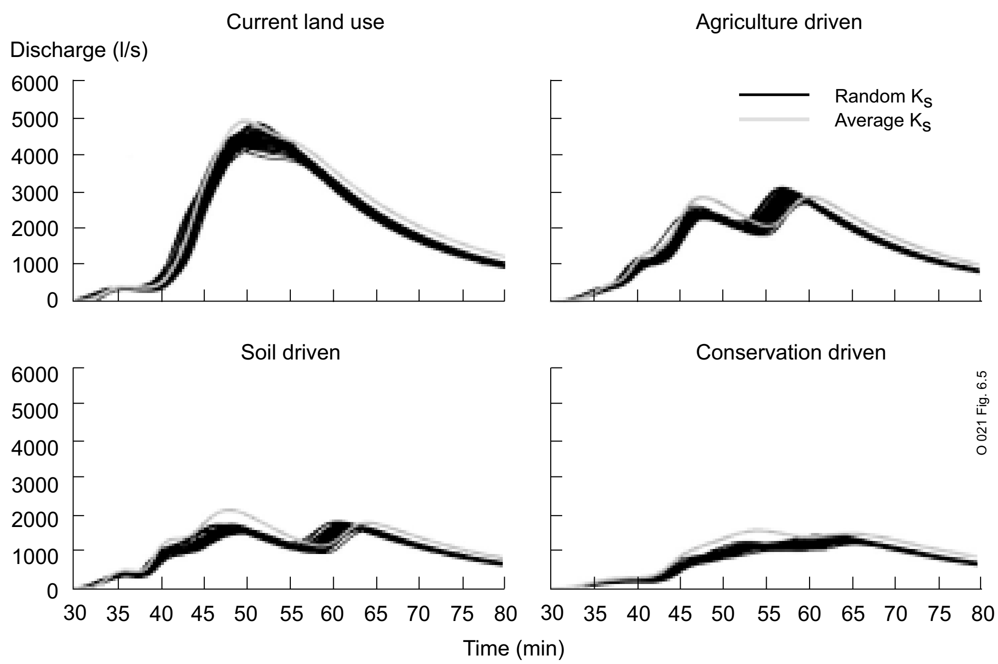

Figure 6.7 Computed hydrographs for four land-use scenarios using stochastic K_s values with 50 repetitions. The results using the mean K_s value are also included (grey lines).

run using the geometric mean of K_s is also shown. Figure 6.8 shows the results for the calculated cumulative sediment load using the stochastic K_s-distribution and the geometric mean of K_s. Table 6.4 presents results for computed discharge and sediment losses. All parameters show higher values using the geometric mean of K_s. Only for the peak time is there no difference between model runs using a geometric mean and those using stochastic K_s-distributions for the current land-use and

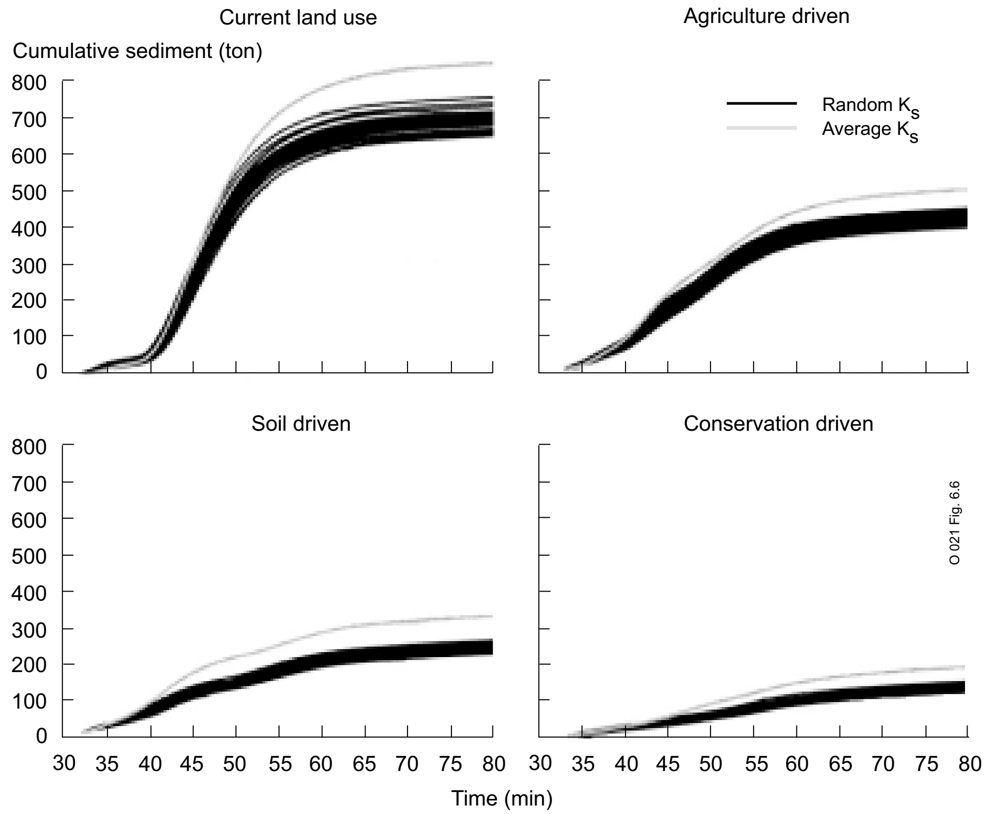

Figure 6.8 Computed sedigraphs for four land-use scenarios using stochastic K_s values with 50 repetitions. The results using the mean K_s value are also included (grey lines).

agriculture-driven scenarios. The second discharge peak for the soil- and conservation-driven scenarios is larger than the first if stochastic K_s-distributions are used, whereas the use of geometric means yields the opposite result, causing a difference of about 10 min in peak discharge.

Séguis et al. (2002) compared seasonal runoff for various grades of variation coefficients and various types of uniform dispersion of K_s values, using the Green-Ampt equations to describe the infiltration, and found lower discharge values when using stochastic modelling than when using mean values. However, they concluded that for short, intense rainfall events, the simulations yielded opposite results, which could possibly be explained by the dominant runoff control factor of the grid cells with high K_s values. Woolhiser and Goodrich (1988), using a simple bucket model to predict infiltration, presented results that changed with rainfall intensity. Saghafian et al. (1995), using the Green-Ampt equation to predict infiltration, concluded that heterogeneous systems of hydraulic conductivity produce greater peak surface runoff than those with uniform values. De Roo et al. (1992) found no difference between the use of uniform K_s values and the mean result of Monte-Carlo simulations using the ANSWERS model, which describes infiltration according to the Holtan model. The differences between these studies might be caused by various factors, including the use of geometric or arithmetic means for the uniform K_s values, as indicated by Saghafian et al. (1995). In addition, the outcome is also influenced by the nature of the models used to describe the infiltration process. In our study, the fact that all parameters had higher values in the geometric mean runs than in the stochastic runs (as shown in Fig 6.7 & 6.8 and Table 6.4) is explained by the domain of K_s values that was used. The geometric mean was based on all measurements, while the lower boundary of the domain of the K_s values for stochastic modelling was defined as the maximum value of the unsaturated conductivity. This leads to an underestimation of the number of grid cells with a very low infiltration rate, causing the amount of discharge to decrease in the stochastic approach.

Table 6.4. Calculated results of discharge and sediment losses, using the LISEM model, for a rain event on August 1, 1998 for four land-use scenarios.

Scenario	Current land use			Agriculture-driven			Soil-driven			Conservation-driven		
	Average K_s †	Monte Carlo analyses‡		Average K_s	Monte Carlo analyses		Average K_s	Monte Carlo analyses		Average K_s	Monte Carlo analyses	
		Mean	*S.D.*		*Mean*	*S.D.*		*Mean*	*S.D.*		*Mean*	*S.D.*
Total discharge (m^3)	7946	6967	61	6401	5216	47	4442	3703	41	3475	2731	44
Peak discharge (l/s)	4931	4475	187	3272	2889	96	2172	1728	51	1499	1266	64
Peak time (min)	50	51	1.12	59	58	0.68	48	58	6.43	54	64	1.00
Discharge/Rainfall (%)	14	13	0.11	12	9	0.09	8	7	0.08	6	5	0.08
Total soil loss (ton)	832	680	20	577	411	13	322	232	9	181	125	6
Average soil loss (kg/ha)	2360	1931	58	1637	1168	38	913	658	25	514	356	16

† *Average K_s = results of the calculation using the geometric mean of the K_s value as input for the model*

‡ *Monte Carlo analyses = results of 50 calculations using stochastic distribution of K_s values*

The differences between the land-use scenarios in terms of discharge and sediment load are presented in Figures 6.9 and 6.10, which show the hydrographs and sedigraphs of all 50 runs for each scenario. In comparison with the results for

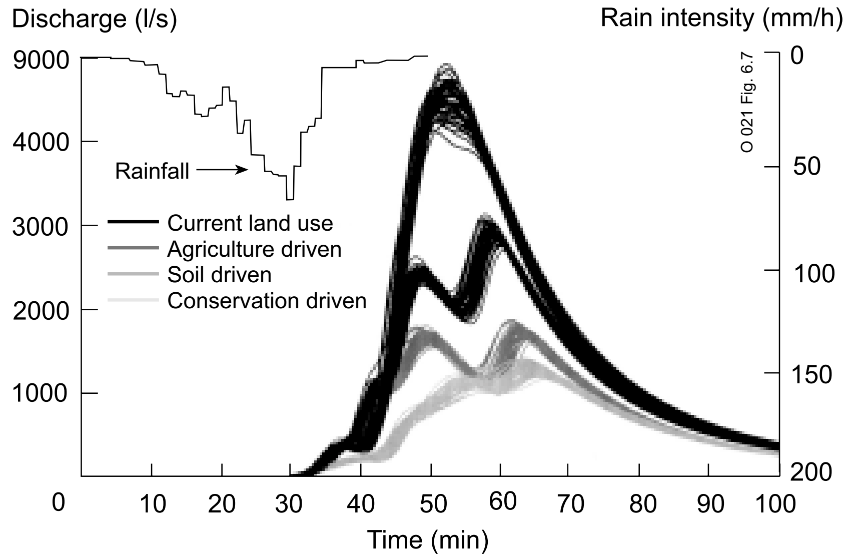

Figure 6.9 Computed hydrographs for four land-use scenarios using stochastic K_s values with 50 repetitions. Calculations were done for an event on August 1, 1998.

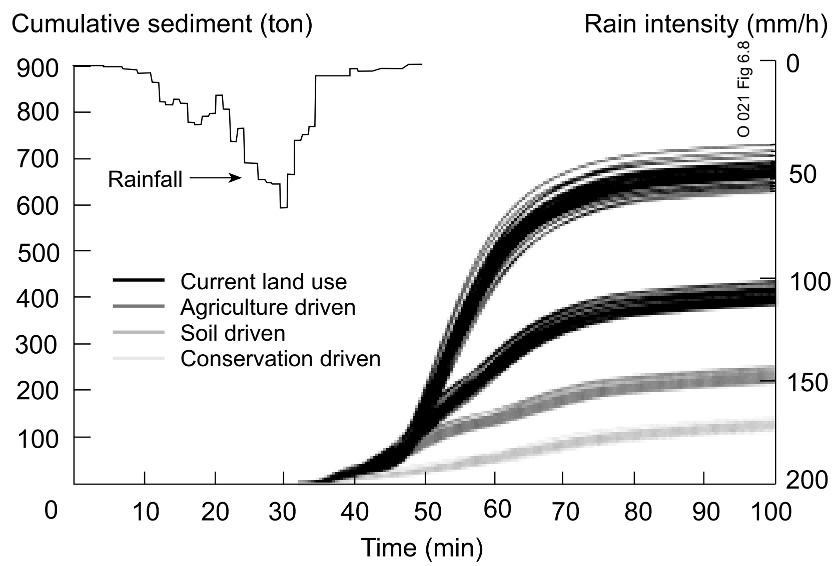

Figure 6.10 Computed sedigraphs for four land-use scenarios using stochastic K_s values with 50 repetitions. Calculations were done for an event on August 1, 1998.

the runs using geometric mean values, the conclusions remain the same, although the difference between the conservation- and soil-driven scenarios proved to be less pronounced. The present study analysed one rainfall event. Given the fact that this was a relatively small event in terms of intensity and amount (Hessel et al., 2003c), the variation in the outcome of each Monte-Carlo simulation might be different for other storm events. The variation may be expected to be larger for smaller events, as has been shown by, e.g., Smith and Hebbert (1979) and by De Roo et al. (1992), while differences between land-use scenarios may be less pronounced for extreme events. Choosing a regular event in terms of recurrence to compare alternatives may be expected to lead to pronounced differences.

6.5.2 Economic impact of scenarios

The alternative land-use scenarios result in cropland changes, and will thus affect household incomes. Figure 6.11 shows the effects of the various scenarios on income, assuming that the crop production changes proportionally to the changes in cropland area. The figure makes a distinction between the two villages, because cash crops (vegetables, orchards) mainly occurred in Leipingta, and were largely absent in Danangou. Fig. 6.11 reveals that the agriculture-driven scenario results in a decrease in cropland, while incomes increase. It is estimated that maize yield, for instance, can increase by 100% if some improvement measures are taken, such as improved fallow, mulching and/or fertilisers (Hoang Fagerström et al., 2003a). This implies that the effort invested in extension work, crop production (and therefore local incomes) can increase without negative effects on discharge and soil erosion.

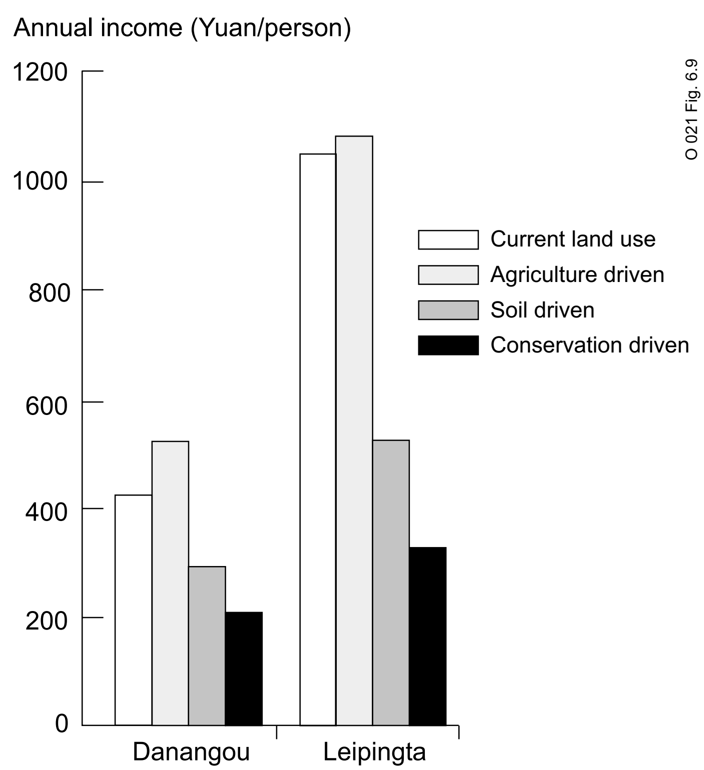

Figure 6.11 Economic effects of four land-use scenarios on annual incomes in two villages in the Danangou catchment.

The soil-driven scenario yields a decrease in incomes, but a greater reduction of soil and water losses than the agriculture-driven scenario. The conservation-driven scenario, which excludes all land steeper than 15 degrees from being used for agriculture, results in a considerable decrease in incomes. This has also been reported by Hoang Fagerström et al. (2003b), who state that government support is needed in this case to ensure sufficient incomes for the farming families.

6.6 CONCLUSIONS

The various land-use scenarios result in statistically significant differences in terms of water and sediment losses. Total soil and water losses in the various alternative scenarios were approximately 24% to 60% lower than those for the current land-use distribution in the watershed. The soil-specific and conservation-driven scenarios resulted in farmers' incomes being reduced by approximately 50% to 70%, whereas the agriculture-driven scenario resulted in a slight increase in their incomes.

Though these specific land-use scenarios represent possible land uses defined by particular interests, a numbers of other options could be defined as well (e.g. Hessel et al., 2003a). Once a database has been compiled for a specific region, containing all necessary parameters of current and alternative land-use systems, on the spot simulations can be performed, allowing interactive negotiation with stakeholders. The database presented in this study covers plant and soil characteristics that are representative of a large part of the Chinese Loess Plateau. This database allows risk analyses for comparable areas (i.e. the major part of the Chinese Loess Plateau) to be conducted with relatively little additional effort. All that is needed are morphological (i.e. Digital Elevation Model) and land-use maps. Using stochastic K_s-distributions produces a model output range that reflects the effect of the variability in input parameters on the model outcome. This allows statistical analyses and comparison of computed results for alternative land-use scenarios, and leads to a more balanced judgement. Thus, modelling results can be used as negotiating tools in the land-use planning process. The users are not presented with a final answer but with a range of options and associated risks (Bouma, 2001). The way the results are presented provides policy-makers with information on plausible effects of various alternatives on conservation, and as such implies a powerful negotiating procedure for defining land-use alternatives.

CHAPTER 7

SUMMARY AND CONCLUSIONS

7 SUMMARY AND CONCLUSIONS

7.1 INTRODUCTION

Soil erosion is a global problem because of its environmental consequences, including sedimentation and pollution in many areas of the world. An estimated 400 million hectares of land have been abandoned due to soil erosion over the past 50 years. The main biophysical factor influencing the quantity of overland flow is the infiltration rate. Prediction of overland flow in catchments depends to a large extent on the characteristics of the infiltration process. Infiltration during a runoff-generating rainfall event is regulated by the hydraulic properties of the various soil layers, that is, the unsaturated or saturated conductivity and soil water retention characteristics, and the antecedent soil moisture conditions. This thesis deals with (i) the effects of spatial and temporal variability of soil physical properties, in particular the saturated hydraulic conductivity, on the generation and prevention of runoff in undulating loessial watersheds, and (ii) the application of an erosion model in the context of land-use planning and negotiation. Specific objectives of the studies were to:

- quantify the spatial variability of saturated conductivity within selected watersheds in China and the Netherlands;
- develop a soil physical schematisation procedure, taking into account spatial differences in soil layers and land use;
- investigate the relation between land-use type and saturated hydraulic conductivity distributions;
- quantify the effects of the spatial variability of saturated conductivity on computed water and soil losses;
- use models as a negotiation tool in a region to explore promising land-use and soil and water conservation measures aiming to reduce water and soil losses, based on related distributions of soil hydraulic properties.

7.2 RESEARCH DESIGN

Research for this thesis was carried out in three small agricultural catchments in the southern loess area in the Netherlands (Limburg Province) and in an agricultural catchment on the Loess Plateau in China (Shaanxi Province). In the Limburg study, soil physical properties of soil horizons within the selected catchments were measured, and the tendency of these soil layers to generate runoff during varying characteristic rainfall events was evaluated. In addition, the effects of heterogeneous saturated conductivity values on model outcome were examined by selecting spots with minimum infiltration rates (fully crusted) and maximum infiltration rates (cracked crusted surfaces). In China, this procedure was further examined by using a Simple Random Sampling approach to statistically identify land-use units in the catchment. The physically based hydrological and soil erosion model LISEM was tested for its accuracy on a single gully system in the Chinese catchment. An alternative land-use distribution was defined for this system, based on knowledge of the soil hydraulic properties as regulating parameters within the runoff and soil erosion process. A procedure to present risk analyses in soil degradation studies was developed for the entire Chinese catchment, using the heterogeneity of the saturated conductivity. Effects of pre-defined alternative land uses on discharge and soil loss were quantified using stochastic modelling and Monte-Carlo analyses.

7.3 RESEARCH FINDINGS

7.3.1 Soil hydraulic properties

Chapter 2 of this thesis focuses on the development of a soil physical schematisation procedure to provide accurate data for erosion modelling. For this purpose, soil hydraulic functions for runoff simulation were collected as part of the Limburg study. Simulations with the SWMS_2D computer program were performed to quantify runoff generation during standard rain events. The outcome of these simulations was used to identify classes of soil horizons with similar behaviour, and soil horizons were merged into soil physical units. This resulted in a database of 25 soil hydraulic functions, each representing one or more top and/or subsoil horizons.

Crust formation and cracking of crusted loamy soils appears to be a general process in loess soils. Chapter 3 reports on a study to measure the hydraulic properties of cracked and non-cracked surface crusts and to evaluate the effects of these surface characteristics on catchment discharge and soil loss in a catchment in the Netherlands, using the LISEM hydrological and soil erosion model. Samples with minimum infiltration rates (fully crusted) and with maximum infiltration rates (cracked crusted surfaces) were taken from fields with bare soil or winter wheat and their soil hydraulic functions were measured. Simulations of discharge and soil loss were performed for each of these two soil surface types, for two different rain events with varying recurrence frequencies. Additionally, simulated discharge and soil loss for the actual land-use distribution were computed. Increase of total and peak discharges was simulated for areas with intact crusts compared to areas with cracks, especially for high frequency rainstorms. Calculated soil loss values were found to decrease with increasing proportions of cracks.

Chapter 4 describes a study quantifying soil hydraulic properties for major land-use units in the Chinese catchment and examining the effects of the statistically identified in-field heterogeneity on model outcome. To determine the hydraulic properties of the soil, a sampling scheme was developed and implemented to measure unsaturated conductivity and water retention characteristics. The saturated conductivity measurements were performed on land-use clusters, based on tillage system and crop and soil differences. A 100 m x 100 m sampling grid was laid out on 14 fields, with 1 m x 1 m grid squares. On each field, ten sampling spots were randomly selected, using the Simple Random Sampling approach. Statistical analyses resulted in six major land-use units, each with its own K_s distribution. The sensitivity of the LISEM model to the spatial heterogeneity of saturated conductivity was analysed by conducting simulations using the geometric mean of the K_s values, and then using this value, plus or minus the standard deviation, to compare calculated discharge and soil loss during a single rain event. The results showed that increasing the geometric mean of K_s with the standard deviation meant that runoff and erosion decreased by about 80%, while decreasing it with the standard deviation resulted in an increase of about 80%. This indicates that the spatial heterogeneity of the saturated conductivity strongly affects the outcome of predicted runoff and erosion in model simulation scenarios.

7.3.2 Model application

To test the accuracy of the LISEM model on a small spatial scale, a single gully system was selected in a catchment on the Loess Plateau in China (Chapter 5). The gully had a length of about 40 m and was about 30 m wide. The watershed feeding the gully covered about 1950 m^2 (including the gully itself). The gully floor had a slope of about 32 – 40 degrees, whereas the slope of the gully walls ranged from 40 to over 60 degrees. Soil water content was measured automatically at several places and depths, as were water and sediment discharges at the outlet of the gully catchment. Calibration of the LISEM model was carried out for one rain event, by slightly adjusting the saturated conductivity values. The measured and calculated hydrographs were in close agreement. Computed soil loss was also comparable to the measured data. Validation was performed for two additional runoff events. The validation of LISEM for these two runoff events showed reasonably good results in terms of computed discharge. In terms of computed soil loss, however, results were rather poor, probably due to limitations of the measuring equipment and the inability of the model to simulate small events correctly. Taking this limitation into account, alternative land-use options for the gully system were evaluated for a large rain event. Scenario analyses showed that forest, as an alternative type of land use for the gully bottom, would result in significantly smaller water and sediment losses. This strongly supports the reforestation policy that was recently suggested and implemented by the central government of the People's Republic of China.

Chapter 6 focuses on ways of presenting the potential effects of promising conservation strategies in a negotiation process with stakeholders to define land-use and soil and water conservation strategies, emphasising risk analyses and economic impacts. Effects of pre-defined land-use scenarios on water and sediment losses were quantified using the LISEM model and average and stochastic distributions of K_s values measured in the field. Land-use scenarios were defined on the basis of physical, economic and agricultural interests, and their effects on farmers' incomes were evaluated using empirically derived equations. The scenarios thus defined are presented as examples of possible land-use strategies. The use of stochastic K_s distributions and Monte Carlo analyses resulted in a range of model outcomes reflecting the effect of spatial heterogeneity upon simulated discharge and soil loss, allowing probabilities of occurrence of the effects of alternative strategies to be presented. Of the three land-use strategies examined, the conservation-driven land-use scenario (which resulted from farmers' participation) reduced water and sediment losses by runoff and erosion most effectively, followed by the soil-driven scenario (which was physically based) and the agriculture-driven scenario (which was economically based). Only the agriculture-driven scenario resulted in a small increase in household income, while a serious loss of income was predicted for the other scenarios.

7.4 GENERAL CONCLUSIONS

7.4.1 Soil physical units

Loess soils are very common all over the world, and are extremely vulnerable to water-induced soil erosion. The Limburg study showed that only differences in hydraulic properties of the surface layer cause differences in calculated discharge and soil loss in loess areas. The China study showed that even if the soil type is the same, differences in land use and management may cause differences in hydraulic properties and thus in calculated discharge and soil loss. A combination of land treatment and soil type determines the input for hydraulic data in water and soil erosion studies. If land treatment and soil type are the same, these land-use units can be merged into soil physical units, despite the fact that crops might differ. This indicates that commonly used pedotransfer functions, based on texture data only, may not provide adequate information for soil conservation studies, even though they express the effects of different densities and organic matter contents.

The findings presented in this thesis can be used to define a preliminary sampling scheme for comparable areas to reduce the number of samples needed to quantify K_s distributions. This sampling scheme should be based on an overlay of soil units and land treatment. For example, if a sampling scheme for the China study had been defined using the findings of this thesis, the number of representative fields would have been reduced to 6, instead of the 14 fields that were actually sampled.

7.4.2 Negotiation tool

Land-use planning is increasingly becoming a process of interaction with the stakeholders, and the term negotiation is therefore more appropriate than planning. In this negotiation process, scientists are the facilitators of knowledge about land-use opportunities and about risk analyses of environmental and socio-economic parameters. As has been shown in this thesis, once a database has been compiled for a specific region, containing all necessary parameters of current and alternative land-use systems, on-the-spot simulations can be performed, allowing interactive negotiation with stakeholders. This database allows risk analyses for comparable areas to be conducted with relatively little additional effort. The use of stochastic K_s distributions and Monte-Carlo analyses produces a range of model output that reflects the effects of the variability of input parameters on the model outcome. This allows statistical analyses and comparisons of computed results for alternative land-use scenarios, and can lead to a more balanced judgement. Thus, modelling results can be used as a negotiating tool in the land-use planning process, in which users are not presented with a final answer but with a range of options and associated risks. The way the results are presented provides policy-makers with information on likely effects of various alternatives on conservation, and as such implies a powerful negotiating procedure for defining land-use alternatives.

7.5 CHALLENGES FOR FUTURE RESEARCH

This thesis has presented findings relating to loess areas, which are very vulnerable to water-induced erosion. Results for other soil types might be different, and need to be examined as well. Focus was on the spatial heterogeneity of infiltration processes, but this thesis also presented evidence for seasonal differences in infiltration. It is likely that infiltration is also transient at smaller than seasonal time scales. The magnitude of infiltration might change in the course of a season, though results reported by published studies on this subject have not been unanimous. Some studies have found that infiltration rate changes even during a single rain event. This transient behaviour of infiltration should be quantified as well, and incorporated in models.

In soil conservation studies, modelling results can become an increasingly important tool in the negotiation process with stakeholders, as strategies to combat soil degradation are jointly developed. Modelling should, of course, not be a goal in itself. Hence, the major challenge is the on-the-spot use of the LISEM model to provide instant input for the negotiation process, which serves to stimulate debate. Developments in ict-technology are leading to a situation where such interactive use of models becomes feasible. The studies discussed in this thesis, however, have shown the need to obtain K_s distributions in order to produce realistic assessments. A soil physical schematisation procedure to get K_s distributions for characteristic combinations of soil type and land use is therefore important to allow on-the-spot activities to take place. Getting the proper data could mean waiting a long time before the model can be run. It would therefore be attractive to derive characteristic soil-type/land-use K_s populations to be included in soil databases. They could then be used in addition to pedotransfer functions to feed the models. Such databases would allow the use of non-destructive measurements. For example, aerial photographs, remote sensing images or farmers' knowledge could be used to identify erosive areas in a region, after which sampling can focus on these areas. After identifying the combinations of soil type and land use for the remainder areas, K_s populations from a soil database can be used to characterise them.

CHAPTER 8

SAMENVATTING EN CONCLUSIES

8 SAMENVATTING EN CONCLUSIES

8.1 INTRODUCTIE

Bodemerosie is een wijdverbreid probleem in veel gebieden van de wereld door zijn consequenties voor het milieu zoals sedimentatie en vervuiling. Als gevolg van bodemerosie is wereldwijd de laatste 50 jaar ongeveer 400 miljoen hectare land niet meer voor landbouw geschikt geraakt. Bodemerosie wordt hoofdzakelijk veroorzaakt door afvoer van regenwater over het bodemoppervlak. De infiltratiehoeveelheid is de belangrijkste bio-fysische factor die de hoeveelheid oppervlakteafvoer bepaalt. Het voorspellen van de hoeveelheid oppervlakteafvoer in stroomgebieden hangt voor een groot deel af van de karakteristieken van het infiltratieproces. Infiltratie gedurende een afvoergenererende regenbui wordt bepaald door de hydrologische eigenschappen van de verschillende bodemlagen. Deze eigenschappen zijn de onverzadigde en verzadigde waterdoorlatendheid, de waterretentiekarakteristiek en het bodemvochtgehalte voorafgaand aan de bui. Dit proefschrift behandelt (i) de effecten van de ruimtelijke en temporele variabiliteit van bodemhydrologische eigenschappen, in het bijzonder de verzadigde doorlatendheid, op het ontstaan en voorkómen van afvoer in heuvelachtige stroomgebieden met een lössbodem, en (ii) de toepassing van een erosiemodel in de context van landgebruikplanning en landgebruikonderhandeling. Specifieke doelen van deze studie zijn:

- het kwantificeren van de ruimtelijke variabiliteit van de verzadigde waterdoorlatendheid in geselecteerde stroomgebieden in Nederland en China;
- het ontwikkelen van een bodemfysische schematisatie procedure, waarbij ruimtelijke verschillen in bodemlagen en landgebruik in ogenschouw worden genomen;
- het onderzoeken van de relatie tussen het landgebruiktype en de verzadigde doorlatendheidsverdeling;
- het kwantificeren van effecten van de ruimtelijke variabiliteit van de verzadigde doorlatendheid op berekend water- en bodemverlies;
- het gebruik van modellen als een onderhandelingsinstrument om veelbelovende landgebruik en water- en bodemconserveringsmaatregelen in een regio te verkennen met het doel water- en bodemverliezen te verminderen, gebaseerd op verdelingen van bodemhydrologische kenmerken.

8.2 ONDERZOEKSOPZET

Het onderzoek is uitgevoerd in drie kleine stroomgebieden in het zuidelijk lössgebied in Nederland (provincie Limburg) en in een stroomgebied op het Löss Plateau in China (provincie Shaanxi). Het landgebruik in de stroomgebieden was overwegend agrarisch. In de Limburg-studie zijn hydrologische eigenschappen van de bodemhorizonten binnen de geselecteerde stroomgebieden gemeten en is de invloed van deze lagen op het genereren van afvoer gedurende verschillende karakteristieke regenbuien geëvalueerd. Aansluitend hierop zijn de effecten van ruimtelijk heterogene verzadigde doorlatendheidswaarden op modeluitkomsten bestudeerd door plekken met minimale infiltratie (volledig verkorst oppervlak) en maximale infiltratie (verkorst oppervlak met scheuren) te bemonsteren. In China is deze procedure verder uitgewerkt door gebruik te maken van Simple Random Sampling om landgebruikstypen in het stroomgebied statistisch te identificeren. Het fysisch gebaseerde hydrologisch- en bodemerosiemodel LISEM is voor een gully-systeem in het Chinese stroomgebied getest op zijn nauwkeurigheid. Er is een alternatief landgebruikspatroon voor dit systeem ontworpen, gebaseerd op kennis van de bodemhydrologische eigenschappen als regulerende parameters in afvoer- en bodemerosieprocessen. Voor het hele Chinese stroomgebied is een procedure ontwikkeld om risicoanalyse te presenteren in bodemdegradatiestudies, waarbij gebruik wordt gemaakt van de ruimtelijke heterogeniteit van de verzadigde doorlatendheid. De effecten van alternatief landgebruik op waterafvoer en bodemerosie zijn gekwantificeerd, waarbij gebruik is gemaakt van stochastisch modelleren en Monte-Carlo analyse.

8.3 ONDERZOEKSRESULTATEN

8.3.1. Bodemhydrologische eigenschappen

Hoofdstuk 2 van dit proefschrift beschrijft de ontwikkeling van een bodemfysische schematisatieprocedure om nauwkeurige data voor erosiemodellering aan te leveren. Hiertoe zijn bodemhydrologische eigenschappen verzameld voor afvoersimulaties als onderdeel van de Limburg-studie. Simulaties zijn uitgevoerd met het hydrologisch model SWMS_2D om afvoergeneratie gedurende standaard regenbuien te kwantificeren. De uitkomsten van deze simulaties zijn gebruikt om verschillende klassen van bodemhorizonten te identificeren en vervolgens samen te voegen in een bodemfysische eenheid. Dit resulteerde in een databank met 25 bodemfysische eenheden, ieder representatief voor een of meer boven- en/of dieperliggende bodemhorizonten.

Het ontstaan van korsten en scheuren op lemige bodems is een veel voorkomend proces in lössgronden. Hoofdstuk 3 beschrijft een onderzoek waarin de hydrologische eigenschappen van het bodemoppervlak met volledige korstvorming en gescheurde korsten gemeten worden. De effecten van deze eigenschappen op stroomgebiedsafvoer en bodemverlies in een stroomgebied in Nederland zijn geëvalueerd met het LISEM model. De bodemhydrologische eigenschappen zijn gemeten aan monsters met minimale infiltratie (volledig verkorst oppervlak) en maximale infiltratie (verkorst oppervlak met scheuren) van braakliggende velden en velden met wintertarwe. Voor elke van deze twee bodemoppervlak-types zijn simulaties van afvoer en bodemverlies uitgevoerd voor twee regenbuien met verschillende herhalingsperioden. Aansluitend zijn de waterafvoer en het bodemverlies voor het aanwezige landgebruik voor het hele stroomgebied berekend. Voor gebieden met een intacte korst werd een verhoging van de totale afvoer en piekafvoer berekend in vergelijking met gebieden met gescheurde korsten, in het bijzonder voor buien met een hoge herhalingsfrequentie. Het berekende bodemverlies bleek af te nemen bij toename van de hoeveelheid scheuren.

Hoofdstuk 4 beschrijft een studie die de bodemhydrologische eigenschappen kwantificeert voor de voornaamste landgebruikseenheden in het Chinese stroomgebied. Hierbij zijn de effecten van de statistisch geïdentificeerde binnenvelds-heterogeniteit op uitkomsten van een bodemerosiemodel onderzocht. Om de hydrologische eigenschappen van de bodem te bepalen is een bemonsteringsschema ontwikkeld en toegepast. De verzadigde doorlatendheidsmetingen zijn uitgevoerd op landgebruikclusters, gebaseerd op verschillen in grondbewerking en gewas- en bodemverschillen. Op 14 velden is een 100 m x 100 m bemonsteringsraster uitgezet, met een 1 m x 1m rastercelverdeling. Op elk veld zijn willekeurig tien bemonsteringsplekken geselecteerd met Simple Random Sampling. Een statistische analyse resulteerde in zes landgebruikseenheden die elk verschilden voor de K_s verdeling. De gevoeligheid van het LISEM model is geanalyseerd voor de ruimtelijke heterogeniteit van de verzadigde doorlatendheid bij de berekening van afvoer en bodemverlies gedurende een bui. Hiertoe zijn simulaties uigevoerd met het geometrisch gemiddelde van de K_s-waarden en deze waarde plus of min de standaard deviatie. De resultaten gaven aan dat een verhoging van het geometrische gemiddelde van de K_s-waarde met de standaarddeviatie de afvoer en bodemverlies verlaagde met ongeveer 80%, terwijl een afname met de standaarddeviatie resulteerde in een verhoging van ongeveer 80%. Dit geeft aan dat de ruimtelijke variabiliteit van de verzadigde doorlatendheid de uitkomsten van waterafvoer en bodemerosie in modelsimulaties aanzienlijk beïnvloedt.

8.3.2 Modeltoepassing

Om de nauwkeurigheid van het LISEM model op een kleine ruimtelijke schaal te testen, is een gully-systeem geselecteerd in het stroomgebied op het Löss Plateau van China (Hoofdstuk 5). De gully had een lengte van ongeveer 40 meter en was ongeveer 30 meter breed. De oppervlakte van het stroomgebied dat werd afgewaterd door het gully-systeem was ongeveer 1950 m^2 (inclusief de gully). De gullybodem had een helling van ongeveer 32 tot 40 graden en de wanden van de gully 40 tot meer dan 60 graden. Het bodemvochtgehalte werd automatisch gemeten op verschillende plaatsen en diepten. De water- en sedimentafvoer werd gemeten bij het uitstroompunt van het gully-stroomgebied. Het LISEM model is gekalibreerd voor een regenbui, door de verzadigde doorlatendheidswaarden aan te passen. De gemeten en berekende hydrografen bleken goed overeen te stemmen. Het berekende bodemverlies was ook vergelijkbaar met de gemeten waarden. De validatie is uitgevoerd voor twee andere afvoergebeurtenissen. De validatie van het LISEM model voor deze twee buien gaf redelijk goede resultaten voor de berekende afvoer. De berekende bodemverliezen kwamen niet goed overeen met de gemeten waarden, vermoedelijk door de beperkingen van de meetapparatuur en de onmogelijkheid van het model om kleine afvoergebeurtenissen adequaat te berekenen. Met in acht name van deze beperkingen is berekend wat de afvoer en het bodemverlies zou zijn bij een alternatief landgebruik in het gully-stroomgebied voor een relatief grote regenbui. Scenarioanalyse gaf aan dat bos als een alternatief landgebruik voor de gullybodem zou resulteren in significant lagere water- en bodemverliezen. Dit ondersteunt de herbebossingpolitiek, die door de centrale overheid van China onlangs is voorgesteld en in gang gezet.

Hoofdstuk 6 beschrijft een methodiek om potentiële effecten van veelbelovende conserveringsstrategieën in een onderhandelingsproces met betrokken partijen te presenteren, zodat landgebruik en water- en bodemconserveringsstrategieën kunnen worden gedefinieerd. Hierbij ligt de nadruk op risicoanalyses en economische gevolgen. Effecten van vooraf gedefinieerde landgebruikscenario's op water- en bodemverliezen zijn gekwantificeerd door gebruik te maken van het LISEM model met als invoer het gemiddelde en de stochastische verdeling van de gemeten K_s-waarden. De landgebruikscenario's zijn gedefinieerd op basis van fysische, economische en agrarische belangen. De effecten van de scenario's op huishoudinkomsten zijn geëvalueerd met gebruikmaking van empirisch vastgestelde vergelijkingen. De aldus verkregen scenario's zijn gebruikt als voorbeelden van mogelijke landgebruikstrategieën. Het gebruik van stochastische K_s-verdelingen en Monte-Carlo analyse resulteerde in een band van modeluitkomsten die het effect van de ruimtelijke heterogeniteit op de gesimuleerde afvoer en het bodemverlies weerspiegelt. Hierbij zijn waarschijnlijkheden van de effecten van alternatieve strategieën gepresenteerd. Van de drie onderzochte landgebruikstrategieën reduceerde het scenario met bodemconservering als uitgangspunt (wat tot stand is gekomen door de participatie van boeren in het definitieproces) het water- en bodemverlies het meest, gevolgd door het scenario dat was gebaseerd op bodemkenmerken (vanuit fysisch oogpunt tot stand gekomen) en het scenario gedefinieerd vanuit de landbouw (vanuit economisch oogpunt tot stand gekomen). Alleen het scenario gedefinieerd vanuit de landbouw resulteerde in een kleine verhoging van het huishoudinkomen, terwijl voor de andere alternatieven een duidelijke verlaging van het inkomen voorspeld is.

8.4 VOORNAAMSTE CONCLUSIES

8.4.1 Bodemfysische eenheden

Lössgronden zijn wijdverbreid aanwezig in de wereld, en zijn extreem gevoelig voor water-geïnduceerd bodemerosie. De Limburg-studie toonde aan dat alleen verschillen in hydrologische eigenschappen van het bodemoppervlak verschillen in de berekende afvoer en het bodemverlies in lössgebieden veroorzaken. De China-studie toonde aan dat zelfs wanneer het bodemtype gelijk is, verschillen in landgebruik en landmanagement verschillen kunnen veroorzaken in de hydrologische eigenschappen en dus daarmee in de berekende afvoer en het bodemverlies. Een combinatie van landbehandeling en bodemtype bepaalt de invoer voor hydrologische data in water- en bodemerosiestudies. Wanneer deze combinatie van landbehandeling en bodemtype gelijk zijn, kunnen deze landgebruikeenheden samengevoegd worden in bodemfysische eenheden, ondanks het feit dat het gewas verschillend kan zijn. Dit geeft aan dat de gebruikelijke vertaalfuncties, gebaseerd op alleen textuurdata, niet altijd voldoende informatie leveren voor bodemconserveringsstudies, zelfs wanneer ze de effecten van verschillende dichtheid en organische stofgehalte meenemen.

De resultaten gepresenteerd in dit proefschrift kunnen worden gebruikt om een voorlopig bemonsteringsschema voor vergelijkbare gebieden op te stellen, zodat de totale hoeveelheid monsters nodig om de K_s-verdeling vast te stellen, beperkt kan blijven. Dit bemonsteringsschema moet gebaseerd zijn op een combinatie van bodemeenheden en landgebruik. Wanneer bijvoorbeeld een bemonsteringsschema voor de China-studie gedefinieerd zou zijn met gebruikmaking van de resultaten van dit proefschrift, zou het aantal representatieve velden gereduceerd zijn van de 14 in werkelijkheid bestudeerde velden tot 6.

8.4.2 Onderhandeling

Landgebruikplanning wordt meer en meer een proces van interactie met betrokkenen en de term onderhandeling is daarom meer van toepassing dan planning. In dit onderhandelingsproces zijn de onderzoekers leveranciers van kennis over landgebruikmogelijkheden en van risicoanalyses van milieukundige en socio-economische variabelen. Wanneer een gegevensset die alle benodigde parameters van huidige en alternatieve landgebruiksystemen bevat een keer is samengesteld voor een specifieke regio, kunnen ter plekke simulaties worden uitgevoerd. Dit maakt interactieve onderhandeling met de betrokkenen mogelijk. Deze gegevensset maakt het daarnaast mogelijk risicoanalyses uit te voeren voor vergelijkbare gebieden met relatief weinig extra inspanning.

Het gebruik van stochastische K_s-verdelingen en Monte-Carlo analyse produceert een band in modeluitkomsten die de effecten van de variabiliteit van invoerparameters op modeluitkomsten reflecteert. Dit maakt statistische analyse en vergelijking van berekende resultaten voor alternatieve landgebruikscenario's mogelijk en kan leiden tot een meer afgewogen beoordeling. Dus, modelresultaten kunnen worden gebruikt als een gereedschap in het onderhandelingproces over landgebruikplanning, waarbij de betrokkenen niet geconfronteerd worden met een gegeven antwoord maar met een bandbreedte van opties en de bijbehorende risico's. De manier waarop de resultaten gepresenteerd worden, verschaft politici informatie over mogelijke effecten van verschillende alternatieven op bodemconservering en vormt aldus een krachtig onderhandelingsinstrument voor het definiëren van alternatief landgebruik.

8.5 UITDAGINGEN VOOR TOEKOMSTIG ONDERZOEK

Dit proefschrift presenteert resultaten met betrekking tot lössgebieden, die erg gevoelig zijn voor bodemerosie door water. Voor andere bodemtypen kunnen de resultaten anders zijn en moeten daarom ook worden onderzocht. De nadruk lag op de ruimtelijke heterogeniteit van het infiltratieproces, maar dit proefschrift presenteert ook bewijs dat de infiltratie seizoensafhankelijk is. Het is te verwachten dat de grootte van de infiltratie ook gedurende het seizoen zal veranderen, hoewel gepubliceerde resultaten op dit gebied niet eenduidig zijn. Sommige studies vonden een verandering van de infiltratiesnelheid gedurende een enkele regenbui. Het temporeel dynamische gedrag van de infiltratie moet ook worden gekwantificeerd en ingebracht in modellen.

In bodemconserveringsstudies worden modelresultaten steeds belangrijker in het onderhandelingsproces met betrokkenen, omdat strategieën om bodemdegradatie aan te pakken gezamenlijk ontwikkeld worden. Modelleren moet natuurlijk geen doel op zich zijn. Om direct voeding te geven aan het onderhandelingsproces is het ter plekke toepassen van het LISEM model de belangrijkste uitdaging. Met gebruikmaking van de resultaten kan het debat worden gestimuleerd. Ontwikkelingen in de ict-technologie leiden tot een situatie waarin het interactieve gebruik van modellen mogelijk wordt. De studies die besproken zijn in dit proefschrift tonen echter aan dat er een noodzaak is om een K_s-verdeling beschikbaar te hebben om realistische inschattingen van water- en bodemverlies te kunnen maken. Een bodemfysische schematisatie om een verdeling van de karakteristieke combinaties van bodemtype en landgebruik te verkrijgen is belangrijk om risicoanalyses van modeluitkomsten tijdens discussiebijeenkomsten te kunnen presenteren. Het verzamelen van de data kan betekenen dat er lang gewacht moet worden voordat het model gedraaid kan worden. Vandaar dat het aantrekkelijk is om karakteristieke bodemtype/landgebruik K_s-populaties te verzamelen en op te nemen in bodemdatabanken. Deze kunnen dan gebruikt worden als aanvulling op vertaalfuncties om erosiemodellen te voeden. Met deze databanken is het mogelijk niet-destructieve methoden te gebruiken. Om erosiegevoelige gebieden te identificeren in een bepaalde regio kunnen dan bijvoorbeeld luchtfoto's, remote sensing beelden of lokale kennis gebruikt worden. Bij de bemonstering kan dan de nadruk op deze gebieden liggen. Na vaststelling van de bodemtype/landgebruik in de resterende gebieden kunnen hieraan vervolgens K_s-populaties uit de bodemdatabank toegekend worden.

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CURRICULUM VITAE

Jannes Stolte is geboren op 15 januari 1963 te Nieuw-Buinen. Na het afronden van de HAVO aan het Dr. Nassau College in Assen in 1982, heeft Jannes de Rijks Hogere Landbouwschool te Groningen doorlopen. Daar heeft hij zich gespecialiseerd in de bodemkunde, wat in 1986 resulteerde in een afstudeerscriptie die handelde over het opzetten van een onderzoek naar de structuur van de Groninger zeekleigronden.

Na zijn studie is Jannes werkzaam geweest bij het toenmalige Consulentenschap voor de Veehouderij te Roermond in de functie van specialist bodem, water en bemesting. Daar heeft hij zich voornamelijk bezig gehouden met het opstellen van drainage- en bemestingsadviezen voor agrariërs. In 1989 maakte hij de overstap naar het net opgerichte DLO-Staring Centrum, en kwam te werken bij het bodemfysische laboratorium. Daar heeft hij zich in eerste instantie gespecialiseerd in het ontwikkelen van bepalingsmethoden voor het meten van de onverzadigde waterdoorlatendheid- en waterretentiekarakteristiek. Later is Jannes zich gaan richten op het gebruik en de toepassing van meetgegevens in regionale studies. In 1992 ging het erosienormeringsonderzoek in Limburg van start, waar Jannes een belangrijke inbreng had bij het opzetten en uitvoeren van veldmetingen, en het interpreteren van meetresultaten. In het EROCHINA-project heeft hij de opgedane kennis op het gebied van de bodemfysica en bodemconservering verder uitgebouwd.

Inmiddels heeft Jannes aan meerdere internationale congressen bijdragen geleverd, en resultaten van zijn werk gepubliceerd in nationale en internationale wetenschappelijke tijdschriften. Jannes is op dit moment actief in een aantal grote internationale onderzoeksprojecten op het gebied van bodem- en waterconservering in onder andere de HinduKush Himalaya, China, het Middellandse zee gebied en eilanden in de Pacifische Oceaan.