Rill initiation and development in relation to dynamic soil properties
Bouma, N.A.

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RILL INITIATION AND DEVELOPMENT IN RELATION TO DYNAMIC SOIL PROPERTIES

Nienke A. Bouma
RILL INITIATION 
AND 
DEVELOPMENT 
IN RELATION TO 
DYNAMIC SOIL PROPERTIES

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DESERMA of the Plan Nacional.
Wij zijn een deel van de aarde
en de aarde is een deel van ons
(Seattle, 1854)
Voorwoord

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Contents

Voorwoord 5

Part I  General Introduction 9

1. Introduction 11

2. Rill initiation and evolution: concepts linking rills to soil water and soil properties 19
   2.1 Introduction 19
   2.2 Flow to drains and rills 20
   2.3 Dynamic soil properties and soil erosion 26

3. Description of the research areas and investigation methods 31
   3.1 General description of the research areas 31
   3.2 Methods 38

Part II  Experimental Results and Discussion 55

4. Properties of badland regoliths and cultivated loess soils affecting erosion processes 57
   4.1 Properties of badland regolith affecting erodibility 58
   4.2 Properties of cultivated loess soils affecting erodibility 83

5. Hydrological response of badland regoliths and cultivated loess soils 101
   5.1 Hydrological response of badland regoliths 103
   5.2 Hydrological response of cultivated loess soils 135

6. Erodibility of badland regoliths and cultivated loess soils 169
   6.1 Erodibility of badland regoliths 170
   6.2 Erodibility of cultivated loess soils 195
Part III  Synthesis; Erodibility and hydrological response of soils susceptible to rill erosion

7. The role of dynamic soil properties for the initiation and development of rill erosion
   7.1 Response of dynamic soil properties on rainfall and slope water in badlands
   7.2 Response of dynamic soil properties on rainfall in cultivated loess areas

8. Evaluation of the drainage model for rill initiation and development
   8.1 Conceptual drainage model for badland regoliths
   8.2 Conceptual drainage model for loess
   8.3 Comparison functionality of model for badland and for loess
   8.4 Conclusions and recommendations

Epilogue

Summary

Samenvatting

Resumen

References

Appendices

Curriculum Vitae
PART I

GENERAL INTRODUCTION
1

Introduction

1.1 Framework

Rills are relatively shallow channels, incised in soil materials, created by concentrated surface or subsurface water flow. They can occur naturally, for example in highly erodible marl regoliths as in Southern Europe, and also as a result of cultivation as in the loess belt of North Western Europe. Nearing et al. (1997) describe rills as small, ephemeral, concentrated flow paths, which function as both sediment source and sediment delivery systems. According to the USDA (1993), rills are only a few inches deep and do not hinder the operation of farm machinery. Although tillage may erase them, rills tend to reoccur after heavy rainfall, especially where the vegetation cover is limited (USDA, 1993). If they are too large to be obliterated by weathering or ploughing they are usually considered to be gullies (Soil Science Society of America, 1984). Illustrations of rills in both, badland and cultivated loess areas, are shown in Photo 1.1 and 1.2.

Rill erosion has been defined by Nearing et al. (1997) as “the removal of soil by concentrated water running through small streamlets or headcuts”. An addition to this definition is given in the glossary of the Canada Department of Agriculture (1976): “an erosion process in which many small channels a few centimetres deep are formed; it occurs mainly on recently cultivated soils”. Most of the studies on rill erosion have focussed on the hydraulics of flow processes in existing rills (Nearing et al., 1997; Lei et al., 1998; De Ploey, 1984). Horton (1945) proposed that rills were formed by headcut retreat when overland flow becomes concentrated and exceeds some critical hydraulic condition. Several researchers later have identified critical hydraulic thresholds for rill initiation and rill channel sedimentation (Savat, 1979; de Ploey, 1984; Govers, 1985 and 1987).

However, it has proven extremely difficult to predict the exact location and conditions under which rills are initiated. Generally accepted explanations of rill formation, do not adequately explain the pattern, distribution and evolution of rill systems. Consequently, for the formation of rills it is extremely important to study rills during their initiation and evolution. This implies that the properties of the soil materials in which the rills are developing can no longer be viewed as constant.

Dynamic regolith properties affecting rill initiation and evolution have only been investigated occasionally. Gerits et al. (1987), Imeson and Verstraten (1986, 1988) and Gerits (1991), found that dynamic physical and chemical soil properties were key parameters in the initia-
CHAPTER 1

Photo 1.1 Badland area suffering from rill erosion, Petrer, Alicante, Spain

Photo 1.2 Loess area suffering from rill erosion, Southern Limburg, The Netherlands
tion and development of rills in badlands. They found macropores produced by swelling and shrinkage and the behaviour as expressed in the consistency, to be particularly important. Swelling and shrinkage cause decrease of the bulk density of the regolith and considerable increase of the macroporosity. The enhanced macroporosity enables concentrated pipeflow to occur above any impeding layer, in this case the un-weathered rock (Farifteh and Soeters, 1999). Bryan and co-workers (Bryan and Rockwell, 1998; Bryan et al., 1998) studied rill initiation in relation to dynamic soil properties and infiltration in badland regolith under laboratory conditions.

In the cultivated loess soils referred to above, dynamic effects resulting from cultivation will also influence rill initiation and evolution (Auzet et al, 1993 and 1995; Hansen, 1989; Imeson and Kwaad, 1990; Papy and Boiffin, 1989; de Ploey, 1989a; Øygarden et al., 1997). The dynamics of the macropores produced by ploughing and the development of a plough pan also enable concentrated subsurface flow to occur. A major conclusion for soils that have strong contrasts in the dynamic (macro)porosity of the top and subsurface layers is that rill initiation requires far lower rainfall intensities than when the runoff producing mechanism is Hortonian overland flow. Imeson and Kwaad (1990) mentioned that rill initiation by shallow subsurface flow, micropipe flow, through macropores in the tilled layer and the possibility of breakdown of clods and peds by wetting of the tilled layer below the soil surface is an under-researched topic.

The initiation and development of rills has several important implications for soil erosion. When rills occur, there is a sudden increase in transport rates and transport distances. Much larger sizes of sediment particles can be transported and there is a greater connectivity in the system. Runoff does not only increase but also reaches river channels more rapidly than before, dramatically increasing erosion rates and colluviation (Rauws and Govers, 1988; Govers, 1985; Poesen, 1987; de Ploey, 1983). In Europe, there are two situations in which rill erosion has been observed frequently. These are in the weathered marls within badlands in the Mediterranean Basin (Gerits, 1991; Gerits et al., 1987; Calvo-Cases et al., 1991; Calvo-Cases and Harvey, 1996; Calzolari and Ungaro, 1998; Calzolari et al., 1993; Torri et al., 1987 and 1994; Bouma and Imeson, 2000) and in the cultivated loess belt of North-Western Europe (Poesen, 1987; de Ploey, 1983; Govers, 1987). Other areas, outside of Europe, in which important rill research has been done, are the Dinosaur Badlands in Alberta, Canada (Bryan et al., 1978; Bryan and Hodges, 1984; Bowyer-Bower and Bryan, 1986; Bryan et al, 1984; Hodges and Bryan, 1982), the Zin Valley Badlands in Israel (Kuhn and Yair, 2004) and the Loess Plateau in China (Stolte et al., 2003; Messing et al., 2003; Zang et al., 2004). A general characterization of badlands was given by Bryan and Yair (1982) and Bryan (2000) wrote a comprehensive review of soil erodibility related to water erosion.

Horton (1945) proposed the ‘hydrophysical approach’ of rill network development. The basic idea was that a minimum length of overland flow is required to produce sufficient runoff to initiate erosion. Unit discharge increases with slope length, consequently flow depth increases down slope. Flow velocity increases with flow depth and energy for rill initiation will reach a critical value at a point where there is a chance for concentration of flow. The erosive force and the rate of overland flow at which erosion can take place is directly proportional to the quantity of soil material to be eroded from the surface, the critical distance to initiate soil erosion, slope angle and runoff intensity. This general concept forms the basis for much current research.
Rill erosion is not only of academic importance; it also has important practical implications. In the badland areas the rills occur because of the high erodibility of the regolith and the lack of vegetation cover. This results in the high risk for hazardous flooding and sedimentation during extreme rainfall events. In the loess areas, erosion by rills leads to the loss and impoverishment of the topsoil and lower crop yields as on-site effects. As an off-site effect, flooding is extremely serious. Studies on measures against erosion on cultivated land are therefore extremely relevant (Morgan and Rickson, 1990).

Modelling approach for rill erosion
Horton (1945) explained rill erosion by flow hydraulics. When overland flow exceeded thresholds of hydraulic conditions rills started to develop. A lot of research was done on hydraulic conditions related to rill erosion. However, these conceptual models could not explain the development and initiation of spatial rill patterns. Other problems were that in many cases rills developed under hydraulic conditions which had not exceeded the thresholds for rill erosion. The need for physically-based models came from the concern for more knowledge of processes and from more attention for spatial patterns in erosion. This resulted in distributed, physically based models, in which a hillslope area is divided into a network with cells, which influence each other (Rose, 1983; Nearing et al., 1989; Wright and Webster, 1991; de Roo et al., 1996). In case of predicting rill patterns, spatial distributed models are important tools.

Modelling of rill erosion can have several purposes. Some of them are, prediction of the amount of soil erosion in a specific area, prediction of rill patterns and testing physically-based models for the mechanisms of rill erosion. One of the first empirical models assessing soil loss from hillslopes and cropfields is the Universal Soil Loss Equation (USLE, Wischmeier and Smith, 1978), in which the mean annual soil loss is predicted by a rainfall erosivity factor, a soil erodibility factor, a slope length factor, a slope steepness factor and an erosion control practice factor. Because of experiences with the model it has been revised into the Revised Universal Soil Loss Equation (RUSLE, Renard et al., 1991). Revisions were made for better application to other land-use types (Morgan, 1995).

Most of the underlying data for this Ph.D. thesis were collected by empirical research. Modelling was in this study used as a tool for development of theory or concept and a comparison for the studied processes.

Critical thresholds for rill initiation
Rill erosion involves complex interactions between flowing water and the soil material. Not only the hydraulics of flow are involved but also the chemical, physical and physico-chemical soil properties, which influence the critical shear stress and the initiation process of rill erosion (de Ploey, 1983). This was also found by Bryan (1987), Rauws (1987), Rauws and Govers (1988) and Auzet et al. (1993). Imeson et al. (1982) studied the relationship of soil physical and chemical properties to the development of badlands already in Morocco and Imeson and Verstraten (1985) in South-East Spain. Gerits (1991) studied the relationship between chemical and physico-chemical thresholds and infiltration and erosion processes in badlands in South-East Spain. He found that after crossing chemical thresholds, other physico-chemical processes start to operate, which are related to various forms of infiltration and erosion. However, it is extremely complicated to predict changes in erosion processes, because of the heterogeneity of the material and its behaviour. Gerits et al. (1987) suggest-
ed that the occurrence of rills on badland slopes could be explained if rills were considered to function as drains. This was developed further by Imeson and Verstraten (1988) who proposed a conceptual rill drainage model for badland regoliths, as well as for cultivated loess soils. According to this model, a prerequisite for rill erosion is the presence of dynamic macro-pores in the surface layer above an impeding subsoil and this soil material should be very vulnerable to slaking.

A very important relationship is that between the erodibility of the soil and soil moisture conditions. Several authors (De Leenheer and De Boodt, 1959; de Ploey, 1989a) have demonstrated that soil erodibility is at a minimum around a soil moisture suction of pF 1 and becomes lower under dryer and wetter conditions. If the soil is nearly water saturated at the onset of rainfall, the soil aggregates have a low consistency and are sensitive to erosion even under low intensity rainfall and saturated overland flow can develop. If the soil is dry, sudden wetting by moderate to high intensity rainfall can also lead to slaking of the outer surfaces of aggregates and macropore flow can take place without the soil matrix needing to be wetted. Under both wet and dry conditions rill erosion can occur but with different critical thresholds. Bryan and Rockwell (1998) and Bryan et al. (1998) showed that rill initiation is strongly influenced by soil moisture dynamics on sands and loamy sands. However, this relationship is very complicated.

In view of the complexity of the above relationships and the lack of the necessary information, the general aim of this Ph.D. study is to investigate the threshold conditions for rill initiation and evolution in both badland marl regoliths and cultivated loess soils. This was done in two research areas that were selected as being representative of the weathered marl areas of Southern Europe (Alicante, Spain), and the loess belt in North-Western Europe (South Limburg, The Netherlands). Both areas are susceptible to rill erosion. The materials in these areas contain many macropores in their topsoil, in one case because of shrinkage and swelling and in the other because of ploughing. These macropores are considered as a critical factor for the theory of rill initiation and development presented here. By comparing rill generation mechanisms in two different types of material, greater insight is obtained in understanding why rills occur at all.

1.2 Aim

The general aim of this study is to investigate critical conditions for the initiation and development of rill erosion (in soils containing many macropores above an impervious layer) in representative marl regoliths and cultivated loess soils.

The following hypotheses have been formulated:

• Rill initiation in badland areas is enhanced by the approximate water saturation of the topsoil with many macropores above an impeding layer and by the occurrence of crack flow.
• In freshly ploughed loess, rill initiation is favoured by the approximate water saturation in the Ap-horizon, by a relatively impermeable layer (plough pan) and by preferential flow through macropores.
• Rill development can be explained by considering them as drains. There is a feedback caused by the relationship between soil moisture and shear strength dynamics.
The specific research questions addressed in the two study areas are:
• How does the runoff pattern develop during and after rainfall?
• Does the approximate saturation and subsequent crack and macropore flow develop above an impeding layer during and after rainfall?
• Does slaking and liquefaction of soil aggregates occur in badland marl regoliths and in cultivated loess areas during rainfall and does this contribute to rill initiation and development?
• Do the results of rainfall simulation experiments corroborate the projections of the rill drainage model for soils with strongly dynamic soil properties?
• Which field and laboratory parameters are good indicators for rill erosion and mass movements?

1.3 Approach

The research was organised into three parts relating to, (i) conceptual model and hypothesis development, (ii) experimental work and (iii) data evaluation, analysis and synthesis (Fig. 1.1).

Under (i) a conceptual model and hypotheses development, a literature survey was made of rill erosion, drainage theories, macropore flow and dynamic soil properties affecting erodibility of badland regoliths and cultivated loess soils.

Under (ii), field studies of hydrological processes, dynamic properties and erosion were made during rainfall simulation experiments. This involved monitoring the amount and type of erosion, soil moisture conditions, runoff, shear strength and surface roughness. In the laboratory soil physical, chemical and physico-chemical properties were measured for both badland regolith and cultivated loess soil materials.

Under (iii) the responses of the different surfaces were established, analysed and compared in order to identify appropriate thresholds for both materials. A synthesis was made highlighting and evaluating the research hypotheses.

1.4 Outline of the thesis

The organisation of this thesis follows the structure of the research. Part 1 (Chapters 1 to 3) is a general introduction to the subject of rill initiation and development. Part 2 (Chapters 4, 5 and 6) presents and discusses the results of the field and laboratory experiments. Part 3 (Chapters 7 and 8) presents the above mentioned analysis and synthesis.

Following this introduction, Part 1 includes a review of the papers about the existing theories on rills and the description of the field area and methods used in this study. Chapter 2 describes the theory of drainage models for soils containing macropores in the topsoil and having an impeding layer. It also describes the theory of erodibility of soil materials related to dynamic soil properties, like shrinking and swelling, (macro)porosity and slaking of the soil material. In Chapter 3 relevant background information on the geology, geomorphology, climate and soils are presented and the methods are described.

The second part of the thesis describes the results and gives the discussion of the exper-
imental work. Chapter 4 describes the soil and regolith material properties and field characteristics. A discussion of the experimental results and hydrological processes in the two areas is made. Chapter 5 describes and discusses the hydrological results of the rainfall simulation experiments. Chapter 6 describes and discusses the measurements for erodibility and the response of both, badland regoliths and cultivated loess soils, upon wetting.

The third part (Chapter 7 and 8) is a synthesis of hydrological processes and response of soil material upon wetting for both areas and theoretical concepts are evaluated. Chapter 7 discusses indicators for rill erosion and in Chapter 8 a conceptual model for both badland regoliths and loess soils is evaluated. Finally the conclusions and recommendations for further research are given.

In the Epilogue considerations are given with respect to present research and relevance of rill erosion research for society, and the consequences for land management practise especially within the European Community.
CHAPTER 1

RESEARCH QUESTIONS

BADLANDS

field

- drainage pattern during and after rainfall

- saturation and preferential flow

- relationship between slaking and liquefaction

- surface characteristics

- sediment concentration

- rill maps

- chemical soil properties

- dynamic soil properties

- mineralogical soil properties

LOESS

laboratory

- rainfall simulation experiments

- soil moisture

- pressure head

- runoff

- hydraulic conductivity

- wetting front

- (macro) porosity

- water retention

- (macro) porosity

- chemical soil properties

- dynamic soil properties

- mineralogical soil properties

SYNTHESIS

badland

results

model

loess

Figure 1.1 Research questions and derived experiments and analyses
2

Rill initiation and evolution: concepts linking rills to soil water and soil properties

2.1 Introduction

In most studies rill erosion and especially rill initiation have been treated, as already mentioned, in terms of flow hydraulics (Horton, 1945). Horton considered rill development to be related to the velocity and hence the depth of overland flow (Gerits et al., 1987). Rills are usually found in materials that are to some degree cohesive, so that there are limitations in applying theory derived from studies of the hydraulic action of water on non-cohesive particles (Meyer and Monke, 1965). In most cohesive soils, detachment processes are affected by physico-chemical interactions between the soil materials and water. The effects of physico-chemical processes on the detachment, transport and deposition of these materials have been described, for example by Gerits (1991), Partheniades (1972) and Grissinger (1966). Chemical conditions of the soil-water system profoundly influence swelling and shrinkage behaviour. This is important for two reasons. Firstly, swelling and subsequent shrinkage can lead to the development of soil macropores. Secondly, swelling reduces the hydraulic conductivity of ped surfaces preventing infiltration into the ped interiors. Swelling during the infiltration process can account for the rapid generation of macropore bypass flow (Bronswijk, 1988; Bouma and Dekker, 1978; Bouma and Wöstien, 1979; Bouma, 1980; Bouma et al., 1981; Flury et al., 1994; Gerits, 1991).

Gerits et al. (1987) concluded that rills in badland regolith could be considered as drains. Unweathered rock acts, in this situation, as an impermeable layer on which a perched water table develops. The saturation of the soil material, caused by the water table, decreases internal cohesion of the soil aggregates. This process counts for the high erosivity of the subsurface flow (Gerits et al., 1987; Imeson and Verstraten, 1988). The model proposed was based on the Donnan equation (Donnan, 1946). The hydrology could be explained by considering flow in micropipes and rills as being comparable (Bryan et. al., 1978). Furthermore, Gerits et al (1987) also included the concept of the minimum drainage area required for micropipe
development and rill initiation analogous to Schumm's constant of channel maintenance (Schumm, 1956). When the crust and subcrust layers of the regolith profiles have low hydraulic conductivity and also a high crack density, a steep hydraulic gradient potentially occurs if the cracks are partially closed. Consequently, the subsurface flow has a very high erosivity. This is accompanied by a very high erodibility resulting from the effects of the soil and water composition on soil behaviour.

Particularly important for the high erodibility are the practical sodium adsorption ratio (SARp; Sposito et al., 1977) and the electrolyte content of the soil solution, as expressed by the electrical conductivity (EC). Depending on the texture and clay mineralogy these parameters influence shrinking and swelling, bulk density, dispersion and shear strength, both of the wet and dry soil. In smectitic clays, a highly porous and permeable structure is created, which permits rapid internal drainage (Imeson, 1986). These conditions are favourable for rill development (Bowyer-Bower and Bryan, 1986). Other important influences on the development of a surface crust are slaking of soil aggregates or peds. Various consistency tests have been developed to study these influences (Singh, 1967; Young and Warkentin, 1975; de Ploey and Mümker, 1981).

In cultivated loess soils the hydrology is greatly influenced by ploughing which produces macropores and leads to subsoil compaction. The situation in the Ap-horizon, in which large peds (in this case sensitive to slaking) separated by many macropores, overlie a relatively impermeable ploughpan, is analogous to that described above for the badland regoliths. It is also analogous to the situation in texture-contrast (duplex) soils in the Keuper marls in Luxemburg, which are also sensitive to piping and gully erosion (Imeson, 1986; v. d. Broek, 1989; Cammeraat, 1992).

The next section describes models that have been developed to describe flow to drains and that have the potential to be applied to rills. Finally, dynamic soil properties and their links to soil erosion are explained.

2.2 Flow to drains and rills

2.2.1 Introduction

Dupuit and Forchheimer (Bos, 1994) solved the problem of flow to parallel canals and pumped wells. The underlying assumptions and solutions to specific situations, i.e. steady flow above an impervious horizontal boundary and a steady water table and a water table subject to recharge, can be found in Bos (1994).

Houghoudt (1940) derived an equation based on Dupuit-Forchheimer for horizontal flow to drains. This equation was derived from the following equations:

\[ q_x = R \left( \frac{1}{2} L - x \right) \]  \hspace{1cm} (2.1)
in which

\[ x = \text{distance from drain (m)} \]

\[ q_x = \text{unit flow rate in x-direction (m}^2/\text{day)} \]

\[ R = \text{rate of recharge per unit surface area (m/day)} \]

\[ L = \text{drain spacing (m)} \]

and

\[ q_x = K_y \frac{dy}{dx} \]  \hspace{1cm} (2.2)

in which

\[ q_x = \text{unit flow rate in x-direction (m}^2/\text{day)} \]

\[ K = \text{hydraulic conductivity soil (m/day)} \]

\[ y = \text{height of water table at x (m)} \]

\[ \frac{dy}{dx} = \text{hydraulic gradient at x (-)} \]

Substituting equation (2.2) in (2.1) gives:

\[ K_y \frac{dy}{dx} = R \left( \frac{1}{2} L - x \right) \]  \hspace{1cm} (2.3)

**Figure 2.1** Flow to drains above an impervious layer (Ritzema, 1994)

Parameters and variables in the above and the following equations are illustrated by Figure 2.1.

Hooghoudt (Ritzema, 1994) set the following limits for integration:

- for \( x = 0, y = D \) \hspace{1cm} (a)
- for \( x = 1/2L, y = H \) \hspace{1cm} (b)

\( D = \) elevation of the water level in the drain (m)

\( H = \) elevation of the watertable midway between the drains (m)
Chapter 2

After integration and substitution of the preceding boundary conditions equation (2.4) is obtained:

\[ K \frac{1}{2} y^2 = R \frac{1}{2} L x + R \frac{1}{2} x^2 + C \]

substitution of limit (a) gives \( C = \frac{1}{2} KD^2 \)

\[ \Rightarrow K \frac{1}{2} y^2 = R \frac{1}{2} L x + R \frac{1}{2} x^2 + \frac{1}{2} KD^2 \]

substitution of limit (b) gives

\[ \frac{1}{2} KH^2 = R \frac{1}{4} L^2 - K \frac{1}{8} L^2 + \frac{1}{2} KD^2 \]

\[ \Rightarrow L^2 = 4K \frac{(H^2 - D^2)}{R} \]

Donnan (1946) (2.4)

When the soil profile is divided into a part above and below drain level the following equations are valid:

\[ H\cdot D = h \]
\[ H + D = 2D + h, \text{ in which } h = \text{ height water table above drain level (m)} \]

Substitution of this concept leads to:

\[ Q = \frac{8K_h D h + 4K_h h^3}{L^2} \] (2.5)

in which
\( Q = \) drain discharge (m/day)
\( D = \) elevation of the water level in the drain (m)
\( L = \) drain spacing (m)
\( h = \) maximum height of the watertable above the water level in the drain (m)
\( K_h = \) hydraulic conductivity of layer above drain level (m/day)
\( K_b = \) hydraulic conductivity below drain level (m/day).

Equation (2.5) describes a situation of a soil profile with two soil layers with different hydraulic conductivity and the drain level at the interface of both soil layers.
2.2.2 The influence of macropores on drainage

The investigated badland regoliths and cultivated loess soils are not homogeneous. They contain discontinuous macropore systems that concentrate flow in unsaturated soils so that Darcy’s law is not applicable.

Several authors have developed models for macropore flow (e.g. Kutilec and Novak (1976), Edwards et al. (1979) and Beven and Germann (1981). A comprehensive review of this subject was made by Beven and Germann (1982). They found that the discontinuity of macropore flow (a) increased with the size and connectivity of the macropores and (b) decreased with increasing capillary tension within the macropores.

Bronswijk (1988) analysed infiltration and the vertical transport of water in a cracked clay soil, treating matrix and crackflow separately. He found that the partitioning of rainfall into infiltration between the matrix and cracks varied continuously. All water infiltrating into cracks is assumed to accumulate at the bottom of the cracks. Vertical infiltration into crack walls is very small, as was also shown by Hoogmoed and Bouma (1980). These authors constructed a simulation model for predicting infiltration into cracked clay soils. Void patterns in swelling clay soils change upon wetting, due to swelling processes, which reduce planar widths. Bouma et al. (1979) were able to predict saturated hydraulic conductivity using micromorphometric observations in a pedal clay soil.

Macropores can play an important role in subsurface flow during storms (Beven and Germann, 1982). Water infiltrating in macropores accumulates at some depth in the soil when macropores become discontinuous (van Stiphout et al., 1987). Depending on the pore connectivity they cause a rapid conduction of water through unsaturated soil and flow in macropores can be turbulent in either unsaturated or saturated soil. An important conclusion is that macropores can create a heterogeneous pattern of saturation at the base of the soil profile or above an impeding layer. This is likely not only to be the case for storm events but also for rainfall simulation experiments.

2.2.3 Adapting drainage models to badland regoliths

For badland regoliths equation (2.4) is adapted to the situation existing in rills (Fig. 2.2a). In this case \( D = 0 \), which means that the bottom of the rill is lying on the impermeable layer, i.e. the unweathered regolith and depth of the water level in the rill is considered as 0. When \( D = 0 \), equation (2.4) is simplified to (Ritzema, 1994):

\[
Q = \frac{4Kth^2}{L^2} \tag{2.6}
\]

in which:
- \( Q \) = rill discharge (m/day)
- \( K_t \) = hydraulic conductivity above drain level (m/day)
- \( h \) = height of the watertable above the waterlevel in the rill (m)
- \( L \) = rill spacing (m)
This equation describes steady state conditions. There are two cases when this is appropriate. The first is that of the complete saturation of the soil profile when the soil is completely swollen without any crack for rapid flow to the rills. The second is when the ped surfaces (which have very low permeability because of rapid swelling) hinder the further wetting of the ped. In this case bypass flow moves through the unsaturated profile as crack flow (Fig. 2.2a). According to Gerits et al. (1987), if rills, micropipes and cracks are considered as drains in (partly) saturated regolith, equation (2.5) can be applied for different stages of runoff. According to equation (2.5), the rate of drainage ($Q$) depends on the hydraulic conductivity of the weathering layer, the macroporosity of the subcrust, the hydraulic gradient ($h$) and the crack density or drain spacing ($L$). A minimum threshold three-dimensional drainage area will be necessary to generate runoff. This will vary in size according to regolith properties.

**Figure 2.2a** A model for horizontal drainage to rills in badland regolith (Imeson and Verstraten, 1988)

With respect to the spacing between rills, Imeson and Verstraten (1988) describe a case whereby this is controlled by the effect of the rill on increasing the shear strength of the surrounding area. Liquefaction or flow is assumed to occur when the weathered regolith above a shard layer is moistened long enough for it to swell into a mobile mass. This results in parallel rills, the spacing of which is controlled by slope, shear strength and permeability.

2.2.4 Adapting drainage models to cultivated loess soils

For cultivated loess soils, Gerits et al. (1987) draw attention to similarities with badland
regoliths. The macroporosity produced in cultivated loess soils by tillage may have the same implications on internal drainage and rill initiation as shrinking and swelling in badland regoliths. Imeson and Verstraten (1988) mention that on these cultivated loess soils, discontinuous infiltration can occur during tillage. In soils sensitive to slaking saturated zones could be developed, lowering the shear resistance of the soil enough for the development of channels by overland flow. Steady state conditions in ploughed loess soil are created during a relatively low intensity rain storm, when the soil surface does not immediately slake. Two situations could occur in the soil profile. The first one is a complete saturation of the soil aggregates and soil profile. The second is slaking of soil clods enforcing bypass flow to the lower part of the Ap-horizon.

For cultivated ploughed loess soils the Donnan equation becomes:

$$Q = \frac{8K_h D h + 4K_b h^2}{L^2}$$

(2.5)

in which,

- $Q$ = rill discharge (m/day)
- $D$ = elevation of the water level in the drain (m)
- $L$ = rill spacing (m)
- $h$ = maximum height of the watertable above the water level in the drain (m)
- $K_h$ = hydraulic conductivity of layer above drain level (m/day)
- $K_b$ = hydraulic conductivity below drain level (m/day)

**Figure 2.2b** A model for horizontal drainage to rills in cultivated loess soil (after Imeson and Verstraten, 1988)
The hydraulic conductivity above and below drain level differ because of the effects of different cycles of wetting on the soil structure and hydrological behaviour of the soil. The soil above drain level is often more permeable than below drain level because of cracks and roots. The situation in a ploughed loess profile is sketched in Fig. 2.2b. The ploughed layer (Ap-horizon) contains abundant macropores, which favour the generation of macropore flow. The less permeable horizons underlying the more permeable layer are the Bt-horizon or a plough sole. Rills should form at the base of the upper layer, at the boundary between Ap-horizon and impervious Bt-horizon or plough sole. In this case the height of drain level \( D \approx 0 \), equation 2.5 becomes equation 2.6 as mentioned in section 2.2.3. For a very shallow rill in ploughed soil is \( D \gg h \) and therefore the second term of equation 2.5 approximates 0, reducing the equation to:

\[
Q = \frac{8K_d D h}{L^2}
\]  

Equation (2.7) describes the flow below drain level. This equation is also adequate for a more extensive rill network with relatively wide spacing between rills.

Different runoff producing mechanisms can occur in cultivated loess soils on hillslopes. Kwaad (1991) found that Horton overland flow prevailed in summer and saturated overland flow in winter. This was confirmed by Ritsema et al. (1996) from pressure head measurements and modelling which also included macropore flow. Their main conclusion was that the structure of the upper soil layer was the most important factor in predicting the hydrological behaviour of these soils.

2.3 Dynamic soil properties and soil erosion

2.3.1. Introduction

An important process in rill initiation concerns the loss of coherence of soil as it becomes moistened. Changes in pore volume in relation to the water content are important. This process is dependent on the potential for volumetric change, the sensitivity to dispersion and on consistency. Soils susceptible to swelling and shrinkage generate macropores by the alternation of wetting and drying and are potentially very sensitive to rill erosion. Shrinking and swelling also control crack sizes and distributions and consequently influence the growth of macropores that can develop into rills, pipes and tunnels. The processes of shrinkage and swelling, slaking, dispersion and the soil properties consistency, aggregate stability and clay mineralogy are closely related to soil erodibility in the studied soils.

Shrinkage and swelling follow drying and wetting cycles and lead to irreversible decreases in the bulk density. When water infiltrates for the first time into badland regoliths the material swells, producing tension cracks. When the material dries out shrinkage cracks are formed. The infiltration of water into a ped is very slow, because the swelling of the outer surface dramatically lowers the hydraulic conductivity. Regolith with a very high swelling ratio (Hodges and Bryan, 1982; Imeson, 1986; Imeson and Verstraten, 1988) produces a popcorn-
like material that is too mobile or dynamic to enable rills to persist or micro pipes to develop into larger features. If the swelling ratio is too low, the infiltration is uniform and flow will be insufficiently concentrated for rills to form.

The consistency of the soil has also been shown to be related to slaking (de Ploey and Mücher, 1981). Material in which rills form has been reported as having a high liquid limit (Gerits et al, 1987), which reflects the ability of material to resist displacement by shallow sliding. The liquid limit is related to a threshold between two exclusive sets of erosional processes; one dominated by flow through macropores which is in material that offers relatively high resistance to liquefaction; the other in material in which flow processes occur at such a low threshold moisture content that subsurface micropipes are unable to form or survive.

Gerits (1991) found that on sites where rills are present, clay is more likely to be dispersed. Due to the effect of the chemistry of the water soluble salts on swelling and dispersion, the critical shear stress for the material from the rilled sites to be entrained is lower than the non-rilled sites (Imeson and Verstraten, 1988). From studies in badlands suffering from shrinkage and swelling the idea has been formed by Imeson and Verstraten (1988) and Gerits et al. (1987) that especially crack flow formed by a steep hydraulic gradient is very erosive in badland regoliths. They thought a steep hydraulic gradient was formed by low crust and subcrust hydraulic conductivity, deep cracks and a high crack density. This high erosive crack flow contributes to a perched water table, which decreases the consistency of the soil aggregates, by which a new micro pipe or rill is created. This process implies a rainfall intensity or water flux high enough to keep surface cracks open and cause an adequately concentrated crack flow. Increase in water flux is the drive for the processes, which contribute to the increase of macropores and followed by rill formation.

From the above, the following relationship between change in pore volume and water flux can be formulated:

\[
\frac{dP}{dF} = C \times P
\]

(2.8)

in which,

- \( P \) = pore volume \((\text{m}^3/\text{m}^3)\)
- \( F \) = water flux as bypass flow in macropores \((\text{m/s})\)
- \( C \) = constant, dependent of dynamic soil properties, physico-chemical thresholds and chemical parameters related to change in soil moisture content; inverse velocity \((\text{s/m})\)

When by exceeding a critical value of \( P \) a newly formed macropore causes the formation of a new rill, a change in hydrology of rill and interrill area takes place, by drainage of the surrounding area.

2.3.2 Dynamic soil properties related to soil erosion in badland regoliths

Clay particles in badland regoliths are often dispersed easily upon the addition of water with a low electrolyte concentration (van Olphen, 1998; Bolt and Bruggenwert, 1978). In cohesive
soils physico-chemical thresholds are important. These thresholds depend on interparticle forces, bonding mechanisms and externally imposed conditions. After crossing a physico-chemical threshold a specific physico-chemical process starts to operate. Gerits (1991) studied externally imposed conditions that affected dispersion. These included raindrop impact and bed shear stress.

Finally the physico-chemical processes playing a role in resistance of the aggregates to erosion result in a specific consistency of the soil aggregates. Several parameters can be derived from measurements of soil strength. The erosion process in badland regoliths creating more macropores and which depends on change in velocity of infiltrating water and physico-chemical and chemical soil properties is described in a specific form of the general equation (2.8):

\[ \frac{dP_b}{dF_b} = C_b \times P_{ib} \]

(2.9)

in which
- \( P_{ib} \) = pore volume of reference/initial situation of badland regolith (m\(^3\)/m\(^3\))
- \( P_b \) = pore volume of badland regolith, dependent of shrink and swell, dispersion, erodibility, soil moisture and water flux (m\(^3\)/m\(^3\))
- \( F_b \) = water flux as bypass flow in cracks and macropores (m/s)
- \( C_b \) = constant, dependent of physico-chemical thresholds and chemical parameters of the regolith related to change in soil moisture content; inverse velocity (s/m)

Description of the parameters shows the difference between equation (2.8) and (2.9). Equation (2.9) is especially valid for badland regoliths. The hypotheses mentioned in Chapter 1 and the experiments developed for badland regolith, described in Chapter 3 have been derived from this equation.

2.3.3 Dynamic soil properties related to soil erosion in cultivated loess soils
In the cultivated loess soils, the formation of macropores above an impervious layer, the soil consistency and dispersibility are important. Both ploughing and slaking are main factors in the erosion process. The shrinkage and swelling capacity of the cultivated loess soils is low. Loess soils are very susceptible to slaking and both the antecedent soil moisture and rate of wetting play a role. The rapid wetting of a dry loess soil leads to aggregates exploding when air is entrapped. For further details of the very complex processes of slaking and welding that occur in these soils reference is made to Kwaad and M"ucher (1994). The soil strength of bulk soil has been studied by several researchers (Dexter, 1988; Singh, 1967; Govers and Loch, 1993; Perfect et al., 1990; Groenevelt, 1989; Hadas and Wolf, 1984; Groenevelt and Kay, 1981; Chittleborough, 1982; Hewitt and Dexter, 1980). Both the number and rate of wetting and drying cycles have large effects on soil behaviour in the field. Dexter (1988) described the process of tilth mellowing resulting from the gradual increase in cracks that reduced the tensile strength of the soil, increasing its friability.

General equation (2.8) relating pore volume change to erodibility of the soil and change
in water flux is adapted for cultivated loess soils as follows:

\[
\frac{dP_i}{dF_i} = C_i \times P_{il} \tag{2.10}
\]

in which

\( P_i = \) macropore volume of reference/initial situation, which is a result from cultivation, i.e. ploughing or harrowing (m³/m³)

\( P_{il} = \) macropore volume of cultivated loess soil, dependent of slaking, welding, loss of consistency, soil moisture content and macropore flow (m³/m³)

\( F_i = \) water flux as bypass flow in macropores (m/s)

\( C_i = \) constant, dependent of ability to slake, thresholds for consistency and antecedent soil moisture content as a controlling factor for slaking and dispersion; inverse velocity (s/m)

For loess soils especially antecedent soil moisture content influences the erodibility of the soil aggregates. Macropores in cultivated loess soils are in the initial situation created by cultivation type, like ploughing or harrowing. The development of macroporosity depends on slaking ability, thresholds for consistency and the amount of bypass flow compared to the antecedent soil moisture content. From this theory, the hypotheses, mentioned in Chapter 1, and the experiments developed for loess soils (Chapter 3) have been derived.
3

Description of the research areas and investigation methods

3.1 General description of the research areas

The locations of the badland regolith field site in South-East Spain and of the cultivated loess soil field site in the southern part of The Netherlands are shown in Figure 3.1.1.

*Figure 3.1.1* Study area in the Petrer Badlands, Spain and in cultivated loess area, The Netherlands (a short description of these areas will be presented in the next paragraph.)
3.1.1 The Petrer Badlands

The field area is located near the village of Petrer, Alicante, SE Spain (Fig. 3.1.1). The area has been intensively investigated by Calvo et al. (1991) and Calvo and Harvey (1996) and it is one of the sites of the Spanish badland research project DESERMA of the Plan Nacional. The badlands are developed in Upper Cretaceous (Senonian) marls (IGME, 1978a and 1978b) and show various degrees of rill erosion and mass movements (Harvey and Calvo, 1991). The presence of the badland slopes is related to the dissection of Pleistocene valley fills, strongly linked to diapiric uplift along an E-W axis near the southern margin of the Prebetic ranges (Harvey and Calvo, 1989). The maximum local relief of the badland area is about 80 m. Dominant geomorphologic processes in the badlands are rill erosion, shallow land sliding and shallow bridge piping (Calvo and Harvey, 1996). Calvo et al. (1991) define these badlands as being zones of deeply dissected soft rock terrain with little or no vegetation on which rapid erosion, dominantly by surface processes, produces a rill and gully network of very high drainage density. They describe the Petrer Badlands as having been incised during the Holocene following the development of pediments (Calvo and Harvey, 1996). On the south facing slopes, no vegetation or lichen cover is present. In contrast, on the north facing slopes, vegetation is found on upper and lower slope positions.

At Petrer, the mean annual precipitation ranges from 296 to 339 mm with an annual average number of rain days of 33 (Calvo and Harvey, 1996). Spring and autumn are the wettest periods (Perez, 1994). Long duration of high intensity rainfall is not common. For example, rainfall with a duration of 60 minutes and an intensity of 70 mm/hr occurs once every ten years at the Valencia meteorological station, which is 45 km from the study area (Fig. 3.1.2). However, shorter showers with duration of 10 minutes and a similar intensity occur every two

![Figure 3.1.2 Rainfall duration curves Valencia, Spain (after Elias and Ruiz, 1979)](image)

**Figure 3.1.2** Rainfall duration curves Valencia, Spain (after Elias and Ruiz, 1979)
Figure 3.1.3a Five minutes peak intensities of rainfall events during the monitored period (1991-1995) in badland area, Petrer, Spain

Figure 3.1.3b Average rainfall intensity of rain events during the monitored period (1991 - 1995) in badland area, Petrer, Spain
years (Elias and Ruiz, 1979). During this Ph.D. study, (autumn 1991 to autumn 1994), the peak intensities that occurred were between 150 and 200 mm/hr in the autumn of 1993 (Fig. 3.1.3a). The highest average rainfall intensity of rain events during the monitored period was 23mm/hr (Fig. 3.1.3b). Measurements were done in the field in November 1991, September 1992, November 1992 and September 1994, as marked in Figures 3.1.3a and b. The rainfall simulation experiments were carried out between September and November 1992. The mean annual temperature is 14.0 °C (Calvo and Harvey, 1996) and the mean maximum monthly temperature is 30.4 °C in July, The mean minimum monthly temperature is 2.2 °C in January (Perez, 1994).

There are many abandoned cultivation terraces within the Petrer badland area, most of which are heavily eroded by pipe and gully erosion. These terraces were constructed between 250 and 300 years ago for the cultivation of olives. Although abandonment began 90 years ago, at a time of rural depopulation, the last terrace was abandoned only in 1977 (Rodriguez, 1992). At present the land is used only for extensive grazing.

The current vegetation is mainly degraded shrubland of the *Rhamno-Quercetum cocciferae* association. The south facing badland slopes have occasional isolated individual plants, mostly *Moricandia arvensis* and *Lygeum spartum*. On colluvial soils and on north facing slopes a denser and more differentiated vegetation is found, dominated by *Coronilla minima*, *Brachypodium retusum*, *Cistus Albidus*, *Bupleurum fruticescens*, *Erica multiflora*, *Helictotrichon filifolium* and *Fumana ericoides* (García et al., 1995).

Three different marl outcrops are found within the field area. For convenience these are referred to by colour (white, brown and grey). Each lithological unit has its characteristic surface morphology and dominant erosion processes. The white marls are dominated by rill and pipe erosion (Photo 3.1), whereas on the brown and grey marls mass movements are more important (Photo 3.2 and Photo 3.3). Considerable pipe erosion also occurs on the brown marls. On the white marls, very shallow mass movements are observed at the sides of rills. These badland regoliths are referred to in this study as marls or marl regoliths, which terms are considered similar.

In general, the soil profiles in the various regolith materials are poorly developed. They are classified as Leptosols or Calcaric or Eutric Regosols (FAO et al, 1998). Weathered regolith profiles vary in depth from 7.5 to 30cm. The profile layers can be subdivided into crust + subcrust, subsurface material, weathered shards, slightly weathered shards and unweathered shards (Table 3.1.1). Surfaces with mass movements generally have deeper weathered profiles than those where rills are found.

General characteristics of the different regolith types are given in Table 3.1.2. Soil chemically, the most noticeable differences are those that distinguish the grey marls from the other regoliths, which are a relatively low SARp and ESP and a high residual alkalinity in the surface layer (Table 4.1.1). All of the materials have a distinctive clay mineralogy. The grey marls have the highest smectite contents, the brown marls the highest illite and the white marls the highest kaolinite content (Table 3.1.2). Other properties are presented in Chapter 4.
RESEARCH AREAS AND INVESTIGATION METHODS

Photo 3.1 White marls; rill erosion

Photo 3.2 Brown marls; mass movements

Photo 3.3 Grey marls; mass movements
Experimental rainfall simulation plots were established on each type of regolith. The brown and grey marls were only encountered on south facing slopes. White marls predominated in the area and found on slopes with all aspects. Experimental plots could therefore be located on slopes with different aspects.

3.1.2 Cultivated Loess Area
Within the area of Weischelian (Pleniglacial) loess in Dutch South Limburg, two research sites were selected at respectively Wijnandsrade and Catsop (Fig. 3.1.1b). At Wijnandsrade the site was suitable for rainfall simulation experiments and at Catsop for studying a pre-existing rill system. The soil has been completely decalcified at Wijnandsrade and at Catsop partially decalcified up to 3m (Ritsema et al., 1996). More than 60% of the loess is generally in the

Table 3.1.1 Regolith profiles in badland area

<table>
<thead>
<tr>
<th>Depth layer</th>
<th>White marls</th>
<th>Brown marls</th>
<th>Grey marls</th>
</tr>
</thead>
<tbody>
<tr>
<td>&lt;1mm crust</td>
<td>&lt;1mm crust</td>
<td>&lt;1mm crust</td>
<td></td>
</tr>
<tr>
<td>0-1cm subcrust</td>
<td>0-2cm subcrust</td>
<td>0-0.5cm subcrust</td>
<td></td>
</tr>
<tr>
<td>1-2.5cm subsurface</td>
<td>2-5.5cm subsurface</td>
<td>0.5-10.5cm subsurface</td>
<td></td>
</tr>
<tr>
<td>2.5-7.0cm weathered shards</td>
<td>5.5-10cm weathered shards and salt crystals</td>
<td>10.5-20.5cm weathered shards</td>
<td></td>
</tr>
<tr>
<td>7.0-10cm slightly weathered shards</td>
<td>10-20cm slightly weathered shards</td>
<td>20.5-30cm slightly weathered shards</td>
<td></td>
</tr>
<tr>
<td>&gt;10cm very slightly weathered shards/bedrock</td>
<td>&gt;20cm bedrock</td>
<td>&gt;30cm bedrock</td>
<td></td>
</tr>
</tbody>
</table>

Table 3.1.2 General characteristics of regolith types, Petrer, Spain

<table>
<thead>
<tr>
<th>General characteristics</th>
<th>White marls</th>
<th>Brown marls</th>
<th>Grey marls</th>
</tr>
</thead>
<tbody>
<tr>
<td>Dominant erosion process</td>
<td>rill erosion</td>
<td>mass movements</td>
<td>mass movements</td>
</tr>
<tr>
<td>Aspect</td>
<td>N358, N240</td>
<td>N214</td>
<td>N179</td>
</tr>
<tr>
<td>Slope angle (°)</td>
<td>43</td>
<td>52</td>
<td>37</td>
</tr>
<tr>
<td>Clay (mass% of clay fraction)</td>
<td>Smectite</td>
<td>Illite</td>
<td>60</td>
</tr>
<tr>
<td>Kaolinite</td>
<td>27</td>
<td>15</td>
<td>6</td>
</tr>
<tr>
<td>Calcite (mass% of fine earth fraction)</td>
<td>70</td>
<td>48</td>
<td>41</td>
</tr>
<tr>
<td>Texture (mass% of mineral particles)</td>
<td>Sand</td>
<td>62</td>
<td>6</td>
</tr>
<tr>
<td>Silt</td>
<td>30</td>
<td>26</td>
<td>33</td>
</tr>
</tbody>
</table>
texture class 16 to 50mm and 20% is in the clay fraction. Illite is the dominant clay mineral. The amount of smectite is 5-10 mass% (Mücher, 1986). The loess soil profiles have been classified as truncated Gleyic Luvisol (Kwaad and Mücher, 1994; van Mulligen, 1988) or truncated Luvisols (De Roo, 1993).

The cultivated loess profiles generally consist of an Ap-horizon, a Bt-horizon and the (partly) decalcified parent material (C-horizon). The thickness of the Ap-horizon varies in the study area between 25 and 40 cm, depending on the amount of erosion. The area is intensively cultivated and has a gently sloping relief with the steepest slopes being 6°. Rill erosion is most common on slopes with a gradient between 1° and 3° (De Roo, 1993).

The average annual precipitation at Wijnandsrade is about 750 mm with rain occurring in all seasons (Kwaad, 1998; Kwaad, 1993; Kwaad and van Mulligen, 1991). Peak rainfall intensities are generally less than 10mm/hr but values up to 40mm/hr regularly occur. High intensity rainfall can occur between April and October (Kwaad, 1998). Kwaad (1993) mentions that runoff-generating rainfall shows a peak intensity that could be as high as 94.0 mm/hr. Van Dijk (2001) measured maximum 5 minutes peak intensities of 55mm/hr during 1992 and 1993. One extreme event during this period had an intensity of 180mm/hr in July 1992. The average annual temperature is 9.5°C. The average monthly temperature in January is 2.0°C and in July 17.2°C (proefboerderij Wijnandsrade, 1992). At Wijnandsrade, the soils are typically truncated Gleyic Luvisols. A perched water table is present within 1.00m of the soil surface during part of the year. During winter, spring and early summer this water table rises to within 10cm of the surface but during summer and autumn it may drop to below 2m (Kwaad, 1993 and 1998). The slope is about 5° and the aspect N300. The predominant crop is maize.

The cropping systems used at Wijnandsrade for this study are ploughing in spring and seedbed preparation and ploughing in autumn, sowing of winter rye and seedbed preparation (Table 3.1.3). In the last system during spring the winter rye was cut away to create a bare soil situation, which is one of the initial situations for the rainfall simulations. At Wijnandsrade, initiation of rills was only observed on valley slopes during high intensity extreme rainfall events. At the bottom of the valleys rills had formed under lower intensity rainfall. They could be seen as channels collecting discharge from the slopes. Therefore, a third system was studied at Wijnandsrade that was a bare slope, which had been ploughed in autumn (Table 3.1.3). A rill system had been formed on this slope during rainfall in winter. On this site surface characteristics were studied during a period of one month.

The average annual precipitation in the Catsop area is 675mm (De Roo, 1993). The soils are classified as truncated Luvisols partly decalcified (De Roo, 1993; Ritsema et al., 1996). The steepest slope gradient is 6°. At the study site, a rill system had developed, after ploughing, during the preceding winter (Table 3.1.3). In winter the initiation of rills is favoured by the presence of bare saturated soils. In the summer high rainfall intensities are a key factor in rill initiation. (De Roo et al., 1994). The study site had been used for the cultivation of potatoes during the previous year and during the winter it was left fallow. Measurements were made at the sites listed in Table 3.1.3, which shows the cultivation practises at each site.
Soil erosion in South Limburg occurs in two different situations. Firstly, in spring, autumn and winter low intensity rainfall events can cause erosion when the topsoil is water saturated and rainfall intensities are just above saturated conductivity (De Roo, 1993). Kwaad (1991) reported a strong positive correlation between winter runoff and total monthly rainfall amount. Whenever the threshold of saturation is reached, large parts of the rainfall become overland flow so that at such times rainfall intensity is less critical than the rainfall amounts. The second situation occurs during heavy thunderstorms in spring and summer when high rainfall intensities produce Horton overland flow during short periods. Soil losses in summer, resulting from this process, are larger than those in winter but runoff in contrast is considerably lower (Kwaad 1991).

3.2 Methods

3.2.1 Introduction
The field and laboratory methods used in this research are described separately. Rainfall simulation experiments were made in the field in order to study soil hydraulic properties, hydrological characteristics and to investigate dynamic soil properties (Table 3.2.1a and b, Table 3.2.2a and b). Physical, physico-chemical, chemical and mineralogical analyses were undertaken to support and elaborate the field investigations (Table 3.2.1b and 3.2.2b).

3.2.2 Field experiments and measurements

Rainfall simulation experiments
Different types of rainfall simulation experiments were done in the badland and loess areas, reflecting the different aims and the local conditions. Details of these experiments are summarised in Tables 5.1.1 and 5.2.3.
Rainfall simulation experiments are particularly useful in semi-arid areas because of the uncertainty of rainfall events. In humid climates rainfall simulation experiments can be used to regulate rainfall intensity and compare different sites under the same rainfall conditions. Large rainfall simulation experiments enable the response of relatively long slopes to be studied. This is important for rill erosion and in studies of flow hydraulics and sediment entrainment. In badland areas these subjects have been studied and an attempt was made to study infiltration. Imeson and Verstraten (1986) describe small rainfall simulators as being more suitable for infiltration studies, because the rainfall intensity can be kept uniform within the experimental plot. In the loess area a small rainfall simulator was used to study the infiltration and some information was collected on slaking and aggregation of the surface soil.

**badland areas**

In the badland areas, a rainfall intensity of 30mm/hr was chosen for the experiments. Comparison of the experimental and the natural rainfall intensity shows that the experimental intensity of 30mm/hr is relatively high (Fig. 3.1.3). The highest average natural intensity of an individual rain event, reached in the area during the period of this research was 22mm/hr. Castillo and Beltran (1979) showed that rain showers with an intensity of 30 mm/hr and a duration of 45 minutes have a return period of 10 years in South-East Spain. In the neighbourhood of Petrer (Valencia) they occur more than once every two years (Fig. 3.1.2).

With an intensity of 30mm/hr, the rainfall simulator produced relatively homogeneous rainfall and allowed water to infiltrate into the regolith profiles. A rainfall simulator was used which could be easily installed and moved on the very steep badland slopes that have an average slope angle of 40°. It had the capacity to sprinkle an area of ca. 10m². The rainfall simulator consists of two rotating sprinklers on a 2m high pole. The water was projected upwards into the air because the falling drops were found in this way to attain a reasonably natural drop-size distribution. The rainfall simulator resembles the one used by Hodges and Bryan (1982). Demineralised water was used, with a very low electrical conductivity (10µS/cm). The duration of the rainfall simulation experiment was 45 minutes. A second one after 24 hours repeated the first experiment.

**Table 3.2.1a** Experimental setup of rainfall simulation experiments in badland regoliths, Petrer, Spain, 1992

<table>
<thead>
<tr>
<th>site nr.</th>
<th>rainfall simulation experiments</th>
<th>site characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td></td>
<td>parent rock/ regolith</td>
</tr>
<tr>
<td>1</td>
<td>+</td>
<td>white</td>
</tr>
<tr>
<td>2</td>
<td>+</td>
<td>white</td>
</tr>
<tr>
<td>3</td>
<td>+</td>
<td>brown</td>
</tr>
<tr>
<td>4</td>
<td>+</td>
<td>white</td>
</tr>
<tr>
<td>5</td>
<td>+</td>
<td>grey</td>
</tr>
<tr>
<td>6</td>
<td>+</td>
<td>white</td>
</tr>
</tbody>
</table>

+ = present or carried out on this site.
Some characteristics of the experimental badland sites are shown in Table 3.1.2. Five sites on different materials were chosen, three sites having rills at the surface, two other sites having mass movements.

Another experiment was carried out at a sixth site where the regolith material above the shard layer was deliberately removed. The development of the renewed surface layer was followed by photographs and field observations on a monthly base. One year later, a rainfall simulation experiment was carried out at this site to study initiation and development of rills on a badland slope on which rills were not yet developed.

cultivated loess areas

In the loess area rills are removed by cultivation and they occur very irregularly in time during extreme events and at specific locations in recently cultivated soils. To actually create a rill and measure the drainage pattern, a rainfall simulator would have to apply water on an area that was too large to be possible considering the limitations of the thesis. A double strategy was therefore adopted whereby firstly a rainfall simulator was used to study the evolution of saturated areas in the soil profile, and secondly soil moisture measurements were made...

<table>
<thead>
<tr>
<th>Cultivation type</th>
<th>Plot nr.</th>
<th>Rainfall simulation experiments</th>
<th>Plot characteristics</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ploughed soil</td>
<td>1</td>
<td>3L+3H</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1H</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3H</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>2H</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>1L</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>2L</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>3L</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>3L+3H</td>
<td>+</td>
</tr>
<tr>
<td>Harrowed soil</td>
<td>1</td>
<td>2H</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>1H</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>3</td>
<td>3H</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>4</td>
<td>3L+3H</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>5</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>6</td>
<td>3L</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>7</td>
<td>2L</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>8</td>
<td>1L</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>9</td>
<td>3L+3H</td>
<td>+</td>
</tr>
<tr>
<td></td>
<td>10</td>
<td>+</td>
<td>+</td>
</tr>
</tbody>
</table>

+ = present on this site
rainfall simulation experiments: 1 = number of experiments
L = low intensity (60mm/hr)
H = high intensity (20mm/hr)

Table 3.2.2a Experimental setup of rainfall simulation experiments on loess under different cultivation practises, during June and July 1992, Wijnadradde, South Limburg, The Netherlands
around a pre-existing rill. Two different sites were selected for the rainfall simulation experiments. Tillage practise at the rainfall simulation sites, which had been recently ploughed and/or harrowed for several years, is shown in Table 3.1.3.

A drip type rainfall simulator was used which supplied rainfall from a 1 * 0.5m^2 plate onto a target plot of 0.30m * 0.60m (Bowyer-Bower and Burt, 1989). At both sites 10 l of water was applied. Experiments were made at high (60mm/hr) and low rainfall (20mm/hr) intensities. The lowest homogeneous rainfall intensity that could be produced by the simulator was 20mm/hr and at this intensity the surface did not seal during the 60 minutes of rainfall. At 60mm/hr the rainfall was uniform and the surface sealed after 20 minutes.

At both sites, 10 plots for the experiments were established and two successive rainfall simulation experiments performed, varying from one to three sets (Table 3.2.2a). One set of rainfall simulation experiments consisted of two experiments with about one hour in between.

### Table 3.2.1b Overview of field and laboratory measurements on badland regoliths, Petrer, 1991, 1992, 1994

<table>
<thead>
<tr>
<th>Field measurements</th>
<th>Time period</th>
<th>Laboratory measurements</th>
<th>Time period</th>
</tr>
</thead>
<tbody>
<tr>
<td>Soil characteristics</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>description of geomorphology</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>profile description</td>
<td>+(-6)</td>
<td>+(-6)</td>
<td>+</td>
</tr>
<tr>
<td>roughness of surface</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>amount and size of cracks</td>
<td>+</td>
<td>+</td>
<td>+</td>
</tr>
<tr>
<td>shear strength at surface</td>
<td>+(-6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>vertical resistance at surface</td>
<td>+(-6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>position and dimension of rills</td>
<td>(6)</td>
<td>+(-6)</td>
<td></td>
</tr>
<tr>
<td>Soil water</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>pressure head in and around rills</td>
<td>+(-6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>soil water content in and around rills</td>
<td>+(-6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Runoff</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>discharge and sediment concentration</td>
<td>+(-6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>EC_{25} of discharge</td>
<td>+(-6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>time to runoff</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>time to ponding</td>
<td>+</td>
<td></td>
<td></td>
</tr>
<tr>
<td>rill flow velocity</td>
<td>+(-6)</td>
<td></td>
<td></td>
</tr>
<tr>
<td>interrill flow velocity</td>
<td>+(-6)</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

* = measured/observed  
(-6) = except for site 6  
(6) = only at site 6
This was to study the effect of dry and wet initial situation. To keep the soil dry from natural rainfall the plots were covered with plastic. Two plots at both sites had been disturbed by a wheel track. Soil sampling took place after the last set of rainfall simulation experiments.

**Soil water pressure and content**
Two soil water parameters were measured. The volumetric soil water content was measured by means of time domain reflectometry (TDR). The pressure head in the soil was measured by using tensiometers and a pressure transducer.

TDR measurements are based on the velocity \(v\) of an electromagnetic signal in a wave-
guide inserted into the soil. This velocity is inversely proportional to the square root of the apparent dielectric permittivity of the soil, \( K_a \) (Topp et al, 1980):

\[
\nu = \frac{c}{\sqrt{K_a}}
\]

\[ (3.1) \]

in which \( c \) is the speed of the electromagnetic waves in vacuum \([3 \times 10^8 \, \text{ms}^{-1}] \) (Heimovaara and de Water, 1993). A Tektronix (Beaverton, Oregon) 1502B metallic cable tester was used to obtain the TDR data. The cable tester measures the time it takes an electromagnetic signal to travel along a sensor installed in the soil. During the field experiments measurements were not repeated, but for the calibration measurements this was done three times. The TDR data were analysed by the procedure presented by Heimovaara (1993). In this research triple-wire probes with a length of 10 cm were used. The total travel time of the wave-guide depends on the soil moisture content and the travel time through the epoxy casing \((\Delta t_0)\) in which the wires are fastened. Ledieu et al. (1986) showed a relationship between soil water content and travel time in the soil. De Loor (1990) proposed to use the apparent refractive index \((n_a)\) instead of travel time in order to obtain a relationship independent of probe length. The refractive index \((n_a)\) is calculated as:

\[
n_a = \frac{c \Delta t_s}{2L}
\]

\[ (3.2) \]

The total travel time \((\Delta t_p)\) is defined as:

\[
\Delta t_p = \Delta t_0 + \Delta t_s
\]

\[ (3.3) \]

Wave-guide through the epoxy resin \(\Delta t_0\) and probe length \(L\) are parameters known by calibration (Heimovaara, 1993), by which travel time through the soil and refractive index can be calculated. The soil water content can then be calculated according to different relationships, e.g. Ledieu et al. (1986), Topp et al. (1980), de Loor (1990), Heimovaara (1993).

The volumetric soil water content was also measured gravimetrically in soil samples having a known volume. The weight was determined before and after drying at 105°C. This destructive method rendered the plot unsuitable for further rainfall simulation experiments.

Soil water pressure was measured by means of soil tensiometers connected to a pressure transducer and read, either manually or automatically. The pressure head values were converted into volumetric soil moisture contents by using the soil water retention characteristic of the soil. The function fitted through the data was calculated by a computer program pFFIT-4 (Freyer, 1989). A problem of using pressure heads is that, when the pressure head in the soil is lower than -500cm the air entry pressure of the porous cup is exceeded and the measurements become unreliable.
badland area

In the badland area TDR measurements were made in the field during the period in which rainfall simulation experiments were carried out, from September until November 1992. Measurements with triple-wire probes were unreliable in this area, because of the high salt content of the badland material. For this purpose it was decided to use a teflon coating on the middle pin of the probe. The coating prevents the signals from having a reflection amplitude that is too high. This is a result of the high salt concentration in the soil solution. When the reflection of the signal is too high, the wave length cannot be estimated between two reflection points. A consequence of the coating is that the bulk electrical conductivity cannot be measured. For the calibration of these probes and the soil material a slightly modified procedure from the normal probes is used to make allowance for the teflon. The wave-guide ($\Delta t_0$) through the epoxy resin and probe length $L$ were estimated before coating the probe and this is still valid after coating. Relationships between travel time of wave-guides inserted into the soil and soil moisture contents were established (Ledieu et al., 1986). The relationship between the refractive index $n_a$ and soil moisture content, eliminating the sensor length, was not used, as the differences in sensor length and the resulting soil moisture content are relatively small and negligible. According to Ledieu et al. (1986), this relationship is improved by including the bulk density of the soil material. But, this parameter has only a small influence on differences in soil moisture contents, which means that it is not needed to be known with great precision. This result is an advantage for TDR measurements in shrinking and swelling soils. The probes were installed vertically and diagonally in and around a rill system (Fig. 3.2.1 and 3.2.2b). Before, during and after the experiments the TDR measurements were recorded automatically by means of a cable tester (Tektronix) and a portable computer.

The following procedure was developed for analysing TDR wave forms, collected in badland material. The travel time through the epoxy casing $\Delta t_0$ was used from the calibration of the probes before they were coated. In two badland materials TDR waveforms and their corresponding soil moisture contents were measured. A regression line was fitted through the measured points. This was done for all badland sites (Fig. 3.2.3). Calibration of white marls northerly and southerly exposed was similar. Therefore, for these two sites one calibration characteristic was established with data from both sites. For the other sites, the regression line calculated for the specific site was used. Unlike Ledieu et al. (1986) the regression lines are not linear. The function that had been used for the white marls is:

$$y = \frac{a}{1 + be^{(-x)}}$$

for northern and southern slope: ($a = 0.290; b = 2574; c = 7.94$)

for south-western slope: ($a = 0.374; b = 1244; c = 6.82$)
For the brown and grey marls the function for an optimal fit was:

\[ y = a + bx + cx^2 \]  

(3.5)

with for brown marls: \( a = -1.47; \ b = 3.23; \ c = -1.13 \)

and for grey marls: \( a = 0.111; \ b = -1.86; \ c = 3.12 \)

For measuring the pressure head in and around a rill system, 5cm long tensiometers were used. They were installed in the badland regoliths similarly to the TDR probes (Fig. 3.2.1 and 3.2.2a). Pressure heads were recorded manually, before, during and after the rainfall simulation experiments.

**loess soils**

TDR measurements were made manually in the loess area in 1994 around a rill system. The field site was located near Catsop in South Limburg, The Netherlands. The triple-wire probes were put in a rill, in the side of a rill or in an interrill area. The probe was inserted vertically into the soil, by which the average soil moisture content of the upper 10cm of the soil was obtained. In the rill side the probe was installed perpendicular to the surface, so the soil moisture content was measured in the part of the soil next to the rill. To determine what relationship between the soil moisture content and measured travel time by the TDR is valid for this soil, some samples were calibrated in the laboratory. It was concluded that, in spite of the relatively low bulk density (Table 4.2.6), the relationship calculated by Topp et al. (1980) was valid for the loess soil for the Ap and Bt-horizon. Consequently, this relationship was used, to calculate the volumetric soil moisture contents.

Pressure heads were measured in the loess area during the rainfall simulation experiments on harrowed and ploughed soil in 1992. Tensiometers were installed horizontally at 4
depths between 13 and 42.5 cm below the surface (Fig. 3.2.4). Before, during and after every experiment pressure heads were measured manually.

During the experiments in 1992, after every rainfall simulation, samples were collected within a plot to measure the soil moisture content at three depths, e.g. at the surface, in the Ap and in the Bt-horizon. The volumetric soil water content was measured by weighing the sample, with a known volume, before and after drying at 105 °C.

Discharge and sediment measurements
In the badland area varied the plot size, used for discharge measurements during the rainfall simulation experiments, varied from 2-12m². Sediment and runoff were measured and sampled every two minutes. From these samples the amount of runoff and sediment, the Electrical Conductivity (EC25) and the practical Sodium Adsorption Ratio (SARp) values were measured or calculated (Tiemessen, 1993). The EC25 and pH values of the soil surface material (1:2.5 w/v) of the plot were measured in the laboratory. The amount of runoff was consid-
Figure 3.2.3 TDR calibration fitting curves for badland regoliths
lered constant during intervals between sampling.

In the loess area, the total discharge of water and sediment was measured and sampled during the rainfall simulation experiments in 1992. The size of the plots was about 0.18m². The concentrated runoff in the rill was collected in sample bottles. Runoff did not occur during every experiment.

In both areas the water from the sampled suspensions was evaporated and the sediment load determined.

Soil surface characteristics and properties
Details of the soil surface were recorded and photographs taken before and after the experiments (Table 3.2.1a and b and 3.2.2a and b; Fig. 3.2.5). Measurement periods are shown in Figure 3.1.3a and b. During the experiments also relevant field observations were recorded. Time to ponding was defined as the time after the start of the experiment, when 40% of the surface was ponded and time to runoff when runoff started. The time when all of the cracks had closed was recorded and also surface sealing was noted. In both areas the soil shear strength, the vertical soil resistance, the roughness of the surface and the crack size and distance were measured before and after the experiments. This played especially a role in the badland area.

Soil shear strength and vertical resistance of the soil surface indicate the response of the soil to wetting under field conditions. These conditions are different from the conditions in laboratory under which the consistency was determined. The soil shear strength and penetration resistance were measured respectively with a pocket shear-meter and pocket penetrometer (Eijkelkamp, The Netherlands). These parameters are related to the soil moisture content during the experiments. The soil shear strength under moist conditions was considered as a good indicator of soil erodibility. Under dry conditions both parameters were considered to reflect the susceptibility of the soil to crust formation and compaction.

The roughness of the surface was measured by using a flexible chain, which was put on the surface profile. Two roughness indices were calculated from the measurements.
Roughness index 1 (RI1) is obtained from the ratio between the length of the chain and the distance at the surface between the measuring points:

\[ RI1 = \frac{L}{D} \quad (3.6) \]

in which

- \( L \) = length chain (m)
- \( D \) = distance of chain on surface (m)

**Figure 3.2.5** Experimental site on white marl regoliths, northerly exposed, Petrer, Spain
Roughness index RI2 is obtained by multiplying RI1 by the amplitude of the microrelief. The second index is necessary for recognising the presence of rills in cases where the surface between rills is smooth.

Rill densities and frequencies were measured on the badland slopes for those rills that drained to the pediment, using the following indices:

\[
\text{Rill index 1} = \frac{T}{A} \times M \quad (\text{cm}^2/\text{m}) \quad (3.7)
\]

\[
\text{Rill index 2} = \frac{T}{SS} \quad (\text{cm}^2/\text{m}^2) \quad (3.8)
\]

\[
\text{Rill index 3} = \frac{V}{SE} \quad (\text{m}^3/\text{m}^2) \quad (3.9)
\]

\[
\text{Rill index 4} = \frac{SR}{SE} \quad (\text{m}^3/\text{m}^2) \quad (3.10)
\]

in which

\(T\) = total cross-sectional areas of rills \quad (cm\(^2\))

\(A\) = number of rills \quad (-)

\(M\) = number of rills per meter slope \quad (m\(^{-1}\))

\(SR\) = surface area of rills on experimental plot \quad (m\(^2\))

\(SS\) = Area of slope section \quad (m\(^2\))

\(V\) = volume of rills on experimental plot \quad (m\(^3\))

\(SE\) = surface area of experimental plot \quad (m\(^2\))

A one-way analysis of variance was used to analyse roughness, crack and rill parameters (significance level of 0.05). The number of samples was \(n=20\). Comparisons between different plots and measurements were made using the Neuman-Keuls test, which is a conservative and reliable test.

### 3.2.3 Laboratory experiments and analyses

#### Physical soil properties

The texture, dry bulk density, macroporosity (non-capillary porosity), water retention characteristic, hydraulic conductivity and soil water content were considered to be the most important soil physical properties to be measured.

Dry bulk density was determined by sampling with 100 cm\(^3\) pF-rings. Samples were dried at 105 °C and weighed. The water retention characteristic was determined by weighing samples of 100 cm\(^3\) at various pressure heads. For the higher pressure head values above pF = 2.7 a pressure of nitrogen was applied to the sample (Vrugt, 1999). Water retention curves during drying and wetting were established with the pF-buret method (Vrugt, 1999). The water retention measurements were fitted and the Van Genuchten parameters were obtained. The three parameters used are \(\alpha\), the reciprocal of the air entry value, \(n\), a measure for the pore
size distribution and φs, the saturated volumetric water content (Wösten and v. Genuchten, 1988; Schaap, 1996).

The amount of macropores was estimated by determining the difference between the bulk density, calculated by drying a soil sample in a pF-ring at 105 °C, and the bulk density calculated from the pF characteristic at pF=0. The difference in volume between these two values are the pores which are filled with water in the range h=0cm and h=-1cm (pF=0). These pores can be called macropores.

The diameter of pores was calculated using the following equation:

\[ z_c = \frac{24}{\rho g r} \cos \phi \]

in which
- \( z_c \) = height of the capillary rise (m)
- \( \sigma \) = surface tension of water (N/m)
- \( \phi \) = angle of contact of the meniscus with the capillary
- \( \rho_1 \) = density of water (kg/m³)
- \( g \) = gravity (N/kg)
- \( r \) = radius of capillary (m)

Equation 3.11 is a standard equation describing the capillary forces caused by the surface tension of the air-water interface (Koorevaar et al., 1983). For calculation of the diameter of the macropores the following parameters values can be used:

- \( \sigma = 0.07 \text{ N/m} \)
- \( \cos \phi = 1 \) at an angle of 0°
- \( \rho_1 = 1000 \text{ kg/m}^3 \)
- \( g = 10 \text{ N/kg} \)

If we use the range of h=-1cm (pF=0) to h=0cm a diameter for macropores is calculated of 2.8mm or larger. These values are calculated for an ideal situation with a glass tube as a capillary. Under real conditions also smaller pores (diameter of 1mm) can act as macropores because of a rougher surface of the pore. In Chapter 4.1 an example is given for calculation of the relative amount of macropores, using a diameter of 1mm.

A second method to calculate the relative amount of macropores in a soil sample was to use the results of the shrinkage and swelling test (see paragraph on shrinkage and swelling later in this chapter). The difference was calculated between the determined dry bulk density of the pF-ring samples and the bulk density calculated by the shrinkage and swelling test for saturated and dry soil clods. This method is further explained in paragraph 4.1.3 and 6.2.2.

The hydraulic conductivity of the soil matrix was determined by the sprinkling infiltrometer method as described in (NEN 5790). For the cultivated loess soils, a 20 cm deep soil column was sampled from the Ap-horizon. In the pressure head range h=0cm to h=-100cm the
hydraulic conductivity was determined by the sprinkling infiltrometer. For the lower pressure head values, the Wind (NEN 5791) method was used. The calibration of the soil water content was obtained, using TDR, by establishing a relationship between the reflection times of the measured TDR waveforms and the gravimetric soil water content. These calibration curves have been compared with the Topp calibration curve to find the most suitable curve. For the harrowed loess soil, from which is assumed that the profile contains less macropores, an attempt was made to determine the unsaturated hydraulic conductivity during a range of pressure head values. However, for the heterogeneous ploughed loess soils, which contain many macropores, this method was not considered to be appropriate. For badland soils the method was not appropriate either. Sampling of an undisturbed sample of 20 cm in depth was impossible in the badland materials. Therefore the experimental field data were used to calculate the hydraulic conductivity (see Chapter 5).

As the badland material is highly susceptible to shrinkage and swelling, bulk densities were consequently corrected for changes in volume. The volume change of a bulk sample could only be measured in a vertical direction, which means that the real field volume changes were somewhat underestimated. The three dimensional volumetric change was determined by a shrink and swell test described later in this chapter.

Chemical soil properties and mineralogy
Determinations were made of organic carbon, carbonate and gypsum contents and of the clay mineralogy in the badland regoliths. Organic carbon was measured by means of the method of Allison (1960).

Carbonate was measured according to Van Wesemael (1955). Gypsum was measured by the determination of sulfate in a dilute water extract of soil (Nelson, 1982). Water soluble salt concentrations were measured after filtration over a 0.1 membrane filter and estimated of the relevant ions by Atomic Absorption/Emission Spectrometry or on an Auto Analyser. The clay mineralogy was analysed semi-quantitatively by means of X-ray diffraction of Mg-, Mg ethylene glycol-, K- saturated and heated at 300°C and 550°C clay samples.

Water soluble salts were not determined in the loess soils because they were not expected to influence the physical chemical behaviour. For these soils, only organic carbon content, carbonate content and clay minerals were estimated.

Physico-chemical soil properties

Aggregation
Aggregation of badland regoliths and loess soils was measured by dry-sieving and analysing soil samples on a Microscan. Data on macro-aggregation were obtained by dry-sieving of aggregate samples of the classes: <2 mm and >2 mm. From the samples <2 mm, the class smaller than 106 μm was extracted to measure the amount of waterstable microaggregates on the Microscan (Cammeraat et al., 1998; Cammeraat et al., 2002; Boix-Fayos, 2001). A scan was made of a sample dispersed in water, from which the size of the microaggregates was
analysed. After that an analysis was made of the same sample to which an amount of ultrasonic energy (15J/s or 7.5 J/s) and in some cases the dispersion agent Na₂PO₄ was added. By this procedure the soil sample was dispersed to primary particles. The difference between both scans give the amount of water stable micro aggregates of the soil sample. For loess soils also a differentiation was made by dry-sieving the aggregates < 2mm in the following classes:
2-1mm, 1-0.5mm, 0.5-0.25mm, 0.25-0.125mm, 0.125-0.106mm.

**shrinkage and swelling**

The COLE-factor (coefficient of linear extensibility, Soil survey staff, 1975; Grossman et al., 1986) was estimated as a measure for swelling and shrinkage. Individual aggregates from badland and loess soils were coated with SARAN resin which, when dry, is permeable to vapour but not to water in the liquid form. The aggregates were moistened at pF values of 1.0 and 1.5. This was done to examine if the initial antecedent soil moisture content influenced swelling and shrinking.

The COLE factor is calculated as:

\[
\text{COLE} = \frac{D_{bd}}{D_{bm}} - 1
\]

\[\text{Db}_{d} = \text{Dry bulk density (kg/m}^3\text{)}\]

\[\text{Db}_{m} = \text{Moist bulk density (kg/m}^3\text{)}\]

A general shrinkage characteristic given in Figure 4.1.6a shows the different stages of shrinkage of a soil aggregate (Cammeraat, 1992). Bronswijk and Evers-Vermeer (1990) described the different shrinkage phases for clay-rich soils. In large water saturated soil samples structural shrinkage takes place. This is, when only large water-filled pores empty and the soil hardly changes in volume. When the large pores are empty the normal shrinkage process starts. During this phase the volume decrease of clay aggregates is equal to water loss. The aggregates remain fully saturated. When air is entering the pores of the aggregates residual shrinkage starts. At this moment water loss is greater than volume decrease. The last phase is zero shrinkage. The soil particles have reached their densest configuration and the volume of aggregates stays constant. Water loss is equal to the increase of air volume in the aggregates.

This method for determination of shrinkage and swelling can also be used to quantify the swelling and shrinkage potential of a soil layer (Bronswijk and Evers-Vermeer, 1990). In this case the assumption should be made that surrounding aggregates in a soil layer do not affect the shrinkage capacity of an aggregate.

During this shrinkage test gravimetric and volumetric soil moisture contents were measured. Relationships between these values were established to use for adaption of bulk density and soil moisture contents to shrinkage and swelling behaviour (Fig. 4.1.7).
CHAPTER 3

soil consistency

Soil consistency parameters are determined in two ways. The liquid limit was determined using a slightly modified version of the procedure described by Singh (1967). This modification involved using a paste made of soil aggregates larger than 2 mm instead of 0.425 mm. From the resulting characteristic the liquid limit and C_{5-10}-index were calculated (de Ploey and Mücher, 1981). The liquid limit index is defined as the gravimetric soil moisture content at the point when the liquid limit is reached at 25 blows with the Cassagrande apparatus. The points at 5 and 10 blows are used to calculate the C_{5-10}-index (De Ploey and Mücher, 1981), which is a measure for the stability of the topsoil. The best fit for the liquid limit curve was found to be \( y = a + b \log x \). For the C_{5-10}-index, the best results were obtained with: \( y = ax^b \). Number of blows is mentioned by the \( x \)-value and the gravimetric soil moisture content by the \( y \)-value. Parameters \( a \) and \( b \) are fit parameters.

A second method was used only for loess soils. Undisturbed aggregates from the fraction >2 mm were wetted at pH=0. These aggregates were put in a Cassagrande apparatus and the blows were counted until the aggregate started to flow. From these data two indices were calculated, i.e.:

Index A = number of blows for liquefaction of the aggregate \hspace{1cm} (3.13)

Index B = \left( \frac{\text{number of blows}}{\text{dry weight clod}} \right) \times \text{grav. soil moisture} \hspace{1cm} (3.14)

In which unities are:
number of blows (-) 
dry weight clod (g) 
gravimetric soil moisture content (g/g)

Index B was used to take into account soil moisture content and the weight of the soil aggregate.
PART II

EXPERIMENTAL RESULTS AND DISCUSSION
4

Properties of badland regoliths and cultivated loess soils affecting erosion processes

Introduction

In this study the hypothesis is stated that rill development is strongly influenced by the reaction of regoliths upon wetting. Soil aggregates can lose their coherence during the wetting process as a result of processes such as dispersion, slaking and welding of the soil material. These effects are reflected in changes in consistency and shear strength. In badlands, rill and pipe erosion are known to be favoured by the development of macropore flows that can lead to the development of saturated zones in the soil and regolith profiles. Macropores can result from swelling and shrinkage behaviour that is strongly controlled by soil chemical properties such as SARp, ESP and EC. In the cultivated loess soils, ploughing produces the necessary macropores and above a plough pan or a less permeable Bt-horizon water saturation might occur.
4.1 Properties of badland regolith affecting erodibility

4.1.1 Chemical and physico-chemical properties

Relevant chemical properties measured in samples from the different regoliths and their horizons are summarised in Table 4.1.1 and 4.1.2.

In general, it is seen that in the water extracts of brown and grey marls more K is present than in the white marls. Especially the brown marls show the highest Na values (Table 4.1.1). It is noted that the EC25 and SARp values of the surface and subsurface layers of the grey marls are much lower than for the brown and white marl regoliths. In addition, the SARp values of the complete grey marls profile are relatively low (2-3). The EC-values of the brown marls are slightly higher than for the white marls. Both regoliths have a SARp that is relatively low (5-10) for the surface layer but which becomes relatively high at depth. On the basis of these data, a simple distinction can be made between the grey marls and the other badland regoliths.

The proportions of aggregated particles smaller than 2 mm are also shown in Table 4.1.1. In all profiles, except the brown marls, the amount of aggregates < 2 mm are decreasing with depth. The grey marls have a relatively high amount of smaller aggregated particles in the surface horizon.

Tiemessen (1993) studied microaggregation and primary particles for the Petrer badlands. Particle size distribution of a soil sample smaller than 106 μm was determined on a Microscan. The amount of particles < 4 μm of badland marls dispersed in demineralised water is between 2 and 15 in mass%, with an outlier of 44% for white marls on the southerly exposed slope (Table 4.1.3a). A soil sample dispersed in demineralised water is a measure for the natural conditions under rainfall. The particles < 4 μm are considered as the primary particles in a sample. White marls (northerly and south-westerly exposed) and brown marls have a very low amount of primary particles after dispersion (Table 4.1.3a). Grey marls have 2 to 5 times more mass% in this fraction. White marls, southerly exposed, has a high amount of 4 μm particles, which differs from the other white marls.

By using ultrasonic energy (15 J/s) in a suspension of a sample, microaggregates break down to primary particles. After the use of this energy, the amount of primary particles (< 4 μm) is lowest for brown and grey marls (Table 4.1.3a). For white marls, these amounts are in the same range and higher than for brown and grey marls. From the differences between ‘water dispersed’ and ‘ultrasonic’ samples is seen that white marls on the southerly exposed slope are more sensitive to dispersion in water. For the other white marls, the ultrasonic energy causes a breakdown of many microaggregates, probably bonded with calcium carbonate (see in Table 4.1.3a waterstable microaggregates). The amount of water stable microaggregates for white marls, southerly exposed, is low. Waterstable microaggregates of the white marls northerly and south-westerly exposed and the brown and grey marls are in the same range.

Texture of the badland marls is given in Table 4.1.3b. The white marls on all slopes are very similar. White marls on south-westerly exposed slope have slightly more clay and white marls on the northerly exposed slope slightly more sand. Brown marls have more silt, while grey marls are more sandy. However, the clay fraction of the grey marls is highest compared to the other regoliths. It is noticed that the silt fraction is higher than sand and clay fraction for all regoliths. This means that possibly part of the primary particles (>4 μm) were not measured as primary particles on the Microscan.
### Table 4.1.1 Fine earth fraction and water soluble salts (w/v = 1:50) of badland regoliths

<table>
<thead>
<tr>
<th>Badland regolith and horizon description</th>
<th>Fine earth fraction (+2mm; mass%)</th>
<th>K (mmol/l)</th>
<th>Na (mmol/l)</th>
<th>NH₄ (mmol/l)</th>
<th>Ca (mmol/l)</th>
<th>Mg (mmol/l)</th>
<th>Cl (mmol/l)</th>
<th>NO₃⁻ NO₂ (mmol/l)</th>
<th>SO₄ (mmol/l)</th>
<th>HCO₃⁻ (mmol/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>White marls, northerly exposed crust + subcrust</td>
<td>14.0</td>
<td>0.176</td>
<td>2.74</td>
<td>0.0015</td>
<td>0.128</td>
<td>0.026</td>
<td>1.55</td>
<td>0.037</td>
<td>0.414</td>
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<td>nd</td>
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<td>slightly weathered shards</td>
<td>3.69</td>
<td>0.149</td>
<td>3.08</td>
<td>0.0060</td>
<td>0.341</td>
<td>0.051</td>
<td>1.09</td>
<td>0.010</td>
<td>1.06</td>
<td>0.628</td>
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<td>0.117</td>
<td>nd</td>
<td>0.0085</td>
<td>0.467</td>
<td>0.030</td>
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<td>0.018</td>
<td>0.289</td>
<td>1.73</td>
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<td>White marls, southerly exposed crust + subcrust</td>
<td>10.6</td>
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<td>nd</td>
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<td>0.900</td>
<td>0.032</td>
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<td>1.20</td>
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<td>0.177</td>
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<td>0.092</td>
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<td>0.005</td>
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<td>0.019</td>
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<td>nd</td>
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<td>nd</td>
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<td>White marls, south-westerly exposed crust + subcrust</td>
<td>13.6</td>
<td>0.128</td>
<td>2.27</td>
<td>0.0053</td>
<td>0.117</td>
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<td>1.22</td>
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<td>0.302</td>
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<td>White marls, experimental slope, southerly exposed crust + subcrust</td>
<td>9.29</td>
<td>0.093</td>
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<td>0.021</td>
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<td>0.635</td>
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</table>

nd = not determined


Tabel 4.1.1. (continued)

<table>
<thead>
<tr>
<th>Badland regolith and horizon description</th>
<th>fine earth fraction (&lt;3mm: mass%)</th>
<th>K (mmol/l)</th>
<th>Na (mmol/l)</th>
<th>NH4 (mmol/l)</th>
<th>Ca (mmol/l)</th>
<th>Mg (mmol/l)</th>
<th>Cl (mmol/l)</th>
<th>NO3+ NO2 (mmol/l)</th>
<th>SO4 (mmol/l)</th>
<th>HCO3 (mmol/l)</th>
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<td>Brown marls, southerly exposed crust + subcrust</td>
<td>13.2</td>
<td>0.250</td>
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<td>0.244</td>
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<td>1.18</td>
<td>0.066</td>
<td>1.81</td>
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<td>puffed soil with fine salt crystals</td>
<td>66.3</td>
<td>0.225</td>
<td>9.07</td>
<td>0.0072</td>
<td>0.241</td>
<td>0.025</td>
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<td>0.206</td>
<td>2.92</td>
<td>1.81</td>
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<td>12.5</td>
<td>0.245</td>
<td>5.39</td>
<td>0.0088</td>
<td>0.671</td>
<td>0.068</td>
<td>2.36</td>
<td>0.099</td>
<td>2.50</td>
<td>0.955</td>
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<td>slightly weathered shards</td>
<td>7.18</td>
<td>0.127</td>
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<td>0.072</td>
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<tr>
<td>Grey marls, southerly exposed crust + subcrust</td>
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<td>0.127</td>
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<td>0.127</td>
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<td>0.014</td>
<td>0.018</td>
<td>0.150</td>
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</tr>
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<td>0.0035</td>
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<td>0.020</td>
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<td>1.49</td>
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<td>8.36</td>
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<td>4.54</td>
<td>0.020</td>
<td>0.424</td>
<td>0.004</td>
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<td>0.723</td>
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nd = not determined
### Properties of Badland Regoliths Affecting Erodibility

**Table 4.1.2 Some chemical properties of badland regoliths**

<table>
<thead>
<tr>
<th>Badland regolith and horizon description</th>
<th>EC(25) 1:2.5 w/v (mS/cm)</th>
<th>pH (H₂O) 1:2.5 w/v</th>
<th>pH (CaCl₂) 1:2.5 w/v</th>
<th>SARp 1:50 w/v (mmol/l)₁/₂</th>
<th>ESP (%) K⁺Cl⁻= 0.5 (mmol/l)⁻¹/₂</th>
<th>Alk(res) 1:50 w/v (mmolc./l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>White marls, northerly exposed crust + subcrust</td>
<td>9.17</td>
<td>8.56</td>
<td>7.82</td>
<td>9.84</td>
<td>12.9</td>
<td>1.00</td>
</tr>
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<td>subsurface material</td>
<td>3.96</td>
<td>8.83</td>
<td>8.09</td>
<td>11.8</td>
<td>15.1</td>
<td>1.51</td>
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<tr>
<td>weathered shards</td>
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<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>slightly weathered shards</td>
<td>4.25</td>
<td>8.54</td>
<td>8.30</td>
<td>6.97</td>
<td>9.46</td>
<td>0</td>
</tr>
<tr>
<td>unweathered shards</td>
<td>nd</td>
<td>8.97</td>
<td>8.07</td>
<td>7.13</td>
<td>9.66</td>
<td>1.40</td>
</tr>
<tr>
<td>White marls, southerly exposed crust + subcrust</td>
<td>5.56</td>
<td>8.84</td>
<td>7.91</td>
<td>9.25</td>
<td>12.2</td>
<td>1.87</td>
</tr>
<tr>
<td>subsurface material</td>
<td>9.42</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>weathered shards</td>
<td>12.5</td>
<td>8.36</td>
<td>8.11</td>
<td>8.36</td>
<td>11.1</td>
<td>0</td>
</tr>
<tr>
<td>slightly weathered shards</td>
<td>13.5</td>
<td>8.30</td>
<td>7.36</td>
<td>5.80</td>
<td>8.01</td>
<td>0</td>
</tr>
<tr>
<td>very slightly weathered shards</td>
<td>nd</td>
<td>9.06</td>
<td>8.39</td>
<td>29.1</td>
<td>30.4</td>
<td>2.67</td>
</tr>
<tr>
<td>unweathered shards</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>White marls, south-westerly exposed crust + subcrust</td>
<td>1.77</td>
<td>8.81</td>
<td>7.92</td>
<td>8.69</td>
<td>11.5</td>
<td>1.11</td>
</tr>
<tr>
<td>subsurface material</td>
<td>3.89</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>weathered shards</td>
<td>8.48</td>
<td>8.50</td>
<td>8.11</td>
<td>10.8</td>
<td>13.9</td>
<td>1.03</td>
</tr>
<tr>
<td>slightly weathered shards</td>
<td>8.81</td>
<td>8.61</td>
<td>7.45</td>
<td>7.08</td>
<td>9.60</td>
<td>0.01</td>
</tr>
<tr>
<td>unweathered shards</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>White marls, experimental slope, southerly exposed crust + subcrust</td>
<td>4.72</td>
<td>nd</td>
<td>nd</td>
<td>10.3</td>
<td>13.4</td>
<td>3.25</td>
</tr>
<tr>
<td>subsurface material</td>
<td>10.0</td>
<td>Nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>weathered shards</td>
<td>7.49</td>
<td>nd</td>
<td>nd</td>
<td>6.88</td>
<td>9.35</td>
<td>0</td>
</tr>
<tr>
<td>slightly weathered shards</td>
<td>5.68</td>
<td>nd</td>
<td>nd</td>
<td>14.5</td>
<td>17.8</td>
<td>2.01</td>
</tr>
<tr>
<td>unweathered shards</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
</tbody>
</table>
The results of the liquid limit test are shown in Figure 4.1.1 and 4.1.2. The liquid limit indexes for the crust and subcrust materials increase in order of white, brown, grey marls. The liquid limit indexes of the grey marls are relatively high. Although, the liquid limit values for the white marls on the north and south facing slopes are rather similar, those from the south-west facing slope have the lowest index and those from the north facing slope the highest values.

On the north facing slope, the slightly weathered shards have a slightly higher liquid limit index than overlying horizons (Fig. 4.1.2).

The results of the C$_{5-10}$-index (which is related to slaking hazard, see Chapter 3.2) are shown in Table 4.1.4. The white marls on the south and south-west exposed slope have the highest values and the white marls on the north exposed slope show the lowest. The brown and grey marls have intermediate values. The most stable materials are the white marls on the south and south-west slope. Within the white marls, the C$_{5-10}$-index (Table 4.1.4) shows

<table>
<thead>
<tr>
<th>Badland regolith and horizon description</th>
<th>EC(25) 1:2.5 w/v (mS/cm)</th>
<th>pH (H$_2$O) 1:2.5 w/v</th>
<th>pH (CaCl$_2$) 1:2.5 w/v</th>
<th>SARp 1:50 w/v (mmol/l)$^{1/2}$</th>
<th>ESP (%) $K_{	ext{NaCl}}=0.5$ (mmol/l)$^{-1/2}$</th>
<th>Alk(res) 1:50 w/v (mmol/l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Brown marls, southerly exposed crust + subcrust</td>
<td>4.49</td>
<td>8.14</td>
<td>7.72</td>
<td>5.16</td>
<td>7.18</td>
<td>0.566</td>
</tr>
<tr>
<td>subsurface material</td>
<td>15.3</td>
<td>8.44</td>
<td>8.05</td>
<td>10.5</td>
<td>13.6</td>
<td>1.01</td>
</tr>
<tr>
<td>puffed soil with fine salt crystals</td>
<td>13.3</td>
<td>8.75</td>
<td>8.47</td>
<td>24.9</td>
<td>27.2</td>
<td>0.701</td>
</tr>
<tr>
<td>weathered shards with salt crystals</td>
<td>9.62</td>
<td>8.49</td>
<td>8.37</td>
<td>8.87</td>
<td>11.8</td>
<td>0</td>
</tr>
<tr>
<td>slightly weathered shards</td>
<td>11.1</td>
<td>8.97</td>
<td>8.40</td>
<td>20.8</td>
<td>23.8</td>
<td>3.04</td>
</tr>
<tr>
<td>unweathered shards</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>Grey marls, southerly exposed crust + subcrust</td>
<td>0.320</td>
<td>8.68</td>
<td>7.54</td>
<td>2.37</td>
<td>3.44</td>
<td>1.37</td>
</tr>
<tr>
<td>subsurface material</td>
<td>2.33</td>
<td>7.90</td>
<td>7.53</td>
<td>2.79</td>
<td>4.01</td>
<td>0</td>
</tr>
<tr>
<td>weathered shards</td>
<td>6.22</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>slightly weathered shards</td>
<td>6.34</td>
<td>8.91</td>
<td>8.50</td>
<td>2.83</td>
<td>4.07</td>
<td>0</td>
</tr>
<tr>
<td>unweathered shards</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
</tbody>
</table>
clear difference between the different aspects. The differences between the horizons is similar to that described for the liquid limit. The subsurface material has a lower C<sub>5-10</sub>-index than the surface material.

**Table 4.1.3a Microaggregation and primary particles of badland regoliths**

<table>
<thead>
<tr>
<th>Badland marls</th>
<th>mass% waterstable microaggregates, &lt; 106 μm</th>
<th>mass% primary particles &lt; 4 μm</th>
<th>after 1 minute ultrasonic (900 J) + sodiumpyrophosphate</th>
</tr>
</thead>
<tbody>
<tr>
<td>White marls north exposed</td>
<td>1.8</td>
<td>63.1</td>
<td>62.8</td>
</tr>
<tr>
<td>south exposed</td>
<td>43.9</td>
<td>72.7</td>
<td>30.4</td>
</tr>
<tr>
<td>south-west exposed</td>
<td>7.6</td>
<td>63.4</td>
<td>57.0</td>
</tr>
<tr>
<td>brown marls; south exposed</td>
<td>4.3</td>
<td>59.7</td>
<td>56.1</td>
</tr>
<tr>
<td>grey marls; south exposed</td>
<td>15.4</td>
<td>59.9</td>
<td>49.1</td>
</tr>
</tbody>
</table>

**Table 4.1.3b Texture of badland regoliths in mass percentage**

<table>
<thead>
<tr>
<th>Badland marls</th>
<th>sand (2 mm - 50 μm)</th>
<th>silt (50 μm - 2 μm)</th>
<th>clay (&lt; 2 μm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>White marls north exposed</td>
<td>9.55</td>
<td>62.0</td>
<td>28.5</td>
</tr>
<tr>
<td>south exposed</td>
<td>6.85</td>
<td>63.5</td>
<td>29.6</td>
</tr>
<tr>
<td>south-west exposed</td>
<td>7.05</td>
<td>60.5</td>
<td>32.5</td>
</tr>
<tr>
<td>brown marls; south exposed</td>
<td>6.11</td>
<td>67.5</td>
<td>26.4</td>
</tr>
<tr>
<td>grey marls; south exposed</td>
<td>19.2</td>
<td>48.3</td>
<td>32.5</td>
</tr>
</tbody>
</table>
4.1.2. (Clay) Mineralogical Composition

The mineralogical composition of the clay fraction and calcite and gypsum contents of the fine earth fraction are shown in Table 4.1.5. Within the white marls the smectite and kaolinite amounts are similar. The highest and lowest amounts of smectite are respectively in the grey and brown marls (Fig. 4.1.3). The brown marls contain highest amount of illite. In the grey marls it is obvious that the clay fraction is almost pure smectite. Within the white marl regoliths there are a few possibly important differences. Higher amounts of smectite and lower amounts of illite are present on the south-west facing slope. The amount of swelling clay minerals decreases from a maximum on the north to a minimum on the south-west facing slope. In the white marls, smectite is possibly the only swelling clay mineral, whereas in the brown marls illite could also be a swelling clay mineral because of the relatively high SARp values and Na-content (Imeson et al., 1982).

According to the clay mineralogy of the materials, the highest shrink and swell capacity is expected in the grey and brown marls. The latter profile contains more than twice the amount of sodium as the white marls (Table 4.1.1). Calcite contents in all of the materials fall within the range of 40 to 80 in mass%. For gypsum the range is of 0.1 to 1.5 in mass% (Table 4.1.5).
## Properties of badland regoliths affecting erodibility

### Table 4.1.4 C₅₋₁₀-index of badland material

<table>
<thead>
<tr>
<th>Badland material</th>
<th>C₅₋₁₀-index</th>
<th>Crust + sub-crust</th>
<th>Sub-surface material</th>
<th>Slightly weathered shards</th>
</tr>
</thead>
<tbody>
<tr>
<td>White marls; south-west</td>
<td>5.5</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>White marls; south</td>
<td>5.0</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>White marls; north</td>
<td>3.9</td>
<td>2.9</td>
<td>5.0</td>
<td>nd</td>
</tr>
<tr>
<td>Brown marls; south</td>
<td>4.0</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>Grey marls; south</td>
<td>4.8</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
</tbody>
</table>

### Figure 4.1.3 Clay mineralogy of white, brown and grey badland regoliths (Mg-ethylene glycol saturated samples)
CHAPTER 4.1

Table 4.1.5 Composition of (clay) mineralogy of badland regoliths

<table>
<thead>
<tr>
<th>Badland regolith and horizon description</th>
<th>Clay mineralogy (mass% of clay fraction)</th>
<th>Calcite (mass% of fine earth fr.)</th>
<th>Gypsum (mass% of fine earth fr.)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>smectite 18Å</td>
<td>vermiculite 14Å</td>
<td>illite 10Å</td>
</tr>
<tr>
<td>White marls, northerly exposed</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>Crust + subcrust</td>
<td>52</td>
<td>very few</td>
<td>15</td>
</tr>
<tr>
<td>subsurface material</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>weathered shards</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>slightly weathered shards</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>unweathered shards</td>
<td>56</td>
<td>very few</td>
<td>17</td>
</tr>
<tr>
<td>White marls, southerly exposed</td>
<td>54</td>
<td>very few</td>
<td>17</td>
</tr>
<tr>
<td>Crust + subcrust</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>subsurface material</td>
<td>55</td>
<td>very few</td>
<td>15</td>
</tr>
<tr>
<td>weathered shards</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>slightly weathered shards</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>very slightly weathered shards</td>
<td>58</td>
<td>very few</td>
<td>15</td>
</tr>
<tr>
<td>unweathered shards</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>White marls south-westerly exposed</td>
<td>75</td>
<td>very few</td>
<td>5</td>
</tr>
<tr>
<td>Crust + subcrust</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>subsurface material</td>
<td>71</td>
<td>very few</td>
<td>6</td>
</tr>
<tr>
<td>weathered shards</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>slightly weathered shards</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>unweathered shards</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>White marls, experimental slope, southerly exposed</td>
<td>78</td>
<td>very few</td>
<td>6</td>
</tr>
<tr>
<td>Crust + subcrust</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>subsurface material</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>weathered shards</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>slightly weathered shards</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
<tr>
<td>unweathered shards</td>
<td>nd</td>
<td>nd</td>
<td>nd</td>
</tr>
</tbody>
</table>

* = approximately
4.1.3. Dynamic soil properties

Dynamic soil properties in badland regoliths are (macro)porosity, bulk density and swelling and shrinkage capacity. Their values depend on soil moisture content and therefore of the amount and intensity of rainfall. In Table 3.1.1 and Figure 3.1.3a and b the amount of rainfall is shown during the period of the field experiments in Petrer. Experimental rain fell in only two events (experiments) of 45 minutes and contributed for 10% to the rainfall during period 3-4 (2 years).

Dry bulk density and (macro)porosity
Dry bulk density values are given for two dates; the first is one year before and the second one week after the rainfall simulation experiments (Fig. 4.1.4). On the north facing slope, similar values were obtained for both dates, whereas in the other cases values were lower after the simulated rainfall. The bulk density decreased from white to brown to grey marls.

The pore size distributions derived from the soil water retention characteristics are shown in Figure 4.1.5a to c. The heterogeneity of the pore size distribution and the saturated volu-
metric water content increase in the sequence white to brown to grey marls. This is possibly a result of a higher swelling and shrinkage capacity, which will cause more variety in pore sizes.

The relative importance of macropores is shown from the difference between the dry bulk density calculated from the fitted water retention characteristic and the dry bulk density. The differences between these bulk density values show the pores which are filled with water between pressure head $h = -1\text{cm}$ and $h = 0\text{cm}$. (Table 4.1.6a). As an example, considering a macropore as a crack through a pF-ring, by using macropore value 3.79 vol.% of white marls, south-westerly exposed, the width of the macropore is 1.5mm.

Swelling and shrinkage capacity
As described in Chapter 3.2, volumetric changes were determined from the relationship between the bulk density and the volumetric and gravimetric soil moisture contents and by calculating the COLE-index. The COLE values, together with the results of the SARAN test for the badland regoliths are shown as function of the volumetric soil moisture content in Figure 4.1.6a to d. For the white marls on all aspects the transition between residual and normal shrinkage lies at a volumetric soil moisture content of about 15 %. For the brown marls this point lies at about 12 %, so that the former has a lower air-entry value and it will start to dry at a lower pF value. The grey marls show a transition point at about 10 %. This shows the highest air-entry value, which is caused by the very frequent small pores in this regolith (Photo 4.1.1). The brown marls have a somewhat higher COLE-index than the white marls, which is not explained by a high amount of smectite, but by the combination of the amount of swelling illite, a high sodium content and high SARp-values (Table 4.1.1 and Table 4.1.2; Imeson et al. 1982). However, the course of the COLE-index of the south-westerly exposed white marls is similar to the brown marls, caused by the high amount of smectite. The COLE-index of the grey marls is even higher which is explained by the high amount of smectite.

![Figure 4.1.4 Dry bulk density of badland regoliths](image-url)
Figure 4.1.5 Water retention characteristics of badland regoliths
The differences in dry bulk density values of the white marls increased by 17% during the drying compared to 29% for the brown marls. The increase of the bulk density of the grey marls was even 77%. The relationships between the volumetric and gravimetric soil moisture contents, derived from the shrinkage and swelling tests are shown in Figures 4.1.7a to c for all badland regoliths. These relationships were used to adapt the dry bulk density for soil

Table 4.1.6a Volume of macropores of badland regoliths; calculated from the difference between the dry bulk density calculated at \( pF = 0 \) from the water retention characteristic and the measured dry bulk density (see Methods)

<table>
<thead>
<tr>
<th>badland regolith</th>
<th>saturated volumetric water content according to water retention characteristic (g/cm(^3))</th>
<th>dry bulk density according to water retention characteristic (g/cm(^3)); assumed particle density=2.7g/cm(^3)</th>
<th>dry bulk density according to dry mass (g/cm(^3))</th>
<th>macropores (volume%); difference in bulk densities</th>
</tr>
</thead>
<tbody>
<tr>
<td>white marls north exposed before experiment</td>
<td>0.37</td>
<td>1.71</td>
<td>1.74</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>after experiment</td>
<td>0.38</td>
<td>1.69</td>
<td>1.74</td>
</tr>
<tr>
<td>white marls south exposed before experiment</td>
<td>0.37</td>
<td>1.71</td>
<td>1.87</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>after experiment</td>
<td>0.42</td>
<td>1.58</td>
<td>1.58</td>
</tr>
<tr>
<td>white marls south-west exposed before experiment</td>
<td>0.38</td>
<td>1.67</td>
<td>1.74</td>
<td>-</td>
</tr>
<tr>
<td></td>
<td>after experiment</td>
<td>0.43</td>
<td>1.55</td>
<td>1.45</td>
</tr>
<tr>
<td>brown marls south exposed before experiment</td>
<td>0.43</td>
<td>1.55</td>
<td>1.49</td>
<td>2.31</td>
</tr>
<tr>
<td></td>
<td>after experiment</td>
<td>0.45</td>
<td>1.50</td>
<td>1.39</td>
</tr>
<tr>
<td>grey marls south exposed before experiment</td>
<td>0.52</td>
<td>1.31</td>
<td>1.18</td>
<td>4.79</td>
</tr>
<tr>
<td></td>
<td>after experiment</td>
<td>0.55</td>
<td>1.22</td>
<td>1.08</td>
</tr>
</tbody>
</table>

Figure 4.1.6a Theoretical shrinkage plot, showing the relationship between moisture content, bulk density and COLE (from Cammeraat, 1992).

The differences in dry bulk density values of the white marls increased by 17% during the drying compared to 29% for the brown marls. The increase of the bulk density of the grey marls was even 77%. The relationships between the volumetric and gravimetric soil moisture contents, derived from the shrinkage and swelling tests are shown in Figures 4.1.7a to c for all badland regoliths. These relationships were used to adapt the dry bulk density for soil
moisture and water retention characteristics. For grey marls the duplo sample has a high deviation from the surface material. Probably this is a slightly weathered shard. The regolith is very variable in weathering stage, so a relationship was fit through both samples. However it should be noticed that corrections calculated with this relationship possibly are too high.

The difference between dry bulk density of a bulk soil sample and water saturated and dry bulk density of the soil clods, was used to calculate the amount of macropores (Table 4.1.6b). This is another method than described earlier in this section. The volume of macropores under dry conditions is low for white marls, northerly and southerly exposed. The volume of

### Table 4.1.6b Dynamics of macropore volume in badland regoliths calculated from the difference between bulk density measured by drying a soil sample in a pF-ring and bulk density at dry and saturated conditions measured from a soil aggregate during a test for volumetric change (see Methods)

<table>
<thead>
<tr>
<th>badland regolith</th>
<th>assumed mineral density: 2.70 g/cm³</th>
<th>dry bulk density according to dry mass (g/cm³)</th>
<th>dry bulk density at saturation, calculated from a volumetric change test (g/cm³)</th>
<th>dry bulk density, calculated from a volumetric change test (g/cm³)</th>
<th>macropores according to difference between dry bulk density from pF-rings and from volumetric change test (volume%)</th>
<th>macropores according to difference between dry bulk density from pF-rings and bulk density from volumetric change test at saturation (volume%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>white marls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>north exposed</td>
<td>1.74</td>
<td>1.54</td>
<td>1.81</td>
<td>2.59</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>south exposed</td>
<td>1.87</td>
<td>1.53</td>
<td>1.83</td>
<td>-</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>south-west exposed</td>
<td>1.60</td>
<td>1.29</td>
<td>1.87</td>
<td>10.2</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>brown marls</td>
<td>1.49</td>
<td>1.44</td>
<td>1.81</td>
<td>11.9</td>
<td>-</td>
<td>-</td>
</tr>
<tr>
<td>grey marls</td>
<td>1.18</td>
<td>0.910</td>
<td>1.55</td>
<td>13.7</td>
<td>-</td>
<td>-</td>
</tr>
</tbody>
</table>
CHAPTER 4.1

(b) White marls

(c) Brown marls

(d) Grey marls

Figure 4.1.6 Shrinkage plots of badlands regoliths
PROPERTIES OF BADLAND REGOLITHS AFFECTING ERODIBILITY

(a) White marls

(b) Brown marls

(c) Grey marls

**Figure 4.1.7** Relationship between gravimetric and volumetric soil moisture content
macropores for the brown and grey marls is five times higher. This is also the case for white marls, south-westerly exposed.

Under saturated conditions macropore volumes became negative. This means that the soil clods in the volumetric change test swelled more than the regolith in a bulk soil sample and probably all macropores in a volume equal to this bulk sample disappeared. In case of a positive value macropores would even exist in this volume at saturation.

4.1.4 Field properties related to erosion

Soil shear strength
Soil shear strength was measured in the field before (dry) and after (wet) rainfall simulation experiments using a pocket shear meter. The vertical resistance of the crust was measured by using a penetrometer.

The white marls (south and south-west facing slopes) had the highest shear strength values before the experiments (dry conditions) started and the grey marls the lowest (Fig. 4.1.8a). The vertical resistance data indicate a resistent crust being present on the white and brown marls (Fig. 4.1.8b). On the grey marls, vertical resistance is very low. After the experiments (wet conditions), the brown marls and white marl (SW facing) sites have similar shear strengths, in spite of the brown marl having a higher moisture content. The grey marls also contain more water, but show a lower soil shear strength value.
The vertical resistance measurements of the badland material under dry conditions (Fig. 4.1.8b) mirrors the soil shear strength data. A similarly resistant crust is present on all materials, except for the grey marls (Photos 4.1.2a to c). Under wet conditions, the vertical resistance is always lower. After the second rainfall simulation experiments, in almost all cases, the vertical resistance decreases again. Especially for the brown and grey marls, the resistances are low. This means that compaction of the upper layer of the soil, due to raindrop impact, is more important for the white marls than for the other materials.

Except for the grey marls, on which a surface crust develops, the shear strength and vertical resistance, gradually return to the original values as the regolith dries out. Two years later the crust on the grey marls had disappeared completely.

Soil surface roughness
The highest values of roughness index RI1 were found on the south and south-west facing slopes of the white marls and on the brown marls (Table 4.1.7a). The index RI2 is highest on the brown marls, while it is lowest on the grey marls and white marls (north facing slope) (Table 4.1.7b).
Crack patterns

Crack patterns on badland surfaces were treated as polygons (Photo 4.1.3). By using polygons with eight sides the surface area of cracks was calculated. In the field the width of the cracks and the space between cracks were measured (Table 4.1.8.a and b). The data were averaged and used to calculate the surface area of cracks (Table 4.1.8.c). It was found that the brown marls had the highest crack surface area (greater than 25%). The fewest cracks were found on the white marls (south-west facing slope). This indicates a lower shrinkage capacity of this material in spite of the fact that the clay mineralogy shows a higher content of smectite than the other white marls and the ability to shrink is similar to the brown marls.
Rill patterns
Characteristics of rills on the different plots are seen on Photos 3.1 to 3.3. Measurements to rills were described in Chapter 3.2. A significant difference was found in rill width between the white marls on the north and south facing slopes and on the brown marls, before the experiments (Table 4.1.9a). Rill depth did not show a significant change (Table 4.1.9b).

Considering rill indices for the different badland materials, generally a higher rill activity is seen on the white marls (Table 4.1.10a to d). However differences between the south facing white and brown marls are small. When considering the volume of the rills cut into the regolith, differences are not very high (Table 4.1.10c). The total rill surface area is highest on the white marls, south facing slope and lowest on the brown marls (Table 4.1.10d).

Photo 4.1.2c Grey badland regolith

Photo 4.1.3 Crack pattern in white badland regolith
4.1.8 Main properties of badland regoliths

The measured soil properties distinguish the badland regolith marls in 3 types.

White badland regolith shows the lowest shrink and swell activity. Dry bulk density is highest of all regolith types. It has a combination of a high amount of smectite and calcium. The texture is dominated by the silt fraction and the clay fraction is 25-30%. However, south-westernly exposed white marls show a shrinkage capacity similar to brown marls and a higher amount of smectite than the other white marls. Surface features are rill and pipe erosion especially in these badland regoliths. Under dry conditions a stable crust was formed.

Brown badland regolith has a higher shrink and swell capacity and a lower bulk density than white marls. Lower amounts of smectite are available, but higher amounts of illite. A considerable amount of sodium is available, which probably enlarge the swelling effect of the clay minerals. The silt fraction is slightly higher than of the white marls. The surface shows dominantly mass movement processes and the presence of a few rills. A less stable crust was formed under dry conditions.

Grey badland regolith has the highest shrink and swell capacity and the lowest bulk density of all regolith types. Texture is dominated by clay and sand. Clay mineralogy is almost pure smectite, which explains the high shrinkage and swelling activity. The amount of calcite is lowest of all materials, however still a considerable part of the fine earth fraction. A very unstable surface crust is available under dry conditions, because of the dominant proces of mass movements. One rill is present on the study plot, however this is probably formed in material higher on the slope.
## Properties of Badland Regoliths Affecting Erodibility

**Table 4.1.7a** Roughness index 1; average values and significant differences between plots and periods

<table>
<thead>
<tr>
<th>Period</th>
<th>Plot on Badland Regolith</th>
<th>White Marls;</th>
<th>White Marls;</th>
<th>White Marls;</th>
<th>Brown Marls;</th>
<th>Grey Marls;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (before exp.)</td>
<td>1.26</td>
<td>n.a.</td>
<td>1.54</td>
<td>n.d.</td>
<td>1.17</td>
<td>1.17</td>
</tr>
<tr>
<td>2 (after exp.)</td>
<td>1.26</td>
<td>1.50</td>
<td>1.39</td>
<td>1.48</td>
<td>1.20</td>
<td>1.20</td>
</tr>
<tr>
<td>3 (2 years after exp.)</td>
<td>1.24</td>
<td>1.43</td>
<td>1.43</td>
<td>1.47</td>
<td>1.10</td>
<td>1.10</td>
</tr>
</tbody>
</table>

**Table 4.1.7b** Roughness index 2; average values and significant differences between plots and periods

<table>
<thead>
<tr>
<th>Period</th>
<th>Plot on Badland Regolith</th>
<th>White Marls;</th>
<th>White Marls;</th>
<th>White Marls;</th>
<th>Brown Marls;</th>
<th>Grey Marls;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (before exp.)</td>
<td>10.5</td>
<td>n.d.</td>
<td>12.4</td>
<td>n.a.</td>
<td>5.84</td>
<td>5.84</td>
</tr>
<tr>
<td>2 (after exp.)</td>
<td>9.87</td>
<td>15.4</td>
<td>12.0</td>
<td>20.1</td>
<td>7.99</td>
<td>7.99</td>
</tr>
<tr>
<td>3 (2 years after exp.)</td>
<td>9.24</td>
<td>13.6</td>
<td>13.6</td>
<td>21.9</td>
<td>5.82</td>
<td>5.82</td>
</tr>
</tbody>
</table>

**Table 4.1.8a** Crackwidth (cm); average values and significant differences between plots and periods

<table>
<thead>
<tr>
<th>Period</th>
<th>Plot on Badland Regolith</th>
<th>White Marls;</th>
<th>White Marls;</th>
<th>White Marls;</th>
<th>Brown Marls;</th>
<th>Grey Marls;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (1year before exp.)</td>
<td>0.36</td>
<td>0.21</td>
<td>0.41</td>
<td>0.96</td>
<td>0.58</td>
<td>0.58</td>
</tr>
<tr>
<td>2 (before exp.)</td>
<td>0.26</td>
<td>n.d.</td>
<td>0.37</td>
<td>1.05</td>
<td>0.40</td>
<td>0.40</td>
</tr>
<tr>
<td>3 (after exp.)</td>
<td>0.28</td>
<td>0.22</td>
<td>0.26</td>
<td>0.60</td>
<td>0.55</td>
<td>0.55</td>
</tr>
<tr>
<td>4 (2 years after exp.)</td>
<td>0.33</td>
<td>0.39</td>
<td>0.49</td>
<td>0.78</td>
<td>0.37</td>
<td>0.37</td>
</tr>
</tbody>
</table>

**Table 4.1.8b** Crackspace (cm); average values and significant differences between plots and periods

<table>
<thead>
<tr>
<th>Period</th>
<th>Plot on Badland Regolith</th>
<th>White Marls;</th>
<th>White Marls;</th>
<th>White Marls;</th>
<th>Brown Marls;</th>
<th>Grey Marls;</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (1year before exp.)</td>
<td>3.17</td>
<td>5.84</td>
<td>3.35</td>
<td>6.46</td>
<td>3.44</td>
<td>3.44</td>
</tr>
<tr>
<td>2 (before exp.)</td>
<td>3.32</td>
<td>n.d.</td>
<td>5.42</td>
<td>10.1</td>
<td>3.70</td>
<td>3.70</td>
</tr>
<tr>
<td>3 (after exp.)</td>
<td>3.86</td>
<td>5.64</td>
<td>3.87</td>
<td>5.78</td>
<td>5.44</td>
<td>5.44</td>
</tr>
<tr>
<td>4 (2 years after exp.)</td>
<td>4.44</td>
<td>5.19</td>
<td>4.50</td>
<td>4.54</td>
<td>6.19</td>
<td>6.19</td>
</tr>
</tbody>
</table>

**Remarks:**

- * = significant different from plot 3 and 4; n.d. = not determined; p = 0.05
Table 4.1.8c  Surface area of cracks per surface area of slope (m$^2$/m$^2$)

<table>
<thead>
<tr>
<th>badland material</th>
<th>surface area cracks</th>
<th>before experiment</th>
<th>after experiment</th>
<th>2 years after experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>white marls; north exposed</td>
<td>0.143</td>
<td>0.126</td>
<td>0.129</td>
<td></td>
</tr>
<tr>
<td>white marls; south exposed</td>
<td>0.120</td>
<td>0.119</td>
<td>0.179</td>
<td></td>
</tr>
<tr>
<td>white marls; southwest exposed</td>
<td>n.d.</td>
<td>0.077</td>
<td>0.123</td>
<td></td>
</tr>
<tr>
<td>brown marls; south exposed</td>
<td>0.238</td>
<td>0.192</td>
<td>0.255</td>
<td></td>
</tr>
<tr>
<td>grey marls; south exposed</td>
<td>0.172</td>
<td>0.154</td>
<td>0.108</td>
<td></td>
</tr>
</tbody>
</table>

n.d. = not determined

Table 4.1.9a  Rillwidth (cm): average values and significant differences between plots and periods

<table>
<thead>
<tr>
<th>period</th>
<th>plot on badland regolith</th>
<th>white marls; S exp.</th>
<th>white marls; S exp.</th>
<th>brown marls; S exp.</th>
<th>grey marls; S exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (before exp.)</td>
<td></td>
<td>1.58</td>
<td>n.d.</td>
<td>1.74</td>
<td>3.82</td>
</tr>
<tr>
<td>2 (after exp.)</td>
<td></td>
<td>1.72</td>
<td>1.89</td>
<td>2.26</td>
<td>4.16</td>
</tr>
<tr>
<td>3 (2 years after exp.)</td>
<td></td>
<td>1.81</td>
<td>1.44</td>
<td>1.95</td>
<td>2.33</td>
</tr>
</tbody>
</table>

* * = significant different from plot 3 and 4; n.d. = not determined; p = 0.05

Table 4.1.9b  Rilldepth (cm): average values; no significant differences between plots and periods

<table>
<thead>
<tr>
<th>period</th>
<th>plot on badland regolith</th>
<th>white marls; S exp.</th>
<th>white marls; S exp.</th>
<th>brown marls; S exp.</th>
<th>grey marls; S exp.</th>
</tr>
</thead>
<tbody>
<tr>
<td>1 (before exp.)</td>
<td></td>
<td>2.12</td>
<td>n.d.</td>
<td>2.70</td>
<td>4.25</td>
</tr>
<tr>
<td>2 (after exp.)</td>
<td></td>
<td>2.35</td>
<td>4.29</td>
<td>3.62</td>
<td>6.75</td>
</tr>
<tr>
<td>3 (2 years after exp.)</td>
<td></td>
<td>2.33</td>
<td>3.37</td>
<td>2.99</td>
<td>5.53</td>
</tr>
</tbody>
</table>

n.d. = not determined; p = 0.05

Table 4.1.10a  Rill index 1: transect of rills, reaching the pediment, per meter slope, reaching pediment (cm$^2$/m) (after Tiemessen, 1993)

<table>
<thead>
<tr>
<th>badland material</th>
<th>rill index 1 (cm$^2$/m)</th>
<th>before experiment</th>
<th>after experiment</th>
<th>2 years after experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>white marls; north exposed</td>
<td>24.9</td>
<td>19.3</td>
<td>24.2</td>
<td></td>
</tr>
<tr>
<td>white marls; south exposed</td>
<td>20.1</td>
<td>34.4</td>
<td>26.4</td>
<td></td>
</tr>
<tr>
<td>white marls; southwest exposed</td>
<td>n.d.</td>
<td>58.2</td>
<td>27.0</td>
<td></td>
</tr>
<tr>
<td>brown marls; south exposed</td>
<td>10.2</td>
<td>10.3</td>
<td>4.8</td>
<td></td>
</tr>
<tr>
<td>grey marls; south exposed</td>
<td>2.02</td>
<td>18.3</td>
<td>5.9</td>
<td></td>
</tr>
</tbody>
</table>
Properties of badland regoliths affecting erodibility

**Table 4.1.10b**  Rill index 2: total of transect of rills, reaching the pediment, per surface area of slope (cm²/m²) (after Tiemessen, 1993)

<table>
<thead>
<tr>
<th>Badland material</th>
<th>Rill index 2 (cm²/m²)</th>
<th>Before experiment</th>
<th>After experiment</th>
<th>2 years after experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>White marls; north exposed</td>
<td>14.0</td>
<td>10.5</td>
<td>13.6</td>
<td></td>
</tr>
<tr>
<td>White marls; south exposed</td>
<td>4.4</td>
<td>7.4</td>
<td>5.6</td>
<td></td>
</tr>
<tr>
<td>White marls; southwest exposed</td>
<td>n.d.</td>
<td>12.7</td>
<td>6.0</td>
<td></td>
</tr>
<tr>
<td>Brown marls; south exposed</td>
<td>4.2</td>
<td>4.2</td>
<td>2.0</td>
<td></td>
</tr>
<tr>
<td>Grey marls; south exposed</td>
<td>0.310</td>
<td>2.85</td>
<td>0.906</td>
<td></td>
</tr>
</tbody>
</table>

n.d. = not determined

**Table 4.1.10c**  Rill index 3: total volume of rills on experimental plot, per surface area of plot (m³/m²)

<table>
<thead>
<tr>
<th>Badland material</th>
<th>Rill index 3 (m³/m²)</th>
<th>Before experiment</th>
<th>After experiment</th>
<th>2 years after experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>White marls; north exposed</td>
<td>0.0025</td>
<td>n.d.</td>
<td>0.0034</td>
<td></td>
</tr>
<tr>
<td>White marls; south exposed</td>
<td>0.0031</td>
<td>0.0052</td>
<td>0.0048</td>
<td></td>
</tr>
<tr>
<td>White marls; southwest exposed</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.0032</td>
<td></td>
</tr>
<tr>
<td>Brown marls; south exposed</td>
<td>0.0017</td>
<td>0.0016</td>
<td>0.00065</td>
<td></td>
</tr>
<tr>
<td>Grey marls; south exposed</td>
<td>0.0015</td>
<td>0.013</td>
<td>0.0039</td>
<td></td>
</tr>
</tbody>
</table>

n.d. = not determined

**Table 4.1.10d**  Rill index 4: total surface area of rills on experimental plot, per surface area of plot (m²/m²)

<table>
<thead>
<tr>
<th>Badland material</th>
<th>Rill index 4 (m²/m²)</th>
<th>Before experiment</th>
<th>After experiment</th>
<th>2 years after experiment</th>
</tr>
</thead>
<tbody>
<tr>
<td>White marls; north exposed</td>
<td>0.050</td>
<td>n.d.</td>
<td>0.068</td>
<td></td>
</tr>
<tr>
<td>White marls; south exposed</td>
<td>0.089</td>
<td>0.090</td>
<td>0.090</td>
<td></td>
</tr>
<tr>
<td>White marls; southwest exposed</td>
<td>n.d.</td>
<td>n.d.</td>
<td>0.041</td>
<td></td>
</tr>
<tr>
<td>Brown marls; south exposed</td>
<td>0.031</td>
<td>0.024</td>
<td>0.012</td>
<td></td>
</tr>
<tr>
<td>Grey marls; south exposed</td>
<td>0.047</td>
<td>0.18</td>
<td>0.068</td>
<td></td>
</tr>
</tbody>
</table>

n.d. = not determined
4.2 Properties of cultivated loess soils affecting erodibility

4.2.1 Introduction
To facilitate the explanation of the results presented below, some additional information is given about the experiments and experimental sites in the loess area. Experiments were made under two cultivation regimes. One cultivation regime was dominated by harrowing, and the other by ploughing. The cultivation of the “harrowed” field consisted of:
• Autumn ploughing, to a depth of 30cm.
• Cultivation of rye during winter.
• Cropping the above ground rye in spring;
• Harrowing of the topsoil just before the start of the experiments.

The “ploughed” experimental field site was treated as follows:
• The soil was left uncultivated during the winter.
• Spring ploughing to a depth of 30 cm.
• The top 5cm of soil was harrowed just before the experiments were started.

The main difference was that the harrowed field had only been harrowed just before the experiments started while the ploughed field had been both freshly ploughed and harrowed. In the harrowed field, the effects of autumn ploughing disappeared during the winter. Winter rye was cultivated on this field. Before the experiments winter rye was sprayed to kill the plants and cut away at the soil surface. The roots were left in the soil, not to disturb the soil structure. Roots were not present frequently as is also seen by the amount of organic matter in Table 4.2.1. No significant difference in soil organic matter was seen between harrowed and ploughed soil.

The effect of harrowing is to produce a loose, 5cm thick surface layer containing many macropores. In the ploughed field, the freshly ploughed soil contained many large voids between the large clods (with a diameter of 10cm). The upper 5cm of the profile was composed of the smaller clods produced by the harrowing. Depending on moisture conditions during cultivation, the surfaces of the artificially broken clods are to varying degrees susceptible to slaking. The type of rainfall also influences how clods respond to wetting. Low intensity rainfall has more opportunity to infiltrate into the clod than rainfall with a higher intensity. This effect combined with the higher energy of high intensity rainfall causes more slaking or welding of clod surfaces (Kwaad and Mücher, 1994). This greater instability at the clod surfaces results in more dispersion and sediment entrainment by a larger amount of flowing water. Under these conditions, macropores play an important role in generating saturated subsurface flow.

4.2.2 Chemical soil properties and clay mineralogy
The electrical conductivity, pH and calcite content of the soil were measured in both the harrowed and ploughed field (Table 4.2.1).

The electrical conductivity ranged from 208 to 291 μS/cm. There is a tendency for the Bt-horizons to have the lowest EC and for the moist Ap-horizons to have the highest EC values. This is possibly a long-term effect of applying artificial fertilisers. The trends in both of the pH
measurements are similar, with somewhat lower pH values in the Bt-horizon. Again this can be explained by fertiliser application providing more basic than acidic components to the Ap-horizon. The loess profiles are deeply decalcified (Mücher, 1973). This is shown by the absence of calcite.

The clay mineralogy is similar in both profiles (Table 4.2.2, Fig. 4.2.1). The method by which the data were generated is semi-quantitative so that only relative values can be presented as percentages of the total clay fraction. The swelling minerals, vermiculite and smectite, are considered together. They are difficult to separate because weathering is still probably continuing with chlorite progressing to either vermiculite or smectite. The total content of swelling minerals ranges from 35 to 55 mass%. The amount of illite in the profiles is between 35 and 50%. Kaolinite and chlorite are also difficult to separate. Chlorite seems to be 3-10% of the clay fraction and kaolinite 15-25%.

### 4.2.3 Physico-chemical soil properties

#### Soil Aggregation

Soil Aggregation will be described with respect to three categories:
1. Total fraction smaller than 2mm and fraction larger than 2mm
2. Fractions between 2mm - 0.106mm
3. Fraction < 0.106mm

### Table 4.2.1 Chemical soil properties loess profiles

<table>
<thead>
<tr>
<th>Field Type</th>
<th>EC&lt;sub&gt;25&lt;/sub&gt; (µS/cm)</th>
<th>pH(H&lt;sub&gt;2&lt;/sub&gt;O) (1:2.5 w/v)</th>
<th>pH(CaCl&lt;sub&gt;2&lt;/sub&gt;) (1:2.5 w/v)</th>
<th>CaCO&lt;sub&gt;3&lt;/sub&gt; (mass%)</th>
<th>Organic carbon (mass%)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ap1 (dry)</td>
<td>231</td>
<td>6.72</td>
<td>6.64</td>
<td>0</td>
<td>1.37</td>
</tr>
<tr>
<td>Ap2 (moist)</td>
<td>253</td>
<td>6.81</td>
<td>6.71</td>
<td>0</td>
<td>1.47</td>
</tr>
<tr>
<td>Bt</td>
<td>208</td>
<td>6.64</td>
<td>6.36</td>
<td>0</td>
<td>0.51</td>
</tr>
</tbody>
</table>

### Table 4.2.2 Clay mineralogy of Ap1 and Ap2 and Bt-horizon in harrowed and ploughed loess soils

<table>
<thead>
<tr>
<th>Horizon</th>
<th>&gt;10 Å smectite/vermiculite (*)</th>
<th>10 Å illite (*)</th>
<th>7 Å kaolinite/chlorite (*)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Harrowed Field</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ap1</td>
<td>40</td>
<td>39</td>
<td>21</td>
</tr>
<tr>
<td>Ap2</td>
<td>33</td>
<td>44</td>
<td>22</td>
</tr>
<tr>
<td>Bt</td>
<td>40</td>
<td>42</td>
<td>18</td>
</tr>
<tr>
<td><strong>Ploughed Field</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ap1</td>
<td>38</td>
<td>41</td>
<td>21</td>
</tr>
<tr>
<td>Ap2</td>
<td>46</td>
<td>32</td>
<td>22</td>
</tr>
<tr>
<td>Bt</td>
<td>36</td>
<td>44</td>
<td>20</td>
</tr>
</tbody>
</table>
The first ratio, larger and smaller than 2mm, is indicative of the soil macro structure produced by soil forming processes that include cultivation. The second range covers the meso-structure. In this range, differences are mainly caused by mechanical erosion processes but also partly by physico-chemical and chemical processes. The range < 0.106 mm is considered as the micro-aggregation. Changes in these fractions were measured before and experimental rainfall.

Category 1 shows the fractions smaller and larger than 2mm (macro-aggregation). At the start of the experiments, the fraction <2mm at the surface of the Ap (harrowed soil), is at a maximum (Fig. 4.2.2a). Values elsewhere in the profile were not so different. Subsequently, during the course of the experiments, the fraction <2mm is always lowest for the plough layer compared to the Bt-horizon. However, on two occasions the fraction <2mm is lowest for the Bt-horizon, compared to the plough layer. This is following the 2 experiments with a low intensity rainfall and after 1 experiment with a high intensity.

In the ploughed profile, the aggregate size distribution before the experiments is similar throughout the entire ploughed layer (Fig. 4.2.2b). In the Bt-horizon it is lower than in the ploughed layer. As in the harrowed profile, the initial distribution does not recur after any of the experiments. In most cases, all horizons show a similar distribution after rainfall experiments, except for three cases in which the surface has a larger fraction <2mm. These are the cases after 3 experiments with low intensity rainfall, after 1 experiment with high intensity rain and after 3 experiments with both low intensity and high intensities.

It can be concluded that the impact of rainfall is directly measured in fractions smaller and larger than 2mm after every experiment throughout the soil profile. However, in other research natural rainfall was found to affect only the top few centimetres of the surface (Kwaad, 1998; Ritsema et al., 1996).

Category 2: Fractions between 2mm - 0.106mm (meso-aggregation)

Six fraction classes were distinguished (Table A and B in Appendix I). The fraction 0.106mm to 0.125mm is always very small in both harrowed and ploughed profiles.
CHAPTER 4.2

(a) harrowed loess soil

(b) ploughed loess soil

Figure 4.2.2 Aggregate size distribution before and after rainfall simulation experiments in cultivated loess soils
The fraction 1-2mm shows a similar trend for both sites: repeated experiments enlarge the importance of this fraction. No specific trend within the profiles has been detected.

Category 3: Fractions < 0.106mm (micro-aggregation)

The micro-aggregation was studied in several profiles during the course of the experiments. Aggregate size distribution was determined for the fraction <106μm, before and after treatment with ultrasound. This treatment was repeated to find out the amount of energy needed to disperse the sample into primary particles. For most samples this seemed to be after about 130s treatment with ultrasound at 50% of the energy level (7.5 J/s).

Figure 4.2.3a shows that in a ploughed profile, after ultrasonic treatment of 130s (975J), even the smallest detected aggregates (<2.0μm) only increase very slightly when more energy is applied. This very slight increase could be an artefact for two reasons. Firstly, particles <2μm are sometimes difficult to detect with the Microscan. Further, primary particles are destroyed by the ultrasonic treatment from which smaller particles can originate. Taking this into account, it seems probable from Figure 4.2.3a and Figure 4.2.3b that after 130s ultrasonic treatment, the primary particle size distribution has been reached.

An indicator derived from the above experiment is “the amount of waterstable aggregates” in the untreated sample. This is calculated from the difference between every detected fraction before and after ultrasonic treatment. The amount of waterstable aggregates is the sum of the differences of the fractions that are higher in the untreated sample. Two assumptions are made, namely that at 130s ultrasound all aggregates have been dispersed into primary particles and that the aggregates with the size of primary particles can be neglected.

In the upper Ap of the harrowed profile before the experiments the fractions 32-106μm and 16-32μm are dominant (Fig. 4.2.4a). This is similar for the sample taken from a harrowed profile after three experiments of low intensity rainfall (Fig. 4.2.4b). After three high intensity experiments, the dominant aggregate size class is 16-32μm in the upper Ap (Fig. 4.2.4d). A single sample, taken from the lower Ap after one high intensity experiment, also showed a higher amount of aggregates in the fraction 16-32μm (Fig. 4.2.4c). After a 130 seconds ultrasonic treatment, grain size distribution was similar in all profiles. Slight differences are seen in ploughed and harrowed profiles before the experiments. The fraction 16-32μm is larger in the harrowed profile. This means that this fraction of micro aggregates becomes more unstable because of rainfall. The fraction 32-106μm is slightly larger in the ploughed profile, which means that stable micro aggregates are larger in ploughed than in harrowed soil. Rainfall on ploughed soil caused destabilisation of these large micro aggregates.

In the ploughed profile, only in the upper Ap and before the experiments was the dominant aggregate size 32-106μm (Fig. 4.2.4f). In the profiles after three experiments with low intensity and two experiments with high intensity the dominant fraction is 16-32μm (Fig. 4.2.4g and h). The samples from the Bt-horizon in harrowed and ploughed soil show a similar aggregate breakdown pattern (Fig. 4.2.4e, i and j).

The total amount of waterstable aggregates was determined by the micro-aggregation analyses (Table 4.2.3). Considering the upper part of the Ap (Ap1) it is obvious that the ploughed profile shows the highest amounts. Referring to the dominant aggregate size, this indicates that in the ploughed profile, more smaller aggregates are waterstable than in the harrowed profile (Fig. 4.2.4). The values for the Bt are small in all three cases.

According to the above results, it is concluded that at both the harrowed and ploughed
The amount of macro aggregates (>2mm) increased during the course of the experiments. It seems that after the first experiment, the most major change occurred. After this initial response, only some minor differences were detected in the surface layer (Ap1). A study of the intermediate fraction 2mm to 0.106mm shows for both profiles an increase in the largest fraction, 1-2mm. Referring to the micro-aggregation in the Bt-horizons, no differences were detected in the aggregate size distributions. The higher amount of waterstable aggregates in the ploughed Ap, compared to the harrowed Ap, was probably caused by cultivation, which causes artificial aggregates with unstable surfaces.

**Figure 4.2.3a** Mass percentage of grain size distribution influenced by ultrasonic power; 0-7cm, ploughed soil, before experiments

**Figure 4.2.3b** Grain size distribution after ultrasonic treatment; 0-7cm, ploughed soil, before experiments
Properties of cultivated loess soils affecting erodibility

Figure 4.2.4 Grain size distribution of fraction < 106μm before and after ultrasonic treatment in cultivated loess soils
Consistency indices were determined in the harrowed and ploughed profiles before and after low intensity rainfall experiments (see paragraph 3.2.3). Figures 4.2.5a and b show the relationships between the number of blows (index A) and the soil moisture content of undisturbed soil aggregates. The relationship in Figure 4.2.5a is not clear and it is apparent that consistency is not dependent of soil moisture alone. Figure 4.2.5b shows the relationship between the number of blows and the wet weight of the aggregate. It seems that the higher the wet weight of the clod the less blows are needed for liquefaction. This is probably explained by the higher mass of a soil clod, which gives more pressure of the Cassagrande cup on the soil clod. Soil moisture increases this effect by its weight and possibly also by the destabilisation effect of slaking or welding of the soil clods (Kwaad and Mücher, 1994). Therefore the parameters gravimetric soil moisture content and dry weight of the soil clod were used to calculate an index for undisturbed consistency (index B; see Table 4.2.4).

Figures 4.2.6 and 7 and Table 4.2.4 give the index values for the profiles during the course of the rainfall experiments. It is obvious that for the Bt-horizons, in all cases, the values are very low. For the surface layer (Ap1) in most of the cases the values decreased during the course of the experiments. However, they differ only slightly compared to the values of the plough layer (Ap2). In the field this was seen by almost no change in surface characteristics after low intensity rainfall experiments. The highest change in values is seen in the plough layer. During the course of the experiments both values decrease. This demonstrates that the plough layer has properties that are dynamically related to the rainfall.

From the liquid limit curve, two indices were derived. The liquid limit is the gravimetric soil moisture content corresponding with 25 blows at the curve, combined from values of remoulded samples (paragraph 3.2.3). The C5-10-index (de Ploey and Mücher, 1981) gives information about the steepest part of the curve. A high C5-10-index means that the soil is stable and not very vulnerable to slaking. For both profiles, harrowed and ploughed, both indices were determined (Table 4.2.5).

For the harrowed profile the differences in the liquid limit values within the profile are negligible. In the ploughed profile the liquid limit in the Bt-horizon is lower. This can be explained by the growth of plants and cultivation in the Ap, which causes a better soil structure.

<table>
<thead>
<tr>
<th>Table 4.2.3</th>
<th>Micro-aggregation &lt; 0.106mm in loess soil</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>amount of waterstable aggregates (weight%)</td>
</tr>
<tr>
<td>harrowed profile</td>
<td></td>
</tr>
<tr>
<td>Ap1 before exp.</td>
<td>26.1</td>
</tr>
<tr>
<td>Ap1 after 3 Li exp.</td>
<td>25.2</td>
</tr>
<tr>
<td>Ap2 after 1 Hi exp.</td>
<td>24.2</td>
</tr>
<tr>
<td>Ap1 after 3 Hi exp.</td>
<td>31.1</td>
</tr>
<tr>
<td>Bt after 3 Li and 3 Hi exp.</td>
<td>23.8</td>
</tr>
<tr>
<td>ploughed profile</td>
<td></td>
</tr>
<tr>
<td>Ap1 before exp.</td>
<td>27.5</td>
</tr>
<tr>
<td>Ap1 after 3 Li exp.</td>
<td>27.3</td>
</tr>
<tr>
<td>Ap1 after 2 Hi exp.</td>
<td>29.2</td>
</tr>
<tr>
<td>Bt after 2 Hi exp.</td>
<td>20.7</td>
</tr>
<tr>
<td>Bt after 3 Li and 3 Hi exp.</td>
<td>19.9</td>
</tr>
</tbody>
</table>
Compared to the cultivated A, the Bt is not subject to tillage and has a worse structure. The C5-10-index values can be easily explained in the harrowed profile. The A is more stable than the Bt, because of aggregate formation (Table 4.2.5). However, for the ploughed profile the Bt seems to be more stable than the A. Maybe this result is caused by ploughing, which affects the soil aggregates in a way that is effective at high soil moisture contents.

The conclusions that can be drawn from the consistency tests are that according to the indices derived for the undisturbed aggregates, the decline in the structure is the highest for the ploughed layer. However, this decline is slightly higher in the harrowed soil than in the ploughed soil. The values from the liquid limit curve of the remoulded soil samples show a similar result for the weak structure of the Bt. The C5-10-index gives contradictory results with
CHAPTER 4.2

4.2.4 Dynamic soil properties

Dynamic soil properties in loess soils depend on cultivation and soil moisture dynamics. The amounts of rainfall in the loess area, during the period of investigation are given in paragraph 3.1.2. In loess soils the most important dynamic soil properties for soil erosion are macroporosity and shrinkage and swelling capacity of the soil.

Macroporosity

The role and dynamics of macropores in loess soil was studied under different conditions (Photo 4.2.1). During a one month period samples of the surface and plough layer were studied under natural conditions (Photo 4.2.2). In addition, at 3 sites, samples were collected from around a
The dynamics of the macropore volume during the experiments do not show a clear trend in the harrowed profile (Table 4.2.6a, Fig. 4.2.8a). It is obvious that in the Bt-horizon, macropores do not play an important role. This is also clear in the ploughed profile (Fig. 4.2.8b, Table 4.2.6a). According to the air-entry value in Table 5.2.1a were throughout the entire ploughed profile during initial conditions more macropores present than in the harrowed profile. This is also shown by the results in Table 4.2.6a, except for the Ap2-horizon. In the ploughed profile a slight decrease of macropore volume in the surface layer (Ap1) is seen. This was also concluded from the analysis of the air entry value (Table 5.2.1a). Compared to the harrowed profile, the Ap1 of the ploughed soil shows a higher susceptibility to a decline of macropore structure. Table 4.2.6a shows that, in general, the macropore volume of the ploughed profile is higher than of the harrowed profile, which could indicate that the ploughed soil has a structure that is possibly more susceptible to macropores decline. The presence of more macropores was also concluded from the lower air-entry value in the surface layer, Ap1, of the ploughed soil during the experiments. The macropore volume of the plough layer, Ap2, increased, whereas in the harrowed profile it did not change. The increase in the ploughed profile agrees with the theory that a ploughed profile is more vulnerable to the development of macropores, because of the semi-permeable layer of the Bt-horizon, which causes a water saturated layer in the plough layer. Finally, the plough layer will become very unstable, the surface collapses and a rill is initiated. The conclusion from calculations with the air-entry value (Table 5.2.1b) that rainfall with low intensity has a higher impact on the structure of a ploughed profile than rainfall with a high intensity is not corroborated by the results.

The results from a one-month period of measurements were obtained in April 1994, for a field that was ploughed in the autumn of 1993 (Fig. 4.2.8c, Table 4.2.6b). The pattern of the macropore volume is very dynamic. When these results are compared with differences between wetting and drying curves (Table 5.2.2b) the slight decrease of the macropore volume in the surface layer is not apparent. However the increase of difference in volumetric soil moisture content at pF = 0.40 in the lower Ap of ploughed soil could indicate an increase in (macro)porosity.

In a rill system it appeared that the macropore volume in the area between two rills is higher than in the rill bottom (Fig. 4.2.8d, Table 4.2.6c). The same results were obtained from the wetting and drying curve calculations of this rill system (Table 5.2.2b).

### Table 4.2.5 Consistency indices of remoulded soil samples

<table>
<thead>
<tr>
<th></th>
<th>liquid limit</th>
<th>C5-10-index</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>harrowed profile</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ap1</td>
<td>0.31</td>
<td>3.0</td>
</tr>
<tr>
<td>Ap2</td>
<td>0.29</td>
<td>3.0</td>
</tr>
<tr>
<td>Bt</td>
<td>0.30</td>
<td>2.1</td>
</tr>
<tr>
<td><strong>ploughed profile</strong></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ap1</td>
<td>0.30</td>
<td>2.6</td>
</tr>
<tr>
<td>Ap2</td>
<td>0.31</td>
<td>2.7</td>
</tr>
<tr>
<td>Bt</td>
<td>0.26</td>
<td>3.8</td>
</tr>
</tbody>
</table>
Swelling and shrinkage

The clay fraction of loess soils comprises 30 to 40 percent (by weight) swelling clay minerals (Table 4.2.2). The implications for the (macro)porosity calculations for soil moisture and water retention curves were therefore studied by testing the shrinkage and swelling capacity of the soil aggregates. As mentioned in paragraph 3.2.3 the change in dry bulk density and the COLE factor were determined.

The dry bulk density and COLE factor of different horizons were plotted against the corresponding volumetric soil moisture content. In Figure 4.2.9a to d the shrinkage phases can be seen, especially normal and residual shrinkage (Fig. 4.1.6a). In the harrowed profile the calculated dry bulk density, from the shrinkage and swelling tests, increases with depth. The

Photo 4.2.1 Surface of harrowed and ploughed site for rainfall simulation experiments

Photo 4.2.2 Study site for surface characteristics at Wijnandsrade, The Netherlands, upslope from a rill system
capacity to shrink and swell is higher for the Bt-horizon than for the Ap-horizon. In the ploughed profile, the calculated dry bulk density becomes lower with depth. This is possibly caused by mixing of the soil layers as a result of ploughing. The ability to shrink and swell is in this case higher for the Bt than for the Ap-horizon. This was caused by higher clay content of the Bt due to clay illuviation from the Ap. The Ap2 and the Bt of the harrowed and ploughed profile show a similar result for shrinkage and swelling. The Ap1 shows a higher dry bulk density for the ploughed profile. The COLE factor, on the other hand, is similar for both. The increase in bulk density for the Ap1 of the harrowed profile is 11% of the bulk density at pF=1. For the Bt the increase is 22%. Figure 4.2.9a and b show that the transition between normal and residual shrinkage, the air entry point, is at about 10% of volumetric soil moisture content (see arrow). This is similar to the Ap1 and the Bt of the ploughed profile. Differences between swelling and shrinkage tests with different pF values as starting points, pF=1 and pF=1.5, are not high. The dry bulk densities found with the test started at pF=1.5 are slightly lower than those with the test started at pF=1.0.

4.2.5 Main properties of cultivated loess soils
Loess soils are well-sorted soils, consisting of ca. 60 mass% of silt and about 20 mass% of clay. The clay fraction consists of about 40 mass% of swelling minerals, smectite and vermiculite, 40 mass% of illite and 20 mass% of kaolinite and chlorite. The soil profiles are deeply calcified.

The general soil profile in the study area consists of about 30cm of an Ap, with an organic carbon content of ca. 1.5 mass%. This horizon is divided in a more surficial layer Ap1 and
Table 4.2.6a Dynamics of macropore volume in loess soil before and after rainfall simulation experiments; calculated from the difference between the bulk density calculated at pF=0 from the water retention characteristic and the bulk density measured by drying a soil sample (see Methods).

<table>
<thead>
<tr>
<th></th>
<th>saturated volumetric water content according to water retention characteristic</th>
<th>bulk density according to water retention characteristic (g/cm³); assumed particle density=2.650g/cm³</th>
<th>bulk density according to dry mass (g/cm³)</th>
<th>macropores (volume%); difference in bulk densities</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>harrowed profile</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>before exp. Ap1</td>
<td>0.51</td>
<td>1.299</td>
<td>1.204</td>
<td>3.57</td>
</tr>
<tr>
<td>Ap2</td>
<td>0.47</td>
<td>1.405</td>
<td>1.266</td>
<td>5.24</td>
</tr>
<tr>
<td>B(t)</td>
<td>0.45</td>
<td>1.458</td>
<td>1.541</td>
<td>-</td>
</tr>
<tr>
<td>after 1LI Ap1</td>
<td>0.45</td>
<td>1.458</td>
<td>1.312</td>
<td>5.48</td>
</tr>
<tr>
<td>Ap2</td>
<td>0.43</td>
<td>1.511</td>
<td>1.487</td>
<td>0.881</td>
</tr>
<tr>
<td>B(t)</td>
<td>0.45</td>
<td>1.458</td>
<td>1.317</td>
<td>5.29</td>
</tr>
<tr>
<td>after 1HI Ap1</td>
<td>0.43</td>
<td>1.511</td>
<td>1.315</td>
<td>7.36</td>
</tr>
<tr>
<td>Ap2</td>
<td>0.46</td>
<td>1.431</td>
<td>1.491</td>
<td>-</td>
</tr>
<tr>
<td>B(t)</td>
<td>0.45</td>
<td>1.458</td>
<td>1.297</td>
<td>6.05</td>
</tr>
<tr>
<td>after 3HI Ap1</td>
<td>0.49</td>
<td>1.352</td>
<td>1.22</td>
<td>4.96</td>
</tr>
<tr>
<td>Ap2</td>
<td>0.43</td>
<td>1.511</td>
<td>1.385</td>
<td>4.75</td>
</tr>
<tr>
<td>B(t)</td>
<td>0.42</td>
<td>1.537</td>
<td>1.504</td>
<td>1.239</td>
</tr>
<tr>
<td><strong>ploughed profile</strong></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>before exp. Ap1</td>
<td>0.43</td>
<td>1.511</td>
<td>1.242</td>
<td>10.12</td>
</tr>
<tr>
<td>Ap2</td>
<td>0.45</td>
<td>1.458</td>
<td>1.329</td>
<td>4.86</td>
</tr>
<tr>
<td>B(t)</td>
<td>0.44</td>
<td>1.484</td>
<td>1.377</td>
<td>4.03</td>
</tr>
<tr>
<td>after 1LI Ap1</td>
<td>0.45</td>
<td>1.458</td>
<td>1.251</td>
<td>7.80</td>
</tr>
<tr>
<td>Ap2</td>
<td>0.43</td>
<td>1.511</td>
<td>1.418</td>
<td>3.51</td>
</tr>
<tr>
<td>B(t)</td>
<td>0.45</td>
<td>1.458</td>
<td>1.345</td>
<td>4.24</td>
</tr>
<tr>
<td>after 1HI Ap1</td>
<td>0.45</td>
<td>1.458</td>
<td>1.244</td>
<td>8.07</td>
</tr>
<tr>
<td>Ap2</td>
<td>0.46</td>
<td>1.431</td>
<td>1.391</td>
<td>1.51</td>
</tr>
<tr>
<td>B(t)</td>
<td>0.42</td>
<td>1.537</td>
<td>1.226</td>
<td>11.75</td>
</tr>
<tr>
<td>after 3HI+3LI Ap1</td>
<td>0.44</td>
<td>1.484</td>
<td>1.297</td>
<td>7.07</td>
</tr>
<tr>
<td>Ap2</td>
<td>0.42</td>
<td>1.537</td>
<td>1.324</td>
<td>8.04</td>
</tr>
<tr>
<td>B(t)</td>
<td>0.415</td>
<td>1.550</td>
<td>1.559</td>
<td>-</td>
</tr>
</tbody>
</table>

a deeper layer Ap2 to study differences in physical and dynamic soil properties. The underlying brighter coloured Bt shows 0.5 mass% of organic carbon.

Differences between the study sites are cultivation, i.e. both ploughed and harrowed and only harrowed. Two other less intensively studied sites were only ploughed. The ploughed
sites showed a higher amount of macropore volume. In few cases micro-aggregation was less stable in ploughed than in only harrowed soils. Also consistency was more unstable for ploughed than for only harrowed soils. The increase in bulk density from pF = 1 to oven dry is two times higher for the Bt than for the Ap. No clear difference in shrinkage capacity is seen between cultivation types.

These properties and relationships are studied further in the following chapters.

### Table 4.2.6b Dynamics of macropore volume in loess soil during 1 month in 1994; calculated from the difference between the bulk density calculated at pF=0 from the water retention characteristic and the bulk density measured by drying a soil sample (see Methods)

<table>
<thead>
<tr>
<th></th>
<th>saturated volumetric water content according to water retention characteristic</th>
<th>bulk density according to water retention characteristic (g/cm³); assumed particle density=2.650g/cm³</th>
<th>bulk density according to dry mass (g/cm³)</th>
<th>macropores (volume%); difference in bulk densities</th>
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</thead>
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<tr>
<td>April 1994</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ap1</td>
<td>0.461</td>
<td>1.428</td>
<td>1.475</td>
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<tr>
<td>Ap2</td>
<td>0.416</td>
<td>1.548</td>
<td>1.561</td>
<td>-</td>
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<tr>
<td>B(t)</td>
<td>0.414</td>
<td>1.553</td>
<td>1.559</td>
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<td>after 1 week</td>
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<td></td>
</tr>
<tr>
<td>Ap1</td>
<td>0.437</td>
<td>1.492</td>
<td>1.404</td>
<td>3.32</td>
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<tr>
<td>Ap2</td>
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<td>4.14</td>
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<td>after 2 weeks</td>
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<tr>
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<tr>
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<td>1.565</td>
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<td>1.373</td>
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<td>1.492</td>
<td>1.454</td>
<td>1.43</td>
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<tr>
<td>after 4 weeks</td>
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<td></td>
<td></td>
</tr>
<tr>
<td>Ap1</td>
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<td>1.511</td>
<td>1.432</td>
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<tr>
<td>Ap2</td>
<td>0.424</td>
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<tr>
<td>B(t)</td>
<td>0.408</td>
<td>1.574</td>
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</table>

### Table 4.2.6c Dynamics of macropore volume in loess soil around a rill system; calculated from the difference between the bulk density calculated at pF=0 from the water retention characteristic and the bulk density measured by drying a soil sample (see Methods)

<table>
<thead>
<tr>
<th></th>
<th>saturated volumetric water content according to water retention characteristic</th>
<th>bulk density according to water retention characteristic (g/cm³); assumed particle density=2.650g/cm³</th>
<th>bulk density according to dry mass (g/cm³)</th>
<th>macropores (volume%); difference in bulk densities</th>
</tr>
</thead>
<tbody>
<tr>
<td>between rills</td>
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<tr>
<td>Ap1</td>
<td>0.434</td>
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<td>in rill</td>
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<td>0.408</td>
<td>1.569</td>
<td>1.503</td>
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</table>
(a) before and after rainfall simulation experiments in harrowed soil

(b) before and after rainfall simulation experiments in ploughed soil

(c) ploughed loess soil during 1 month in April 1994

(d) ploughed loess in and around a rill system

Fig. 4.2.8 Dynamics of macropore volume in loess soil under different conditions
**Figure 4.2.9** Bulk density and COLE-factor of cultivated loess soils
5

Hydrological response of badland regoliths and cultivated loess soils

Introduction

One of the hypotheses in this study is that a difference in structure of a soil profile explains rill erosion in two soil types. The first soil type is a badland regolith, located in South-East Spain, which consists of a profile with a layer of weathered shards resting on an unweathered impermeable rock layer. The other soil type is a ploughed loess soil, located in Southern Limburg, The Netherlands, in which the plough layer (Ap) is lying on a more or less impermeable B-horizon with a plough sole (Imeson and Verstraten, 1988). Infiltration of rainfall into the weathered and ploughed layer and stagnation of water on the impermeable layer were thought to cause saturation of the soil layer above the impermeable layer (Ritzema, 1994). Saturation would be caused by quick vertical macropore flow through cracks and macropores. Rill flow would be caused by horizontal subsurface flow over the impermeable layer, making the upper part of the profile unstable. Collapse of the surface layer would cause surface depressions from which rills can be initiated and developed.

Infiltration in these profiles was examined in this study. Evidence was sought for the occurrence of a water saturated layer above the impermeable layer. Another important measurement was the determination of macropore flow. Discontinuous infiltration and saturation of part of the soil profile was studied by means of rainfall simulation experiments and soil moisture measurements. Changes in hydrological behaviour of the soil caused by infiltration, saturation and wetting and drying of the soil were studied by field observations and by measurements of water retention curves. Discharge was measured to calculate the partitioning of rainfall between runoff and infiltration.

The objective of this chapter is to describe and discuss the results of measurements and experiments in badland regoliths and loess soils related to soil moisture and the hydrological balance.

Results of the experiments are described in separate chapters (5.1 and 5.2), however in a similar way. The measurements and results of water movement in the badland regoliths and loess soils are described separately from the measurements of the relevant soil characteristics related to soil moisture and water contents. Patterns of pressure head and soil moisture...
CHAPTER 5.1

content as measured spatially and in time during the course of the experiments are described and evaluated. Then, the water retention characteristics measured in the laboratory are shown and the effect of hysteresis is discussed. In the last part of the chapter, hydrological balance and drainage patterns in relation to rill erosion are discussed.
5.1 Hydrological response of badland regoliths

5.1.1 Introduction
In the badland area near Petrer (Alicante, Spain) three sites were chosen according to geomorphological features at the surface, i.e. rill density and amount of mass movement. Crust type also differentiates the three sites.

The sites are characterised as follows:
1. white marls: high rill density; little mass movement; flat, stable crust (as domed crust, described by Finlayson, 1987). On this material three plots were chosen, with a different aspect, namely North, South and South-West.
2. brown marls: few rills; mass movement on the side of rills; mass movement in interrill areas; rough, unstable crust (as pinnacle crust, described by Finlayson, 1987, however without lichen). One south facing plot was chosen on this material.
3. grey marls: very few rills; high mass movement density at the surface, mudflows; very unstable, flat crust. One south facing plot was chosen on this material.

The plots were chosen with a micro-topography that enabled them to be treated as individual parts of the slope. Pressure head and soil water content were measured in order to be able to detect water movement in the regolith profile, which might provide evidence for either saturation above the impermeable layer or macropore flow through the profile. On every plot, a rill extending to the pediment was chosen to sample runoff from. Around this rill ten tensiometers and twelve TDR-probes (Chapter 3.2.2) were installed in two rows with ca. 0.50 m height in between, along the contour lines of the slope (Fig. 3.2.1). This arrangement was chosen to measure spatial differences around a rill system. Codes were given to every point measured by tensiometer or TDR probe according to the following properties:

1. badland material: W = white; B = brown; G = grey
2. aspect: n = North; s = South; sw = South-West
3. drainage function: R = in the rill bottom; E = side of the rill; I = interrill
4. position on slope: H = high; L = low
5. experiment: 1 = first experiment; 2 = repeated experiment (after 24 hours)

The rainfall simulation experiments were performed as follows. Demineralised water was applied for 45 minutes from two rotating sprinklers mounted on a pole 2 meters above the ground. The rainfall intensity varied between 15mm/hr and 42.7mm/hr (Table 5.1.1). This was caused by disturbance of the wind, but also because of differences in water pressure, caused by difference in height between pump and rainfall simulator. Every experiment was repeated after 24 hours. However, on white marls, the north facing slope, three experiments were made, of which the first one was a trial experiment. Some of the results from this experiment are nevertheless used in this study. Sampling for water retention characteristics and TDR calibration was done in most of the cases on or near the site of the plot. For all sites profile
descriptions were made (Table 3.1.1).

5.1.2 Spatial and temporal dynamics of soil water in a rill system during wetting and drying

Pressure head and water content were measured during the course of a rainfall simulation experiment in respectively the upper 5cm and 10cm of the regolith (Table 3.2.1b). Six tensiometers and eight TDR probes were installed in the side of a rill, two tensiometers and TDR probes in a rill and two in interrill areas (Fig. 3.2.1). These different locations were chosen in order to measure the spatial and temporal drainage pattern on a slope incised by rills. Pressure head was measured in order to detect saturation, but also to obtain the data needed to construct a field water retention curve. Soil water content was measured in order to determine spatial and temporal soil water flow along a slope and especially towards rills. These results might give an answer to the following research questions (Chapter 1.2):

1. What is the spatial and temporal drainage pattern around a rill system?
2. Does water saturation of the regolith occur above an impeding layer, caused by subsurface flow?

In badland regolith susceptible to swelling and shrinkage, infiltration is very complicated. Water can infiltrate through the soil matrix, but also through cracks or macropores as preferential or subsurface flow. While water is infiltrating the soil starts to swell, whereas during drying the soil shrinks. This causes differences in bulk density and consequently differences in volumetric soil moisture content. Pore volume is changing constantly, which probably has a strong effect on the differences of soil moisture at a certain pF on the wetting and drying curve, the so called hysteresis. In general the soil pores can retain more water during desorption than during absorption under a similar pF. This is due to the irregular and composite sizes and shapes of the pores. In addition, the contact angle $\phi$ between the water meniscus and the solid soil surface of the pore could be lower during wetting than during drying. In swelling and shrinking soils, during wetting the soil is swelling which causes a pore size distribution with more smaller pores. During drying relatively more macropores are created. As macropores have a too large radius to retain capillary water it should be expected that during drying of badland regolith the soil is dryer than during wetting under a similar pF. This is the

<table>
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<tr>
<th>plot</th>
<th>rainfall</th>
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<th>cracks</th>
<th>cracks</th>
<th>total</th>
<th>runoff</th>
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<td>start</td>
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<td>(mm/hr)</td>
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<td>n.d.</td>
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<td>—</td>
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<td>65.5</td>
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<tr>
<td>bs</td>
<td>13</td>
<td>42.0</td>
<td>15.2</td>
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<td>46.5</td>
<td>0.10</td>
<td>365</td>
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<tr>
<td></td>
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<td>42.0</td>
<td>5.8</td>
<td>4.0</td>
<td>—</td>
<td>105</td>
<td>0.25</td>
<td>305</td>
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<tr>
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<td>4.4</td>
<td>9.4</td>
<td>58.0</td>
<td>0.70</td>
<td>28.5</td>
</tr>
</tbody>
</table>

n.d. = not determined
— = cracks did not close
* = infiltration and runoff coeff. derived from runoff data; runoff is possibly too high because of runoff from adjacent slope segments

Table 5.1.1 Hydrological data of rainfall simulation experiments on badlands
opposite of the hysteresis theory mentioned above.

**Soil moisture and soil water pressure during rainfall**

White, brown and grey marls have different properties and surface morphology. Therefore the results of the rainfall experiments are considered separately for each regolith.

*white marls (Wn, Ws, Wsw)*

The results of the soil water pressure measurements in this regolith show for all plots and aspects a quick saturation of the upper part of the regolith profile (Fig. 5.1.1). The measuring points in the side of a rill show a more irregular response to infiltration than in a rill or interrill areas (Fig. 5.1.1a). This could indicate more water movement in the side of the rill and possibly subsurface or macropore flow. Considering differences between rills and the surrounding area, it was seen that in the upper part of the rill, water infiltrated very slowly (Fig. 5.1.1b). However, finally the regolith under the rill was also saturated. This process is seen on the northerly and southerly exposed marls (App. II, Fig. 4b). On the interrill areas most points showed an increase of soil water pressure until saturation (Fig. 5.1.1b). After 2 experiments it appeared that contact problems between the regolith and tensiometer occurred (App. II, Fig. 2).

The soil moisture content in the side of the rills in the white marls increased suddenly, immediately after the start of the experiment or after 10 or 20 minutes (Fig. 5.1.2a and 5.1.4a). In the rill and the interrill areas the increase of soil moisture was considerably less (Fig. 5.1.2b and 5.1.4b). In a few cases no water infiltrated under rills. Some measuring points lying below one another responded similarly to rainfall, mostly in the side of a rill or in a rill (Fig. 5.1.2). On south-westerly exposed white marls the measuring points higher on the slope showed a quicker wetting than the lower points (Fig. 5.1.4).

Spatial drainage data plotted against time show that on the north-facing slope, there was little or no infiltration under a rill (Fig. 5.1.11). However, on the south-facing slope the measuring point in the rill bottom became wetter than the other measuring points, except for the side of the measured rill (Fig. 5.1.12). On the south-west facing slope the regolith under the rill remained reasonably dry (Fig. 5.1.13). In general the difference between the measuring points was quite high. This strengthens the fact that preferential flow through macropores is one of the most important infiltration processes in these materials. A tendency was seen that on the lower part of the slope, slightly more water infiltrated than on the higher part. This could be caused by overland flow generated on the lower part of the slope and infiltrating into macropores. On the south-westerly exposed slope the opposite was observed (Fig. 5.1.13). In this case more water infiltrated on the higher part of the slope and more overland flow was generated on the lower part due to less infiltration into macropores.

*brown marls (Bs)*

In this material the pressure head measurements show a bad response to rainfall (Fig. 5.1.5). Brown marls have more macropores and cracks than white marls, which possibly disturbs the measurements. Only some measuring points on the mass movement surface (IH(1) and IL(1)) and in the rill (RH and RL) show reliable results (Fig. 5.1.5b). In the rill bottom, at the lowest point (RL) on the slope, a gradual increase in pressure head was established. At the highest point pressure heads were almost constant, indicating dry conditions. On the mass
CHAPTER 5.1

Figure 5.1.1 Soil water pressure during experiments on white marls, northerly aspect

Figure 5.1.2 Soil water content during experiments on white marls, northerly aspect

Figure 5.1.3 Soil water pressure during experiments on white marls, northerly aspect
HYDROLOGICAL RESPONSE OF BADLAND REGOLITHS

Figure 5.1.3 Initial soil water content, white marls, south-westerly aspect

(a) side of rill

(b) rill and interrill area

Figure 5.1.4 Soil water content during experiments on white marls, south-westerly aspect
Figure 5.1.5 Soil water pressure during experiments on brown marls, southerly exposed

Figure 5.1.7 Soil water content during experiments on brown marls, southerly exposed
HYDROLOGICAL RESPONSE OF BADLAND REGOLITHS

Figure 5.1.8: Soil water pressure during experiments on grey marls, southerly exposed

Figure 5.1.10: Soil water content during experiments on grey marls, southerly exposed
movement surface, the pressure heads increased almost to saturation.

The antecedent soil moisture contents in the brown marls were higher than in the white marls (Fig. 5.1.3, Fig. 5.1.6). Also the maximum values, reached during the rainfall experiments, were considerably higher (Fig. 5.1.4a, Fig. 5.1.7b). The mass movement area showed the largest increase in soil moisture contents (Fig. 5.1.7b). This supports the observed saturation conditions of this area (Fig. 5.1.5b). Several measuring points on the lower slope responded more rapidly than others on higher slope positions (Fig. 5.1.7). An explanation for this could be that on this experimental plot, the points lower on the slope, occupy a triangular area limited by two rills, which could cause a convergence of flow lines, and consequently a quicker response and a wetter lower slope.

Rills behaved slightly different from their surrounding area. The interrill area on the lower row showed higher soil moisture contents than the other points (Fig. 5.1.14). This also supports the saturation of the surface layer detected by soil water pressure.

As will be mentioned in Chapter 5.1.5, the amount of infiltrated water was higher for the brown and grey regoliths than for the white regoliths. On the brown marls this happened especially during the first rainfall experiment. During the second one the amount of infiltrated water was less, probably due to crusting.

grey marls (Gs)
In the grey marls, soil water pressure increased during rainfall, but not until saturation (Fig. 5.1.8). Several points showed similar wetting trends in time. These are IH(1) and IH(2), EH(1)

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**Figure 5.1.6** Antecedent volumetric soil water content of the upper 10cm of the brown marls, southerly exposed

<table>
<thead>
<tr>
<th>location on slope</th>
<th>soil water (cm³/cm³)</th>
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</thead>
<tbody>
<tr>
<td>IH(1)</td>
<td></td>
</tr>
<tr>
<td>RH</td>
<td></td>
</tr>
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<td>EH(2)</td>
<td></td>
</tr>
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<td>IL(3)</td>
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<table>
<thead>
<tr>
<th>location on slope</th>
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<tbody>
<tr>
<td>EH(1)</td>
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<td>RH</td>
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<td>IL(3)</td>
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and EH(2), EL(1) and EL(2), RH and RL. These last two measuring points showed a similar increase as their adjacent ones, EH(1) and EH(2). This high degree of similarity indicated that the structure of this regolith profile is less irregular than the white and the brown marl regoliths.

Almost no difference existed in pressure heads between points in a rill bottom and on the surface or in the side of a rill. The second experiment showed a sudden increase of soil water pressure at two locations, RH and EH(2), (App. II, Fig. 10a and b). This is interesting, because crust formation after the first experiment influenced infiltration and runoff.

Unlike the soil water pressure, the soil moisture contents in a rill could be distinguished from the values of the surrounding area. Both measuring points in the rill (RH and RL) showed either the largest increase in soil moisture content and the largest absolute soil moisture content, during the first experiment (Fig. 5.1.10b). The lower point (RL) reacted 20 minutes later than the higher point (RH). Soil moisture content is, except for under the rill, in general higher in the upper part of the slope than in the lower part during both experiments (Fig. 5.1.10, Fig. 5.1.15, App. II, Fig. 20). During experiment two, soil moisture values were higher than during the first one.

The spatial pattern in the soil moisture content (Fig. 5.1.15) showed some remarkable differences. Under the rill more infiltration took place during both experiments. And, as mentioned above, more water infiltrated in the upper part of the slope than in the lower part. On the grey marls the increase of the volumetric soil moisture content was higher during the second experiment, but it was more variable if the different points on the slope are considered (Fig. 5.1.15).

**Soil moisture before and after the rainfall experiments**

The antecedent soil moisture content of the badland regolith shows higher amounts for brown and grey marls than for white marls. The antecedent soil moisture content of white marls before the first experiment ranges from 0 to 0.1 cm³/cm³ (Fig. 5.1.3). For the grey marls is this between 0 and 0.3 cm³/cm³ (Fig. 5.1.9) and for the brown marls between 0 and 0.5 cm³/cm³ (Fig. 5.1.6).

After rainfall the soil moisture values in the white marls were higher during a short period (Fig. 5.1.2 and 5.1.4). After 24 hours the soil moisture content almost decreased to the antecedent values (App. II, Fig. 15a and b). The regolith of the brown marls showed a high soil moisture content after the rainfall experiments. After the first experiment the highest soil moisture value was 0.7 cm³/cm³ (Fig. 5.1.7); however, after the second one it was even 0.8 cm³/cm³ (App. II, Fig. 18). The regolith did not dry out quickly after the first experiment. After 24 hours soil moisture was in some cases still twice as high as the antecedent soil moisture content (App. II, Fig. 17b). Most antecedent values of the second experiment were around 0.5 cm³/cm³. This also applied for the grey marls, which even showed higher soil moisture contents. Most of the measured points showed still 24 hours after the first experiment a soil moisture content twice as high as the antecedent soil moisture content (App. II, Fig. 19b). Most antecedent values were around 0.35 cm³/cm³.
5.1.3 Analysis of soil moisture contents during and after rainfall

Simple functions were fitted through the soil water measurements (Hyans, 1995). Wetting and drying periods were fitted separately, because they were quite different. The best-fit functions are shown in Table 5.1.2. Figures 5.1.16 to 5.1.18 give examples of the curves for all badland materials. Appendix III shows all soil moisture data and their fitted functions. No clear difference was observed between the function types of the different badland regoliths. The main difference for the badland marls was the amount of water that infiltrated during the experiments (Fig. 5.1.16 to Fig. 5.1.18). In the white marls the maximum increase in volumetric soil moisture content was 0.25 m$^3$/m$^3$. According to runoff data no water infiltrated during the second experiment on northerly exposed white marls (Table 5.1.1). However soil moisture data show infiltration, which confirms that these runoff data are not reliable to calculate infiltration. The brown marls showed an increase of 0.5 m$^3$/m$^3$, whereas the grey marls showed even an increase of more than 0.5 m$^3$/m$^3$.

Fit functions were used to find field relationships between pressure head and water content. These relationships, which could give some evidence about hysteresis and crackflow, are described in section 5.1.4.

However, the fitted curves of the water contents were also used to identify the infiltration process. The fitted form of the infiltration curve showed something about the behaviour of the infiltration rate. It gives also some information about crack or preferential flow and subsurface flow. The variation in the curve forms (functions and their parameters) was used to find differences in infiltration characteristics at the various measuring points on the slope. The curve fitted for the drying period says something about the depth of infiltration. For example, when a drying curve is very steep and decreases quickly, much water is evaporating from the surface.
Soil moisture content during rainfall simulation experiments in white badland regoliths, Peter, Spain

Figure 5.1.11
White marls, northerly exposed; experiment 2

Figure 5.1.12
White marls, southerly exposed

Figure 5.1.13
White marls, southwesterly exposed; experiment 1

Legend
volumetric soil moisture content (m3/m3)
-0.20
-0.19
-0.18
-0.17
-0.16
-0.15
-0.14
-0.13
-0.12
-0.11
-0.10
-0.09
-0.08
-0.07
-0.06
-0.05
-0.04
-0.03
-0.02
-0.01
-0.00

= start experiment
= end experiment
Soil moisture content during rainfall simulation experiments in brown and grey badland regolith, Petrer, Spain

Figure 5.1.14
Brown marls, southerly exposed

(a) experiment 1
(b) experiment 2

(higher row) location on slope

Figure 5.1.15
Grey marls, southerly exposed

(a) experiment 1
(b) experiment 2

(higher row) location on slope

Legend
volumetric soil moisture content (m3/m3)

= start experiment
= end experiment
This means that most of the infiltrated water was kept in the upper part of the regolith. When a drying curve decreases very slowly, the water most probably infiltrated much deeper into the soil. Especially, when the upper part of the soil dries out very quickly and keeps a very low water content, it will protect the underlying layers from drying.

An analysis was made of the different best-fit functions in relation to the badland material and location on the slope.

**Infiltration**

Firstly, the wetting part was studied. The curves were divided into concave, convex, straight wetting curves or 'no wetting'. 'No wetting' of the measured point meant no infiltration in that part of the regolith. A concave (C) curve meant an increase of the infiltration rate until the steepest part of the curve. A convex (V) curve meant a decrease of the infiltration rate until the top of the curve. A combined concave-convex (C/V) curve showed an increase in infiltration rate followed by a decrease in infiltration rate until the top of the curve. A straight (S) curve meant a constant infiltration rate, without ponding or overland flow. A convex curve probably...
Figure 5.1.16 Soil moisture change during rainfall simulation experiments on badland regoliths, white marls

Fig. 5.1.17 Soil moisture change during rainfall simulation experiments on badland regoliths, brown marls
Figure 5.1.18 Soil moisture change during rainfall simulation experiments on badland regoliths, grey marls
indicated quick sealing or closing of surface cracks. A concave curve probably showed infiltration through the soil matrix and after a while crack flow while ponding occurred at the surface, which caused a sudden increase in infiltration rate. In Table 5.1.3, for every regolith material, rainfall experiment and position on the slope the form of the curve is given. From this table, Tables 5.1.4 and 5 were derived, giving the number of forms per badland material and per location on the slope. To make a good comparison, percentages of the total number of measured points are given. The amount of infiltrated water can be derived from the differ-

### Table 5.1.3 Form of wetting part of the best-fit curve per experiment and position

<table>
<thead>
<tr>
<th>position on slope</th>
<th>plot-run position</th>
<th>wn2</th>
<th>ws1</th>
<th>ws2</th>
<th>wsw1</th>
<th>bs1</th>
<th>bs2</th>
<th>gs1</th>
<th>gs2</th>
</tr>
</thead>
<tbody>
<tr>
<td>side of rill</td>
<td>A1</td>
<td>C</td>
<td>C/V</td>
<td>V</td>
<td>C</td>
<td>V</td>
<td>V</td>
<td>S</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>A2</td>
<td>N</td>
<td>N</td>
<td>N</td>
<td>C/V</td>
<td>C</td>
<td>S</td>
<td>C</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>A3</td>
<td>V</td>
<td>N</td>
<td>C</td>
<td>C/V</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>A4</td>
<td>V</td>
<td>C</td>
<td>V</td>
<td>C/V</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>B1</td>
<td>C</td>
<td>C</td>
<td>V</td>
<td>C/V</td>
<td>S</td>
<td>V</td>
<td>C</td>
<td>C/V</td>
</tr>
<tr>
<td></td>
<td>B2</td>
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<td>S</td>
<td>N</td>
<td>C</td>
<td>S</td>
<td>C</td>
<td>C</td>
<td>S</td>
</tr>
<tr>
<td></td>
<td>B3</td>
<td>V</td>
<td>C</td>
<td>V</td>
<td>S</td>
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<td>x</td>
</tr>
<tr>
<td></td>
<td>B4</td>
<td>V</td>
<td>C</td>
<td>C/V</td>
<td>C</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td>rill bottom</td>
<td>R1</td>
<td>N</td>
<td>C</td>
<td>C/V</td>
<td>C/V</td>
<td>C</td>
<td>S</td>
<td>C</td>
<td>C/V</td>
</tr>
<tr>
<td></td>
<td>R2</td>
<td>N</td>
<td>C</td>
<td>V</td>
<td>S</td>
<td>S</td>
<td>S</td>
<td>C</td>
<td>C/V</td>
</tr>
<tr>
<td>interrill area</td>
<td>C1a</td>
<td>V</td>
<td>N</td>
<td>C/V</td>
<td>S</td>
<td>C</td>
<td>S</td>
<td>C/V</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>C1b</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>S</td>
<td>S</td>
<td>C/V</td>
<td>C</td>
</tr>
<tr>
<td></td>
<td>C1c</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>C</td>
<td>V</td>
<td>C/V</td>
<td>V</td>
</tr>
<tr>
<td></td>
<td>C2a</td>
<td>C</td>
<td>V</td>
<td>V</td>
<td>C</td>
<td>N</td>
<td>S</td>
<td>S</td>
<td>C/V</td>
</tr>
<tr>
<td></td>
<td>C2b</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>S</td>
<td>S</td>
<td>C/V</td>
<td>C/V</td>
</tr>
<tr>
<td></td>
<td>C2c</td>
<td>x</td>
<td>x</td>
<td>C/V</td>
<td>C/V</td>
<td>C</td>
<td>C/V</td>
<td>C</td>
<td>C/V</td>
</tr>
</tbody>
</table>

C=concave, V=convex, C/V=concave/convex, S=straight, N=no response, x=no measurement

### Table 5.1.4 Number of forms of best-fit curves per experiment and regolith material

<table>
<thead>
<tr>
<th>curve</th>
<th>no response</th>
<th>concave</th>
<th>convex</th>
<th>concave/convex</th>
<th>straight</th>
<th>total number of measured points</th>
</tr>
</thead>
<tbody>
<tr>
<td>plot</td>
<td>number of response types</td>
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<td></td>
<td></td>
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<td>13</td>
<td>11</td>
<td>10</td>
<td>4</td>
<td>47</td>
</tr>
<tr>
<td></td>
<td>(19)</td>
<td>(28)</td>
<td>(23)</td>
<td>(21)</td>
<td>(8.5)</td>
<td></td>
</tr>
<tr>
<td>brown marls (%)</td>
<td>1</td>
<td>5</td>
<td>5</td>
<td>1</td>
<td>12</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>(4)</td>
<td>(21)</td>
<td>(21)</td>
<td>(4)</td>
<td>(50)</td>
<td></td>
</tr>
<tr>
<td>grey marls %</td>
<td>0</td>
<td>10</td>
<td>1</td>
<td>10</td>
<td>3</td>
<td>24</td>
</tr>
<tr>
<td></td>
<td>(0)</td>
<td>(42)</td>
<td>(4)</td>
<td>(42)</td>
<td>(12.5)</td>
<td></td>
</tr>
</tbody>
</table>
ence between the minimum and maximum value of the wetting curve. These values are given in Table 5.1.6.

When taking into account all positions of the plots on the white marls (Table 5.1.4) the highest percentage of curves is concave. Not much difference is seen between the percentages for convex, concave/convex and no response. For the white marls on points in the side of a rill, concave and convex give the highest numbers of cases (Table 5.1.5). In the rills, 'no response', concave and concave/convex curves have the highest percentages. For interrill areas, concave, convex and concave/convex curves have the highest numbers. In the white marls the south-westerly exposed plot showed the greatest increase in soil moisture content during the experiment. This was in the side of a rill (Table 5.1.6). By comparing the points in the rill bottom, one exceptional moist point (0.14 m³/m³) on the south-west exposed slope was obtained. All the other points in the rill bottom on white marls showed an increase of soil moisture content less than 0.09 m³/m³.

In the brown marls, half of the measuring points (50%) have a straight curve, whereas concave and convex take 21% (Table 5.1.4). For the brown marls, at points in the side of a rill, convex and straight segments predominate. In the rill bottom, straight segments mostly occur, which is also the case in the interrill areas (Table 5.1.5). The increase in soil moisture content during the experiments is higher in brown marls than in white marls (Table 5.1.6). During the first experiment on both the brown and grey marls they have values in a similar range. Only the points in the rill bottom of the brown marls show a smaller difference in soil moisture contents than those on the grey marls. The second experiment on brown marls resembles the experiments on white marls.

For the grey marls the wetting curve forms concave and concave/convex are in a majority (Table 5.1.4). At points in the side of a rill the concave curves dominate. In the rill bottom, concave and concave/convex are most common. In the interrill areas concave/convex gives the highest percentage (Table 5.1.5). As mentioned before, the increase in soil moisture content during the first experiment is similar to those of the first experiment on brown marls. However, the measured points in the rill bottom show more increase in soil moisture than those in brown marls. The second experiment on grey marls showed a higher infiltration rate than in the first experiment. In general, this was the experiment with the highest overall infiltration rate.

**Drying phase**

The drying curves of the experiments have been studied by comparing changes in soil moisture contents within a specific time interval. To find differences between shallow and deep infiltration, changes between the maximum soil moisture content and the soil moisture content after two hours of drying were calculated (Table 5.1.7). No analysis was made of the form of the fitted curves, because this is highly dependent on the measurement period. The data from Table 5.1.7 are absolute data. More interesting for comparing the points and experiments is, which part of the infiltrated water ‘disappeared’ after two hours; these data are given in Table 5.1.8. During the second experiment, on the northerly exposed white marls, some points lost half of the infiltrated water within two hours. This was also the case for the first experiment on southerly and south-westerly exposed white marls. After the second experiment on the southerly exposed white marls, the loss of water seemed to be slower. According to this data, the hydrological behaviour of the regolith during the experiments appeared to be
## Table 5.1.5 Number of forms of best-fit curves per experiment

<table>
<thead>
<tr>
<th>curve plot and point</th>
<th>no response</th>
<th>concave</th>
<th>convex</th>
<th>concave/ convex</th>
<th>straight</th>
<th>total number of measured points</th>
</tr>
</thead>
<tbody>
<tr>
<td>white marls side of rill (%)</td>
<td>6 (19)</td>
<td>9 (28)</td>
<td>9 (28)</td>
<td>6 (19)</td>
<td>2 (6)</td>
<td>32</td>
</tr>
<tr>
<td>rill bottom (%)</td>
<td>2 (25)</td>
<td>2 (25)</td>
<td>1 (12.5)</td>
<td>2 (25)</td>
<td>1 (12.5)</td>
<td>8</td>
</tr>
<tr>
<td>internill (%)</td>
<td>1 (12.5)</td>
<td>2 (25)</td>
<td>2 (25)</td>
<td>2 (25)</td>
<td>1 (12.5)</td>
<td>8</td>
</tr>
<tr>
<td>brown marls side of rill (%)</td>
<td>0 (0)</td>
<td>2 (25)</td>
<td>3 (37.5)</td>
<td>0 (0)</td>
<td>3 (37.5)</td>
<td>8</td>
</tr>
<tr>
<td>rill bottom (%)</td>
<td>0 (0)</td>
<td>1 (25)</td>
<td>0 (0)</td>
<td>0 (0)</td>
<td>3 (75)</td>
<td>4</td>
</tr>
<tr>
<td>internill (%)</td>
<td>1 (8)</td>
<td>2 (17)</td>
<td>2 (17)</td>
<td>1 (8)</td>
<td>6 (50)</td>
<td>12</td>
</tr>
<tr>
<td>grey marls side of rill (%)</td>
<td>0 (0)</td>
<td>5 (62.5)</td>
<td>0 (0)</td>
<td>1 (12.5)</td>
<td>2 (25)</td>
<td>8</td>
</tr>
<tr>
<td>rill bottom (%)</td>
<td>0 (0)</td>
<td>2 (50)</td>
<td>0 (0)</td>
<td>2 (50)</td>
<td>0 (0)</td>
<td>4</td>
</tr>
<tr>
<td>internill (%)</td>
<td>0 (0)</td>
<td>3 (25)</td>
<td>1 (8)</td>
<td>7 (58)</td>
<td>1 (8.3)</td>
<td>12</td>
</tr>
</tbody>
</table>

*0= no wetting, x= no measurement*

## Table 5.1.6 Difference between minimum and maximum value of soil moisture of the

```
<table>
<thead>
<tr>
<th>location on slope</th>
<th>plot-run position</th>
<th>wn2</th>
<th>ws1</th>
<th>ws2</th>
<th>wsw1</th>
<th>bs1</th>
<th>bs2</th>
<th>gs1</th>
<th>gs2</th>
</tr>
</thead>
<tbody>
<tr>
<td>side of rill</td>
<td>EH1</td>
<td>0.10</td>
<td>0.11</td>
<td>0.04</td>
<td>0.08</td>
<td>0.23</td>
<td>0.17</td>
<td>0.31</td>
<td>0.53</td>
</tr>
<tr>
<td></td>
<td>EH2</td>
<td>0.02</td>
<td>0</td>
<td>0</td>
<td>0.17</td>
<td>0.25</td>
<td>0</td>
<td>0.20</td>
<td>0.40</td>
</tr>
<tr>
<td></td>
<td>EH3</td>
<td>0.06</td>
<td>0</td>
<td>0</td>
<td>0.03</td>
<td>0.20</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>EH4</td>
<td>0.05</td>
<td>0.01</td>
<td>0.02</td>
<td>0.28</td>
<td>x</td>
<td>x</td>
<td>x</td>
<td>x</td>
</tr>
<tr>
<td></td>
<td>EL1</td>
<td>0.06</td>
<td>0.03</td>
<td>0.02</td>
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<td>0.12</td>
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<td>0.03</td>
<td>0.20</td>
<td>0.06</td>
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<td>x</td>
<td>x</td>
<td>x</td>
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<tr>
<td>rill bottom</td>
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<td>0.14</td>
<td>0.30</td>
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<td>0.02</td>
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<td>0.30</td>
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</tr>
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<td>x</td>
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<td>0.41</td>
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### Table 5.1.7 Difference between maximum of wetting curve and value at t=165 min.

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<th>ws2</th>
<th>wsw1</th>
<th>bs1</th>
<th>bs2</th>
<th>gs1</th>
<th>gs2</th>
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<td></td>
<td></td>
</tr>
<tr>
<td>EH1</td>
<td></td>
<td>0.02</td>
<td>0.04</td>
<td>0.01</td>
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0=no wetting and drying  
*no drying before t=165 minutes  
-n=no reliable data  
-x=no measurement  

### Table 5.1.8 Part of infiltrated water, 'disappeared' at t=165 minutes

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0=no wetting and drying  
*x=no measurement or no calculated drying from the drying curve
similar for southerly and south-westerly exposed white marl slopes.

On the southerly exposed brown marls, the response seemed to be the reverse of that for white marls. The water loss was less after the first experiment compared to the second one. In the rill bottom more water had been disappeared after two hours than the amount of infiltrated water. This might be a measurement error. However, it is interesting to study the total hydrological balance of the slope (Chapter 5.1.5 and 5.1.6).

On the grey marls water loss during the second experiment was slightly lower than during the first experiment on this material. For both measuring points in the rill bottom (RH and RL) a similar problem was encountered after the second experiment as on the brown marls. More water disappeared than infiltrated water. In the rill bottom the amount of disappeared water was over 0.50 m³/m³, which means that the soil was drying out very quickly. An answer to this problem is probably, the upper part of the grey regolith, which started to flow during the second experiment. The upper few centimetres of the regolith became oversaturated compared to the underlying regolith. This liquified layer lost its structure and became a structureless mudflow. After finishing the rainfall simulation experiment apparently this layer dried very quickly.

Summarising, it can be concluded that for the wetting phase of the regoliths grey and brown marls show a higher infiltration rate than the white marls. On the white marls all types of infiltration response occurred. This means a very variable infiltration pattern. On the brown marls 'no response' and 'concave/convex' curves hardly occurred. On the grey marls 'no response' and 'convex' curves hardly occurred. So, a more specific type of infiltration occurred on the last two materials. The infiltration rate was kept high during the experiment, which is shown by the low numbers of convex and concave/convex curves. 'No response' only occurred once in the brown marls, which shows a good infiltrability or a more homogeneous infiltration than in the white marls.

From the drying phase data it was concluded that on the white marls, northerly, southerly and south-westerly exposed much water had been disappeared quickly, which seems to indicate a shallow infiltration. On the brown marls this happened also during the second experiment. This means that the infiltration capacity decreased after the first experiment. On the grey marls the infiltration capacity seemed to increase after the first experiment, because after the second experiment the drying process of the material was slower than during the first experiment.

5.1.4 Water retention and hysteresis

Laboratory water retention curves were compared with water retention curves derived from field data during wetting in order to find out hysteresis phenomena. The data for water retention characteristics during wetting in the field were measured pressure heads and fitted volumetric soil water contents.

From the white marls only a few data were available, because of the problems in the field to measure pressure heads. During the first experiment on southerly exposed white marls the field data showed a reliable curve. However, the difference between the water content of the absorption (field data) and desorption (laboratory data) curve was very large. Figures 5.1.19a and b show differences of 0.3 m³/m³. No striking differences were found between the positions on the slope. During the second experiment on southerly exposed white marls a similar result
had been found. Whereas the point in the rill bottom showed a very slightly higher soil moisture content with corresponding pressure head values (Fig. 5.1.20a and b).

Field data from the brown marls show a good fit with the desorption curve on the surface suffering from mass movement (Fig. 5.1.21a). Other data from this surface deviate slightly from the desorption curve (Fig. 5.1.21b). Differences are much less than for the white marls.

In the grey marls most points showed a slightly lower water content (Fig. 5.1.22a). During the second experiment some points even showed a higher soil moisture content than the desorption curve (Fig. 5.1.22b). However, differences were again much less than those in the white marls.

It is clear that the white marl regoliths showed an evident effect of hysteresis caused by pore geometry. In the brown and grey marl regoliths this effect was less evident. Only the grey marls showed a wetter soil during the wetting phase and this regolith was drier during desorption of water. This indicated an opposite effect of hysteresis (Chapter 5.1.2). It is obvious that the relative differences between water retention characteristic and field data did not change by correction for shrinkage and swelling (Fig. 5.1.22a and b). Possibly other effects related to swelling and shrinkage, as macropores or bypass-flow, caused the opposite hysteresis. Especially the grey marls have a high shrinkage and swelling capacity (Chapter 4.1).

A problem that could appear in especially the white marls, was that the measured soil water content during the first part of the wetting was too low because of the shallow water front. Consequently, the real soil moisture content was higher in the first few centimetres of the profile, because part of the TDR probes was entering the dry part of the regolith. In this case pressure head values measured in the upper 5 cm of the soil gave more realistic data.

5.1.5 Hydrological balance of badland slopes

The runoff characteristics of both rainfall experiments on north facing white marls were almost identical (Fig. 5.1.23). The rainfall intensity was slightly lower during the second experiment, so runoff started a few seconds later (Table 5.1.1). However, the runoff coefficient of the second experiment was higher and thus the amount of infiltrated water was smaller. The runoff characteristics of the experiments on south facing white marls were more variable (Fig. 5.1.24). The runoff coefficient of the second experiment was about 2 times higher than of the first experiment. However, it was still lower than the coefficients of both experiments on the north facing slope (Table 5.1.1). A similar effect was seen on the south-westerly exposed white marls. Despite the high rainfall intensities, the runoff coefficients were quite low (Table 5.1.1). The cracks in the south facing white badland material did not close during the first experiment, though during the second experiment they were already partly closed after 3.5 minutes. On the south-westerly exposed white marls the cracks closing time was 14 and 7.3 minutes respectively (Table 5.1.1). On southerly exposed brown marls, even under the highest rainfall intensity of 42mm/hr the runoff coefficients were still quite low. The cracks closed after 4 and 10 minutes, but the surface was not sealed completely (Table 5.1.1). On southerly exposed grey marls runoff coefficients were variable. The coefficient during the second experiment on grey marls was more than ten times higher than during the first one. The cracks closing time was similar to the first experiment on grey marls (Table 5.1.1).

In Figures 5.1.25 to 5.1.29 the cumulative runoff, rainfall and infiltration were compared. In all badland materials, except for experiment 1 on the south-westerly exposed white marls and on the southerly exposed grey marls, runoff started before the cracks had completely
CHAPTER 5.1

Figure 5.1.19 Hysteresis Ws1

(a) Rill (RH)

(b) Intermill (IL)

Figure 5.1.20 Hysteresis Ws2

(a) Rill (RH)

(b) Rill (RL)

Figure 5.1.21 Hysteresis Bs2

(a) Intermill (IH(1))

(b) Intermill (IL(1))

Figure 5.1.22 Hysteresis Gs

(a) Gs1

(b) Gs2

Interrill (IL(2))

Slide of rill (EL(2))
closed (Table 5.1.1). These could be favourite conditions for macropore flow draining into a
rill. Though, cracks already started closing before runoff in rills had started. Some irregulari-
ties in the cumulative runoff curve could indicate macropore flow after the cracks are closed.
Field observations show that before the cracks had completely closed, overland flow infiltrat-
ed into cracks. The cumulative runoff was on all materials and aspects higher during the sec-
ond run. On the northerly exposed white marls, it was evident that infiltration also declined
during the second run. On the southerly and south-westerly exposed white marls, infiltration
did not decrease, however rainfall intensity was higher during the second run. On brown
marls infiltration was slightly lower, during the second run. In this case the surface was not
sealed completely, which was a more favourable condition for infiltration. On grey marls, dur-
ing the second run, cumulative infiltration decreased comparable to white marls northerly
exposed. After the first run already a closed crust had been formed, which showed a crack
pattern at the beginning of the second run.

5.1.6 Discussion and conclusions

Modelling rills as drains
In this section the hydrological processes on badland slopes are explained. The hypothesis
mentioned in Chapter 1 and 2, is a model based on a drainage model developed by
Hooghoudt (1940) and Donnan (1946) (Gerits et al., 1987). In this model rills act as drains.
Equation (2.6) should be valid for badland regolith profiles. Parameter \( Q \) is in this equation
equivalent to rill discharge. Hydraulic conductivity above drain level \( K_t \) could be calculated
from the infiltration depth after the experiment, as macropore flow was seen as a dominant
mechanism of infiltration. Hydraulic head \( h \) is the difference in height between the phreatic
surface of the apparent ground water level and the rill flow. This parameter is very complicat-
ed to measure in badland regolith. Drain spacing \( L \) is the distance between rills. In Chapter 8
this model is evaluated according to the field and laboratory measurements.

Water drains as subsurface or macropore flow into the rills. The flow direction is deter-
mined by the development of a saturated layer above an impermeable layer (Fig. 2.2a). This
saturated layer is caused by steady state input of rainfall and infiltrates as macropore flow into
the regolith profile. The continuous inflow of water results in a saturated zone forming
between two rills, in which the hydraulic head decreases from a maximum value in the mid-
dle of the interrill area towards a minimum value in the rill. Because of this difference in
hydraulic head a continuous flow is created towards the rills.

Soil water pressure in a rill system
On the northerly exposed white marls the pressure head values appeared to react very quick-
ly in general. After an increase during the first half of the experiment the pressure heads
seemed to stay constant until the end of the experiment indicating a quick saturation of the
upper part of the regolith. On the southerly exposed white marls the increase of the pressure
head values seemed to be more gradual during the experiment. However similar to the
northerly exposed white marls the pressure heads increased until a constant final value so
the topsoil was saturated. During the drying phase on the southerly exposed white marls the
pressure head values decreased very slightly. The measurements during both experiments
on the south-westerly exposed white marls showed a lot of noise. This could be caused by
the contact problems of the tensiometers with the highly porous regolith, the exceeded air-entry values and the sensitivity of the water to temperature changes. No difference seemed to be obvious on this plot between measuring points in rills, in the side or in between two rills.

The regolith of the brown marls was more susceptible to mass movement and contained wider cracks than the regolith of the white marls (northerly and southerly exposed). From the experiment was seen that more points on the slope of the brown marls did not respond at all on the rainfall than on the white marls. So, probably infiltration in this regolith was more preferential along certain cracks than in the other regolith. Another feature is that because of the high crack density in the regolith of the brown marls, more measurements could have failed (Chapter 3.2).

The results of the experiments on the grey marls also showed that not much difference in pressure head existed between points in the rill bottom and on the surface. The variability in pressure head values did not seem to be related to this surface morphology. On this plot less tensiometers seemed to have problems with contact with the soil or the exceeded air-entry pressure. The pressure head values were mostly lying below 0 cm. This showed that the regolith was not saturated very quickly, during the experiments.

**Soil moisture profiles in relation to drainage conditions**

According to the theory based on Hooghoudt (1940) and Donnan (1946) the soil moisture content under a rill should stay constant during the experiment, because of the impermeable
layer under the rill. In the side of a rill the regolith should become saturated, whereas in between two rills, macropore flow occurs.

On the white marls soil moisture increased less under a rill or in an interrill area than in the side of the rills. This supports the drainage model for rills. However, field observations showed that under a rill also infiltration was found. This means that the regolith layer under the rill was partly weathered. The high variability of soil moisture values could be an indication for macropore flow. Most runoff infiltrated in the lower part of the slope, which could be caused by the high crack density at the surface.

This last phenomenon was also found on the brown marls. A very high crack density caused in this case a high infiltration capacity. Soil moisture values were higher than in the

---

**Figure 5.1.25** Cumulative rainfall, runoff and infiltration White marls, N exposed

**Figure 5.1.26** Cumulative rainfall, runoff and infiltration White marls, S exposed

**Figure 5.1.27** Cumulative rainfall, runoff and infiltration White marls, SW exposed
white marls. The interrill area showed the highest increase and therefore caused saturation. Rills did not show a difference in infiltration from the surroundings. This shows that in the brown marls probably cracks are more important for hydrology than rills.

The opposite effect of infiltration into a rill on the grey marls showed a peculiar response of the material. Runoff flowed and infiltrated into a rill. The highest soil moisture values on the plot of this material were under the rill. This gives also evidence for a weathered layer under the rill. During the second experiment soil moisture was also measured of a liquified layer in the rill, which evidently had very high soil moisture values. These values during the second experiment were possibly caused by the formation of a crust after the first experiment. Before the first experiment no crust was found at the surface. This caused a direct infiltration of the rainfall into the soil matrix. The direct fall of rainfall into the cracks and macropores was thought to be very small. After the first experiment a crust had formed. This crust reduced infiltration into the soil matrix, but overland flow was formed and concentrated on this crust and infiltrated locally into the cracks and macropores.

**Hydrological balance**

A possible explanation for the lower runoff coefficients on the white marls of plot 2 and 4 compared to the white marls of plot 1 is the aspect of the slope. Plot 1 is facing north, whereas 2 and 4 are facing south and south-west. The fluctuation in temperature and consequently soil moisture is less on the north facing slope. The fluctuations in temperature are very high on the other two slopes. These fluctuations cause a high variation in soil moisture content, which
causes much shrinkage and swelling. These processes create a lower bulk density (a higher crack density), and thus relatively more infiltration.

Plot 3 and 5 (brown and grey marls), which show more mass movement, showed a very high amount of infiltration. This is caused by the lower bulk density of these regoliths. However the second experiment on the grey marls showed a sudden decrease in infiltration. This is caused by the homogeneous surface crust formed after the first experiment.

Infiltration models of Horton (1940) and Philip (1957, 1969) describe infiltration characteristics of a badland situation. The model of Horton (equation 5.1) describes the characteristic with an empirical function, however Eagleson (1970) and Raudviki (1979) showed that it can be derived from Richard's equation (Chow et al., 1988).

Horton's equation:

\[
fp = f_c + (f_0 - f_c)e^{k t}
\]

\[5.1\]

\[f_p\] = the infiltration capacity at some time \(t\)

\[f_c\] = a final or equilibrium capacity

\[f_0\] = initial infiltration capacity

\[k\] = a constant representing the rate of decrease in \(f\) capacity

Despite Gerits' (1991) results that Horton's equation (equation 5.2) described well the situation in badlands it is useful for this study to describe the infiltration characteristic with physical parameters, which has been done by Philip (1957, 1969):

\[
F(t) = S \sqrt{t} + Kt
\]

\[5.2\]

\[S\] = sorptivity (a function of soil suction potential) (Green and Ampt, 1911)

\[K\] = hydraulic conductivity

\[F(t)\] = cumulative infiltration

The model of Green and Ampt (Chow et al., 1988) is an analytical solution to a physical theory. According to Alonso et al. (1994), for badlands, the model of Philip is the best deterministic approach to describe the infiltration in badlands. The model of Horton is the best empirical approach. Consequently, for calculation of the hydraulic conductivity and infiltration depth of badland regolith Philip's equation was used.

During the early stage of infiltration, sorptivity \(S\) is the dominant parameter, because \(Kt\rightarrow0\). After a certain time \(S \sqrt{t}\) becomes negligible and gravity is the most important driving force represented by \(K\), the hydraulic conductivity. In order to calculate the hydraulic conductivity with Philip's equation (equation 5.2), sorptivity was calculated during the second time step of measured runoff. With this sorptivity, hydraulic conductivity was calculated. The highest value for hydraulic conductivity per run is mentioned in Table 5.1.9. Hydraulic conductivity was also calculated for the period when \(S \sqrt{t}\) is negligible. The highest hydraulic conductivity in this case was always higher than resulted from the preceding calculation. Infiltration depths calculated from the hydraulic conductivity values show highest values for brown marls. The lower values for white and grey marls are in the same range.
Table 5.1.9 Hydrological parameters calculated according to Philip's equation

<table>
<thead>
<tr>
<th>Badland material; exposition</th>
<th>Run number</th>
<th>Sorptivity (S) (ms^{-1/2})</th>
<th>Highest hydraulic conductivity (K_1) calculated with (S) during run (cm/day)</th>
<th>Infiltration depth after 45 minutes, calculated with (K_1) (cm)</th>
<th>Highest hydraulic conductivity (K_2) with ((S \rightarrow 0)) is negligible (cm/day)</th>
<th>Infiltration depth after 45 minutes, calculated with (K_2) (cm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>White marls; northerly</td>
<td>1</td>
<td>0.116*10^{-3}</td>
<td>3.94</td>
<td>0.123</td>
<td>57.4</td>
<td>1.79</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.101*10^{-3}</td>
<td>0.971</td>
<td>0.030</td>
<td>46.6</td>
<td>1.46</td>
</tr>
<tr>
<td>White marls; southerly</td>
<td>1</td>
<td>0.161*10^{-3}</td>
<td>4.25</td>
<td>0.133</td>
<td>35.1</td>
<td>1.10</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.249*10^{-3}</td>
<td>21.8</td>
<td>0.680</td>
<td>87.7</td>
<td>2.74</td>
</tr>
<tr>
<td>White marls; southwesterly</td>
<td>1</td>
<td>0.195*10^{-3}</td>
<td>18.5</td>
<td>0.579</td>
<td>55.5</td>
<td>1.73</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.246*10^{-3}</td>
<td>10.9</td>
<td>0.340</td>
<td>88.1</td>
<td>2.75</td>
</tr>
<tr>
<td>Brown marls; southerly</td>
<td>1</td>
<td>0.360*10^{-3}</td>
<td>26.8</td>
<td>0.836</td>
<td>100</td>
<td>3.14</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.256*10^{-3}</td>
<td>34.3</td>
<td>1.07</td>
<td>99.6</td>
<td>3.11</td>
</tr>
<tr>
<td>Grey marls; southerly</td>
<td>1</td>
<td>0.163*10^{-3}</td>
<td>12.5</td>
<td>0.389</td>
<td>42.3</td>
<td>1.32</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>0.116*10^{-3}</td>
<td>4.72</td>
<td>0.148</td>
<td>47.4</td>
<td>1.48</td>
</tr>
</tbody>
</table>
Considering the results in Table 5.1.9 infiltration depth is very small (ca. 2-3cm). According to field observations the infiltration depth of white marls differed from 5-10cm and of the brown and grey marls from 10-15cm (Photo 5.1.1 to 5.1.3). From the field observations it was obvious that highest infiltration depth was seen along macropores. This means that macropore flow caused a deeper infiltration. Kuhn and Yair (2004) measured an infiltration capacity between 60 and 120cm/day on badland slopes with a dense rill network. This is higher than the hydraulic conductivity of white marls, which supports the idea of macropore flow. Finally it has to be noticed that the values of infiltration depth in Table 5.1.9 describe the situation of a homogeneous soil profile without macropores. This gives clear evidence for the importance of macropores and macropore flow for infiltration in badland soils.

Soil moisture under dry conditions
Volumetric soil moisture contents in the white badland regoliths under dry and wet conditions were lowest from all studied badland regolith. This regolith also dried out most quickly after the experiments, namely within 24 hours.

Brown and grey marls both showed a considerably higher soil moisture content under dry and wet conditions. Grey marls showed the highest soil moisture content during the experiments. However, brown marls showed higher soil moisture values 24 hours after the first experiment. Which means that brown marls dried out very slowly, which also counted for grey marls.

This shows, together with the soil moisture results during the experiments that brown and grey marls can store more water than white marls.

Conclusions
From the above results the following conclusions can be drawn. On the north facing slope of the white marls no water is infiltrating under a rill, but as on the other plots in white marls the upper part of the regolith becomes saturated during the experiment. From the soil moisture profiles after the experiments was observed, that the wetting front was very variable in depth, which indicates an important influence of macropore flow. The brown marls showing wider cracks, more mass movement and less rill erosion show much preferential flow, indicated by the high variability of the measured soil moisture contents and pressure heads. However, despite the fact that the grey marls show a high shrinkage and swelling capacity, the infiltration front is more homogeneous than in the other materials. This indicates less importance of macropore flow.

From the runoff characteristics is seen that relatively more runoff is generated by the white marls, whereas the characteristics of the second experiments on the brown and grey marls are very similar to the characteristics of the white marls.

Except for the white marls on the north facing slope infiltration under rills was found on all materials. On the white marls the upper part of the soil became saturated. However, macropore flow seems to be an important infiltration process in especially the white and brown marls. These facts are used to improve the model of Gerits et al. (1987).
CHAPTER 5.1

Photo 5.1.1 Infiltration profile of white marl regolith, Petrer, Spain

Photo 5.1.2 Infiltration profile of brown marl regolith, Petrer, Spain
Photo 5.1.3 Infiltration profile of grey marl regolith, Petrer, Spain
5.2 Hydrological response of cultivated loess soils

5.2.1 Introduction

Infiltration processes in loess soils were investigated by means of rainfall simulation experiments. A full description of the methods and measurements is given in Chapter 3.2.

This chapter describes and discusses the results of the measurements related to water movement in the soil. These consist of the soil water pressure, soil water content, water retention and hydraulic conductivity, and the hydrological balance, which includes the runoff.

To investigate the applicability of the drainage model of Hooghoudt (1940) it is important to be able to describe the infiltration process in a soil profile. To find out if macropore flow is important, the rates of infiltration in the soil profile should be identified. Imeson and Kwaad (1994) concluded that in loess soils an improved knowledge of the hydraulic characteristics and of water movement in the tilled layer might lead to an understanding of the threshold conditions for the initiation of rills.

Imeson and Verstraten (1988) suggested similarities in the initiation of rills in ploughed loess soil and in badland regolith material. Ploughing produces macropores, which play a similar role as naturally occurring cracks and pipes in badland regolith (Gerits et al., 1987). This ploughed system would be more susceptible to rill erosion than a cultivated system without macropores.

To test this idea, different experiments were made to compare tillage treatments. One site was therefore freshly ploughed and harrowed in spring ('ploughed site'), another site was ploughed in autumn and only harrowed in spring before the rainfall simulation experiments ('harrowed site'). In order to test the model of Hooghoudt (1940) for this soil type a water saturated layer should develop above a relatively impermeable layer. This implies a pressure head around 0 cm water pressure just above the plough sole or Bt-horizon, lower than 0 cm in case of negative pressure in the full-capillary zone or higher than 0 cm in case of positive pressure in saturated zone.

To determine the effect of rainfall intensity two intensities were used (referred to as HI (high intensity) and LI (low intensity)). In addition, measurements were made in a rill system that had developed on ploughed soil. In this case only field measurements were carried out without using rainfall simulation experiments.

- The results are described in the following order:
  - ploughed and harrowed soil with low rainfall intensity
  - ploughed and harrowed soil with high rainfall intensity
  - harrowed soil with low rainfall intensity
  - harrowed soil with high rainfall intensity
  - comparison low and high rainfall intensities for ploughed and harrowed soil
  - wheeltrack in ploughed and harrowed soil with low rainfall intensity
  - ploughed and harrowed soil with sequential low and high rainfall intensities
  - ploughed soil under natural rainfall

No observations were made on harrowed soil under natural rainfall.

Codes of the experiments are explained as follows:

1 = number of experiment
L or LI = low intensity
H or HI = high intensity
5.2.2 Infiltration into a loess profile

The behaviour of water during infiltration into loess soil was measured by means of several parameters. Soil water pressures and soil moisture contents were measured in the field to investigate water fluxes and an apparent groundwater level, caused by saturation of a part of the soil profile. Water retention characteristics and hydraulic conductivity were determined by laboratory measurements. These parameters show the behaviour of the soil in relation to porosity and infiltration rate.

Soil water pressure dynamics during rainfall experiments

The importance of measuring pressure heads during the rainfall simulation experiments is for investigation of the redistribution and possible stagnation of water, on a relatively impermeable layer, in the soil profile. The occurrence of macropore flow is important because this flow corroborates the hypothesis that subsurface flow through macropores occurs in ploughed loess soils and possibly accelerates the infiltration to the impermeable soil layer.

Ploughed and harrowed soils, low rainfall intensity

In order to investigate water saturation above the Bt-horizon the results of the ploughed system with low intensity rainfall were analysed. Experiment 2La (Fig. 5.2.1) showed an increase in soil water pressure in the upper part of the Ap-horizon. During the following experiment (2Lb) just above the plough sole an increase in pressure head occurred (Fig. 5.2.1). Under the plough sole, in the Bt-horizon, this value was constant. Consequently it can be concluded that the water saturation front stagnated on the Bt-horizon. This is also indicated by the pressure head data which reached a maximum above 0 cm pressure head, which was kept during the experiment (Fig. 5.2.1). During experiment 2La only the points at 13 cm and 24 cm depth the soil became saturated, while during experiment 2Lb this water saturation front had reached 33 cm depth.

When comparing the ploughed and the harrowed soil (Fig. 5.2.1), soil water pressure increased at more depths in the ploughed soil during experiment 2La than in the harrowed soil. During experiment 2Lb the increase in soil water pressure in the ploughed soil starts earlier than in the harrowed soil.

Ploughed and harrowed soils, high rainfall intensity

Figure 5.2.2 shows a slightly quicker wetting of the harrowed soil profile during experiment 5Ha than of the ploughed soil. In the ploughed soil the soil water pressure was constant at some more measuring points than in the harrowed soil. However the reaction of the measuring points in ploughed soil on rainfall was stronger. In both soils, the soil water pressure continued to increase after the experiment was finished.
Figure 5.2.1 Soil water pressure in depth during low intensity rainfall in ploughed and harrowed loess soil
**Figure 5.2.2** Soil water pressure in depth during high intensity rainfall in ploughed and harrowed loess soil
ploughed soils, low and high rainfall intensities

The influence of the rainfall intensity on infiltration is shown by a comparison of the results for the ploughed field at different rainfall intensities. From Figure 5.2.2 it can be seen that the increase of the soil water pressure in the Ap-horizon started early during experiment 5Ha. This also happened for the lower part of the Ap-horizon during experiment 5Hb. Most of the other parts of the soil horizon did not show changes in soil water pressure. In Figure 5.2.1 it is seen that the soil water pressure in the lower part of the ploughed layer and in the Bt-horizon remained unchanged under low intensity rainfall. However, the initial soil water pressure profiles were higher than field capacity (pF<2.0), which implies that within the soil matrix water flows under gravitational driving force and no capillary forces are acting. In general results show that high rainfall intensity on ploughed soil resulted in a less deep, but quicker infiltration front than under low rainfall intensity.

Soil water dynamics during rainfall experiments

The volumetric soil water content was determined by taking soil samples after the rainfall simulation experiments. As shown in Chapter 3.2, this was only done after every repeated event. Samples were taken at three depths in the profile, i.e. in the upper Ap, in the lower Ap and in the Bt under the plough sole. Soil moisture profiles are given in Figure 5.2.3. The aim of measuring the volumetric soil moisture content was to determine the infiltration profile.

ploughed and harrowed soils, low intensity

The difference between the soil moisture contents under and above the Bt-horizon after the experiments with low intensity rainfall in the ploughed soil was greater than those between the various depths in the harrowed field (Fig. 5.2.3a). This indicates infiltration inhomogeneity in the ploughed soil. Compared to the antecedent values of both soils, the deepest layers did not change in soil moisture content (Photo 5.2.1a). The data of the harrowed soil indicate that most of the infiltrated water stayed in the topsoil (Photo 5.2.1b).

ploughed and harrowed soils, high intensity

The difference between the results of the high intensity experiments for the harrowed and ploughed soil was more distinct than for the low intensity experiments (Fig. 5.2.3a). In the ploughed soil the results show that the infiltrated water accumulated just above the plough sole. For the harrowed soil compared to the low intensity experiments more water is kept in the topsoil.

ploughed and harrowed soils influenced by wheel pressure

Rainfall simulation experiments at both low and high intensities were also made on plots compacted by the pressure of wheels. These infiltration profiles were very similar for both ploughed and harrowed fields at high and low intensities (Fig. 5.2.3b). All infiltration profiles show a higher soil moisture content in the topsoil. The subsoil under -20cm remains drier.

Water retention and hydraulic conductivity

Water movement in soil was characterised by water retention characteristics and hydraulic conductivity. Water retention characteristics show for example the air entry value of the soil profile and the pF-range in which most of the water was drained from the soil. Water reten-
CHAPTER 5.2

Figure 5.2.3a Soil moisture profiles before and after various events

Figure 5.2.3b Soil moisture profiles before and after various events in a wheeltrack
Photo 5.2.1a Profile after low intensity rainfall on ploughed soil

Photo 5.2.1b Profile after high intensity rainfall on harrowed soil
tion characteristics established during both wetting and drying show the importance of the hysteresis phenomena.

Soil samples of the upper 5cm of the soil were taken before and after the rainfall simulation experiments. Water retention characteristics were established in the laboratory during drying (Chapter 3.2.3). From a field that had been ploughed in the autumn after which a rill system had developed, samples were taken in and around the rills. In addition, samples were taken every week in April upslope from a rill system in a field that was also ploughed in the autumn. From these samples water retention curves during drying and wetting were established to study the effect of hysteresis. Wetting and drying curves were also established for samples taken in a rill system in ploughed soil. The soil was sampled in a rill, at a rill side and in interrill areas.

Unsaturated hydraulic conductivity was determined from a soil sample from the harrowed field. For an inhomogeneous soil like ploughed loess soil containing many macro pores this method was not considered to be appropriate.

Fitted water retention characteristics (Chapter 3.2.3) delivered the following parameters,

### Table 5.2.1a Air-entry value (1/α) and pore size distribution (n) before and after a series of 3LI and 3HI rainfall simulation experiments

<table>
<thead>
<tr>
<th>depth (cm)</th>
<th>ploughed 1/α (-cm)</th>
<th>harrowed 1/α (-cm)</th>
<th>ploughed n (-)</th>
<th>harrowed n (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>initial conditions</td>
<td>after final exp.</td>
<td>initial conditions</td>
<td>after final exp.</td>
</tr>
<tr>
<td>5-10 (Ap1)</td>
<td>10.9</td>
<td>48.5</td>
<td>14.1</td>
<td>17.4</td>
</tr>
<tr>
<td>15-20 (Ap2)</td>
<td>11.6</td>
<td>20.2</td>
<td>18.8</td>
<td>48.5</td>
</tr>
<tr>
<td>40-45 (Bt)</td>
<td>11.0</td>
<td>151</td>
<td>108</td>
<td>n.a.</td>
</tr>
</tbody>
</table>

n.a. = not available

### Table 5.2.1b Air-entry value (1/α) and pore size distribution (n) before and after rainfall simulation experiments (low intensity, high intensity and low/high intensity sequence)

<table>
<thead>
<tr>
<th>depth = ca. 2-7cm</th>
<th>ploughed 1/α (-cm)</th>
<th>harrowed 1/α (-cm)</th>
<th>ploughed n (-)</th>
<th>harrowed n (-)</th>
</tr>
</thead>
<tbody>
<tr>
<td>initial conditions</td>
<td>10.9</td>
<td>14.1</td>
<td>1.18</td>
<td>1.24</td>
</tr>
<tr>
<td>after 1LI</td>
<td>37.7</td>
<td>56.5</td>
<td>1.24</td>
<td>1.25</td>
</tr>
<tr>
<td>after 2LI*</td>
<td>92.0</td>
<td>159</td>
<td>1.27</td>
<td>1.32</td>
</tr>
<tr>
<td>after 3LI</td>
<td>64.9</td>
<td>35.2</td>
<td>1.25</td>
<td>1.22</td>
</tr>
<tr>
<td>after 1HI</td>
<td>17.8</td>
<td>89.0</td>
<td>1.21</td>
<td>1.28</td>
</tr>
<tr>
<td>after 2HI*</td>
<td>56.9</td>
<td>81.1</td>
<td>1.24</td>
<td>1.26</td>
</tr>
<tr>
<td>after 3HI</td>
<td>30.7</td>
<td>42.9</td>
<td>1.22</td>
<td>1.24</td>
</tr>
<tr>
<td>after 3LI + 3HI</td>
<td>48.5</td>
<td>17.4</td>
<td>1.25</td>
<td>1.23</td>
</tr>
</tbody>
</table>

* = plot with wheel track
HYDROLOGICAL RESPONSE OF CULTIVATED LOESS SOILS

(a) initial conditions in harrowed and ploughed soil (5-10cm)

(b) conditions after successive low intensity events in ploughed soil (2-7cm)

(c) conditions after 3 low intensity and 3 high intensity events in harrowed and ploughed soil (2-7cm)

Figure 5.2.4 Water retention characteristics before and after rainfall events
saturated volumetric soil moisture content ($\theta_s$), the air-entry value ($1/\alpha$) and the pore size distribution ($n$). The values of $q_s$ for all fitted situations are given in Table 4.2.6a to c. The air-entry value (-cm) is a measure for the pressure head at which most of the water drains from the profile. This depends on pore size and pore quantity. The higher the air-entry value, the lower the pressure head at which water drains from the soil. Pore size distribution shows the quantity of different pore sizes. The higher $n$, the more uniform is the pore size distribution. Both parameters are important for the investigation of macropores.

**air-entry value and pore size distribution**

Differences in air-entry values and pore size distributions in the course of the experiments on the ploughed soil are shown by the water retention characteristics in Figures 5.2.4a to c. The initial air-entry value of the ploughed soil (Fig. 5.2.4a) was lower than after one or more rain events with low intensity (Fig. 5.2.4b). The $n$-value after two low intensity rainfall experiments increased with respect to the initial one, which means that the pore size distribution was more uniform (homogeneous) after a few rain events. In the upper part of the profile (Table 5.2.1b) the air-entry value increased with number of rainfall experiments with low intensity. Comparisons between the rainfall experiments show that in the ploughed soil the lower rainfall intensity had more impact than the high rainfall intensity. The uniformity of the pore size distribution ($n$) increased after the first low intensity experiment and fluctuated somewhat after that. A sequence of the low intensity experiments is given in Figure 5.2.4b.

A series of 3LI and 3HI rainfall simulation experiments had a high impact on the structure of the upper part of the ploughed soil (Table 5.2.1a). Air-entry value and pore size distribution showed a clear increase after the final experiment. Another striking point was the change in air-entry value and pore size distribution of the Bt-horizon.

When comparing the results in the upper part of the profile, between the various experiments, the air-entry values were in general higher in the harrowed than in the ploughed soil (Table 5.2.1b). In the harrowed soil both intensities seemed to have a high impact. The uni-
formity of the pore size distribution ($n$) was in general lower in the ploughed soil than in the
harrowed soil. In both profiles the $n$-values became higher during a sequence of experiments.
However, in the harrowed soil the last value of the low intensity sequence and the high inten-
sity sequence was lower again.

In Table 5.2.1a, samples from soil profiles of 45cm depth were compared between har-
rowed and ploughed profiles and before and after a series of 3LI and 3HI rainfall simulation
experiments. Before the experiments the air-entry value was higher in the harrowed soil than
in the ploughed soil in the entire profile. This corroborates the idea that the ploughed soil con-
tains more macropores than the harrowed soil. After the experiments, the air-entry value of
the ploughed soil in the upper part of the profile was much higher than in the harrowed soil.
This means that macropores in this part of the ploughed soil had disappeared, whereas in the
harrowed soil hardly anything had been changed. Figure 5.2.4c shows the difference
between these situations. The $p$F-range in which water was released from the soil was small-
er for the ploughed soil than for the harrowed soil. Deeper in the Ap-horizon, just above the
Bt-horizon, some macropores had disappeared in the ploughed soil; in the harrowed soil in
this part of the Ap-horizon more macropores disappeared. Macroporosity changes were not
expected to occur in Bt-horizons. However, the air-entry value became much higher in the
ploughed soil compared to the initial situation. Pore size distribution values were generally
smaller in ploughed than in harrowed soil in the initial situation. After the final experiments dif-
ferences disappeared.

For soils suffering from wheel pressure, the air-entry value and pore size distribution val-
ues after low intensity rainfall were higher than for soils without wheel pressure. This effect
was even higher in harrowed soils (Table 5.2.1b).

soil water retention
Wetting and drying scanning curves were established in the $pF$-range of 0.40 to 2.20 (Fig.
5.2.5; Chapter 3.2.3). The driving force in this range is dominated by gravity (Koorevaar et al.,
1983). The effect of the pore size distribution on the water retention and consequently
soil drainage was studied by comparing the released amount of water from the different
soil profiles in this $pF$-range during drying. This drainage of soils was also governed by
the amount of inped macropores (smaller than 1mm). Together with exped macropores (1mm
and larger; Chapter 3.2.3) these inped macropores could possibly cause preferential flow.
The difference in soil moisture content corresponding with the lowest $pF$ of the wetting and
drying curve (Fig. 5.2.5) gives an idea of the contribution of macropores to soil drainage.
Finally to examine the effect of hysteresis in different profiles and under various conditions,
the maximum difference in soil moisture content at corresponding $pF$-values between the dry-
ing and wetting curve was determined.

To study the effect of natural rainfall on the structure of the soil and consequently the
soil drainage process, the wetting and drying curves were established, from samples of the soil
profiles taken every few days during one month. The soil was a ploughed loess soil, showing
an Ap in the upper 30cm, followed by a Bt-horizon. The profile, inclusive the Bt-horizon was
sampled at the beginning and at the end. In between, only the upper and lower Ap-horizons
were sampled, because the Bt-horizon was not expected to change.

The amount of water released from the samples between $pF$ 0.40 and 2.20 seems to
increase in the Ap-horizon during the experiment (Fig. 5.2.6). The field soil moisture content
**Figure 5.2.6** A time sequence during 1 month of the percentage of volumetric soil water released from soil samples during drying in the pF-range: 0.4-2.20 in ploughed Wijnandsrade, The Netherlands, 1994
during sampling is presented to show the response of the soil to rainfall (Fig. 5.2.7).

Especially for the lower part of the Ap-horizon, the amount of released water became more the drier the sampled soil. This indicates that more macropores could be created by drying, or cycles of drying and wetting. In the upper part of the Ap-horizon the trend was less clear. This could be explained by the quick response of the upper part of the soil to rainfall and by the effect on infiltration of a surface crust. In the lower part of the Ap-horizon these effects were delayed or filtered. The released water in the Bt-horizon was similar in both samples.

The difference between volumetric soil moisture content at pF=0.40 of the wetting and drying curve was variable in the upper Ap during the experimental period (Table 5.2.2a). The

**Figure 5.2.7** Rainfall in Wijnandsrade during spring 1994

during sampling is presented to show the response of the soil to rainfall (Fig. 5.2.7).

Especially for the lower part of the Ap-horizon, the amount of released water became more the drier the sampled soil. This indicates that more macropores could be created by drying, or cycles of drying and wetting. In the upper part of the Ap-horizon the trend was less clear. This could be explained by the quick response of the upper part of the soil to rainfall and by the effect on infiltration of a surface crust. In the lower part of the Ap-horizon these effects were delayed or filtered. The released water in the Bt-horizon was similar in both samples.

The difference between volumetric soil moisture content at pF=0.40 of the wetting and drying curve was variable in the upper Ap during the experimental period (Table 5.2.2a). The

**Figure 5.2.8** Percentage of volumetric soil water released from soil samples during drying in pF-range: 0.40-2.20, in a rill system in ploughed soil, Catsop, The Netherlands, April 1994
trend seems to be a slight decrease of the difference, which should indicate more importance for the smaller pores, possibly caused by compaction of the soil. In the lower Ap-horizon, a general trend was the increase of the difference in soil moisture content between the wetting and drying curve, which suggests a more important role for macropores in relation to drainage.

Hysteresis appeared to play a more important role the drier the soil. This is shown by the maximum difference in soil moisture content (Table 5.2.2a). It is not in agreement with the difference in soil moisture content at pF=0.40 for the topsoil of the Ap-horizon. This indicates that the hysteresis effect of the topsoil of the Ap-horizon was more important at higher pF-values and therefore macropores were less important.

From samples taken from a rill and from the side of a rill relatively less water was released than from samples taken in between two rills (Fig. 5.2.8). This means that in a rill and in the side of a rill smaller pores are more important for drainage than in between two rills. This indicates a more compact structure around a rill and a drainage system that was influenced by larger (macro-) pores in the interrill areas (Chapter 2.2.4). The difference in soil moisture content at pF=0.40 between the wetting and drying curve showed a clearly higher value for the sample in the interrill area (Table 5.2.2b). This indicates a more important role for macropores in the drainage process in the interrill area than in the rill area, which agrees with the above

<table>
<thead>
<tr>
<th>Location on slope (upper Ap)</th>
<th>Difference of vol. soil moisture content between drying and wetting curve at pF = ca. 0.40</th>
<th>Maximum difference in vol. soil moisture content at a similar pF between drying and wetting curve</th>
</tr>
</thead>
<tbody>
<tr>
<td>in rill</td>
<td>0.017 (0.33)*</td>
<td>0.017 (0.33)*</td>
</tr>
<tr>
<td>side rill</td>
<td>0.015 (0.36)*</td>
<td>0.022 (0.36)*</td>
</tr>
<tr>
<td>in between rills</td>
<td>0.037 (0.34)*</td>
<td>0.037 (0.34)*</td>
</tr>
</tbody>
</table>

( )* = volumetric soil moisture at sampling
results. The maximum difference between the wetting and drying curves (Table 5.2.2b), which was taken as a value for the effect of hysteresis, was highest in the interrill area.

**Figure 5.2.9** Hydraulic conductivity at 2 depths in harrowed soil, according to sprinkling infiltrometer and method of Wind

The hydraulic conductivity was, as mentioned in Chapter 3.2.3, determined from the Ap of the harrowed soil in the pF-range of 0 to 2.5. It is calculated with Darcy's law (Koorevaar et al., 1983):
Figures 5.2.9a and b show the differences in these curves between the upper and lower part of the Ap-horizon. The lower part (at -23 cm) seems to have a higher hydraulic conductivity at higher pF-values, indicating that bigger pores are available in this layer. This means that the upper part of the profile was more compacted than the lower part. During the rainfall simulation experiments the pressure head values ranged from 0 to ca. -100 cm (pF=0 to 2; Fig. 5.2.1 and 5.2.2). This is the range in which the hydraulic conductivity was determined with the sprinkling infiltrometer and the Wind method (Chapter 3.2.3). The K(h) characteristics show that during the field experiments (pF=0 to 2) the hydraulic conductivity ranged from 16 (logK=1.2) to 0.01 (logK=-2) cm/day. The average saturated hydraulic conductivity (Ks) of the harrowed soil is 16.5 cm/day. For soils with a high macropore content an adaptation could be done by the modified Mualem-Van Genuchten model (Stolte et al., 1997).

5.2.3 Hydrological response of harrowed and ploughed loess soils

The previous measurements of soil water pressure and soil moisture content are, in this chapter, combined with runoff measurements to characterise the hydrological situation of the cultivated sites. Knowledge of the hydrological parameters contributes to the understanding of the infiltration processes. To characterise runoff, a runoff coefficient was calculated for every experiment. A water balance was established, from all hydrological parameters, for each rainfall experiment and tillage type, in order to get an overview of the relevance of the different parameters for the total hydrological situation.

Runoff and infiltration in ploughed loess soils

In the ploughed field no runoff occurred during any of the rainfall simulation experiments at low intensities (LI, 20 mm/hr, Table 5.2.3a and 5.2.3b), nor was any runoff detected at higher initial soil moisture contents (experiment LIB). Neither three successive LI rainfall simulation experiments generated runoff. Figure 5.2.10a shows an increase in soil moisture content following the three experiments.

Taking into account the rainfall simulation experiments at high intensities (HI, 60 mm/hr, Table 5.2.3a) the first experiment 1HIA and the repeated experiment on wet soil, 1HIB and the second experiment 2HIA did not generate runoff. Experiment 2HIB, with a higher initial soil moisture content, generated runoff, which increased during the following runs of experiment 3HI. This situation is summarised in Figure 5.2.10b. The soil moisture profiles showed that the last experiment 3HIB had a lower soil moisture content in the topsoil of the Ap-horizon than in the subsoil of this horizon and in the Bt-horizon. The high runoff component agrees with the small change in soil moisture content during the experiment and therefore the low infiltration capacity under these conditions in the ploughed soil.

The successive rainfall of 3 low intensity experiments followed by 3 high intensity experiments (Table 5.2.3b) gave slightly deviating results compared to the other experiments.
Table 5.2.3a Hydrological characteristics of rainfall simulation experiments in ploughed and harrowed loess soils

<table>
<thead>
<tr>
<th>Experiment</th>
<th>Runoff Coefficient</th>
<th>Total Sediment Yield (g/m²)</th>
<th>Rainfall Intensity (mm/hr)</th>
</tr>
</thead>
<tbody>
<tr>
<td>Ploughed Profile</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Low Intensity</td>
<td>1LI A</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2LI A</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>3LI A</td>
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<td>0</td>
</tr>
<tr>
<td></td>
<td>B</td>
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<td>0</td>
</tr>
<tr>
<td>High Intensity</td>
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<td>0</td>
</tr>
<tr>
<td></td>
<td>B</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
<td></td>
<td>2HI A</td>
<td>0</td>
<td>0</td>
</tr>
<tr>
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<td>B</td>
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<td>0</td>
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<td></td>
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<td>3</td>
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<td>Harrowed Profile</td>
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<tr>
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<tr>
<td></td>
<td>B</td>
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</tr>
<tr>
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</tr>
<tr>
<td></td>
<td>B</td>
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<tr>
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</tr>
<tr>
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<tr>
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</tr>
<tr>
<td></td>
<td>B</td>
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</tr>
<tr>
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<td>3</td>
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<td></td>
<td>B</td>
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(20) = percentage ponded surface
Table 5.2.3b Hydrological characteristics of rainfall simulation experiments in ploughed and harrowed loess soils; a sequence of low and high intensity experiments

<table>
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<tr>
<th>experiment</th>
<th>runoff coefficient</th>
<th>total sediment yield (g/m²)</th>
<th>rainfall intensity (mm/hr)</th>
<th>runoff coefficient</th>
<th>total sediment yield (g/m²)</th>
<th>rainfall intensity (mm/hr)</th>
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<tr>
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<td></td>
<td></td>
</tr>
<tr>
<td>1LI A</td>
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<td>0</td>
<td>18.9</td>
<td>0</td>
<td>0</td>
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</tr>
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<td>B</td>
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<td>0</td>
<td>19.3</td>
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</tr>
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<td>0</td>
<td>18.8</td>
</tr>
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<td>0.05</td>
<td>6</td>
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<td>56.0</td>
</tr>
<tr>
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</tr>
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<td>ploughed profile</td>
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<td></td>
</tr>
<tr>
<td>1LI A</td>
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<td>18.7</td>
<td>0</td>
<td>0</td>
<td>15.0</td>
</tr>
<tr>
<td>B</td>
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<td>18.7</td>
<td>0</td>
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<td>17.9</td>
</tr>
<tr>
<td>2LI A</td>
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<td>0</td>
<td>16.6</td>
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<td>B</td>
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<td>28.4</td>
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</tr>
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<td>3LI A</td>
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<td>B</td>
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<tr>
<td>4HI A</td>
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<td>7</td>
<td>39.3</td>
<td>0.15</td>
<td>9</td>
<td>63.2</td>
</tr>
<tr>
<td>B</td>
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<td>2</td>
<td>35.3</td>
<td>0.15</td>
<td>9</td>
<td>59.0</td>
</tr>
<tr>
<td>5HI A</td>
<td>0.05</td>
<td>8</td>
<td>54.5</td>
<td>0.20</td>
<td>10</td>
<td>64.9</td>
</tr>
<tr>
<td>B</td>
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<td>4</td>
<td>55.8</td>
<td>0.15</td>
<td>7</td>
<td>63.2</td>
</tr>
<tr>
<td>6HI A</td>
<td>0.20</td>
<td>11</td>
<td>58.3</td>
<td>0.25</td>
<td>17</td>
<td>66.9</td>
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<tr>
<td>B</td>
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<td>25</td>
<td>63.8</td>
<td>0.20</td>
<td>14</td>
<td>61.4</td>
</tr>
</tbody>
</table>
During the low intensity experiments the conditions were similar to Figure 5.2.10a (Fig. 5.2.10c), but during the first experiment with high intensity after the three experiments with low intensity runoff was generated. This differs from the results of experiments with only high intensity rainfall (Fig. 5.2.10b). A comparison of these results with the measured pressure heads in Figures 5.2.1 and 5.2.2 showed that the conditions during the experiments 2LIA and B were more wet than during 5HIA and B. This supports the results above.

In the wheeltrack in ploughed soil (Table 5.2.3a) runoff was generated already during the first run of experiment 2LI. The second run of this experiment caused even more runoff at a slightly higher intensity. The experiments with high intensity already caused runoff during the first run of the first experiment (1HIA). The second run of this experiment caused an increase in runoff even at a lower rainfall intensity. Experiment 2HI shows lower runoff during the first run, which was probably caused by the lower rainfall intensity. However, the second run showed an amount of runoff corresponding to all rainfall input. Figure 5.2.10d shows the hydrological balance for this situation. The soil moisture profiles show a slightly higher soil moisture content after the LI experiments compared to the HI experiments, which was expected in view of the preceding results.

Runoff and infiltration in harrowed loess soils
Low intensity rainfall did not generate runoff in harrowed soils (Table 5.2.3a and b). Runoff generation did not even occur after the infiltration capacity had been decreased by preceding rainfall. Figure 5.2.10a shows that compared to experiment 1LI the soil moisture profile after experiment 3LI has been changed to a more homogeneous water saturation profile in the Ap-horizon. This means that also the subsoil of the Ap-horizon became saturated.

High intensity rainfall on harrowed soil caused a similar effect as in the ploughed soil (Table 5.2.3a), but with more runoff in the third experiment (Fig. 5.2.10b).

The series of six successive rainfall simulation experiments, 3LI and 3HI experiments, show a rather similar result as for the ploughed soil (Table 5.2.3b), although the amount of runoff is less in case of the harrowed soil. This means that the ploughed soil has a lower infiltration capacity than the harrowed soil. The resulting soil moisture profiles of the successive rainfall simulation experiments are shown in Figure 5.2.10c. A difference with the conditions during only high intensity rainfall is that in that case no pre-wetting by low intensity rainfall occurred. Antecedent soil moisture content is considerably important for erodibility and vulnerability to slaking and apparently for overland flow.

Runoff and soil moisture in a wheeltrack (Fig. 5.2.10d) showed differences between harrowed and ploughed soil for low and high intensity experiments. For low intensity rainfall harrowed soil showed more runoff. Whereas for high intensity rainfall ploughed soil showed more runoff (Table 5.2.3a).

The difference between the amount of runoff and the infiltration profile of the ploughed and harrowed soil could be caused by the higher instability of the soil surface of the ploughed soil. Because of the ploughing, soil clods were broken artificially resulting in more unstable soil clods or aggregates. Harrowing is a less destructive tillage type and clods were broken along their natural structural planes.

Comparing the above results of high intensity rainfall with the pressure head values (Fig. 5.2.2) it can be concluded that in the harrowed field the complete soil profile, including Bt-horizon became more wet, whereas in the ploughed field wetting only occurred in the Ap-horizon.
Figure 5.2.10a three successive low intensity rainfall experiments in ploughed and harrowed soil
(legend see Figure 5.2.12)
**Figure 5.2.10b** three successive high intensity rainfall experiments in ploughed and harrowed soil
(for legend see Figure 5.2.12)
Figure 5.2.10c: Six successive low and high intensity rainfall experiments in ploughed and harrowed soil
(legend see Figure 5.2.12)
**Figure 5.2.10d** two successive low and two successive high intensity rainfall experiments in a wheeltrack in ploughed and harrowed soil (for legend see Figure 5.2.12)
However, in the harrowed soil was more runoff generated, which is an indication for a higher infiltration capacity in ploughed soil, caused by by-pass flow and consequently macropores.

**Drainage conditions in a rill system in ploughed loess soil under natural rainfall conditions**

Soil moisture contents were determined in a rill system to investigate the spatial drainage pattern. In a ploughed loess field in which rills were formed in early spring, soil moisture measurements were carried out in and around rills. The results of the measurements are given in Figure 5.2.11. The differences in soil moisture contents between the individual measurements were small, ranging from 0.34 to 0.40 m³/m³, both limits measured in the side of a rill. The soil moisture content in a rill was relatively high. In the interrill area soil moisture contents were relatively low. In general the variations in soil moisture contents were too small to show a specific drainage pattern in the rill system.

### 5.2.4 Discussion

The hydrological parameters are discussed in order to find differences in response of various tilled loess soils to rainfall. The knowledge of these processes is appropriate for measures against erosion, especially on a catchment scale (v. Dijk, 2001; v. Dijk and Kwaad, 1996; Ritsema et al., 1996; de Roo et al., 1996).

**Infiltration into cultivated loess profiles**

Expected infiltration profiles are given in Figure 5.2.12. The soil moisture values are relative values depending on bulk density and initial soil moisture conditions. After rainfall with a relatively low intensity, during which no surface runoff is generated in the ploughed field, a water saturated layer will be formed above the Bt-horizon or plough sole. The soil moisture content in the Bt-horizon will not change, because of the relative impermeability of this layer. A saturated layer might be formed in the first few centimetres of the Ap-horizon in the harrowed soil after which the soil moisture content decreases in depth. Rainfall with a relatively higher intensity causing runoff will result in an infiltration profile very similar for both cultivation systems. This results in a very shallow saturated layer at the surface, decreasing in depth. For the ploughed field, the soil moisture content under the Bt-horizon will be similar to the initial soil moisture content. Low intensity rainfall is around 20mm/hr and high intensity rainfall is around 50mm/hr, similar to the experiments mentioned in this chapter.

From the soil water pressure data during low intensity rainfall it can be concluded that the infiltration front moved more quickly downwards in ploughed soil than in harrowed soil, but stagnated on the relatively impermeable plough sole. Macropore flow can be detected by a sudden quick wetting of a point compared to its surrounding points. This is likely to occur in the ploughed soil and not in the harrowed soil. The quicker response and a response at several depths in the ploughed soil indicate a quicker infiltration, which was likely to be caused by macropore flow (Fig. 5.2.1 and Fig. 5.2.2). Chen and Wagenet (1992) found that the occurrence of macropore flow depended principally upon surface boundary conditions. This means that stability of the soil at the surface is a relevant parameter for macropore flow. The stability at the surface of ploughed soil in general was lower than of harrowed soil, which creates favourable conditions for macropore flow in a ploughed soil.

Differences found in soil water pressure heads between the two cultivation systems under
High rainfall intensities are unexpected. It was expected that because of the macropores in ploughed soil more water would be able to infiltrate. According to the data this is not true for the high rainfall intensities. This might indicate a weaker structure for the ploughed soil than for the harrowed soil, caused by cultivation. The weak structure can be very sensitive to slaking at the surface during high intensity rainfall. This probably played a less important role at lower rainfall intensities.

Some conclusions can be drawn from the soil moisture data. In the ploughed field a wetter infiltration front was found just above the plough sole on top of the Bt-horizon during both high and low intensity rainfall (Fig. 5.2.3a). However, less infiltration took place during high intensity than during low intensity rainfall. In the harrowed field no difference was found between the two intensities. It seems that higher rainfall intensity has more impact on the infiltration profile in the ploughed field than on the infiltration profile in the harrowed soil, compared to low intensity rainfall. However, the compaction of the soil by wheel pressure has a higher impact, for both infiltration profiles, than the rainfall intensity. Under higher rainfall intensity, the stability of aggregates is more important for the infiltration capacity of the soil. The fluctuation in aggregate stability during the growing season is rather complex (Van Eijsden, 1986). In general it seems to be high during May, June and July compared to August and September, probably influenced by seasonal soil moisture content, temperature and cultivation. The results show in this case a lower infiltration capacity of the ploughed loess soil compared to the harrowed loess soil (Fig. 5.2.3a). Freebairn and Gupta (1990) showed that on a bare freshly cultivated plot, the infiltration rate under simulated rain (100mm/hr) decreased to 40mm/hr. This final infiltration rate was always lower than on plant covered plots, indicating the importance of surface crusts in controlling the rate of water entry. The alteration in the state of the soil surface during rainfall on tilled soils greatly affects a number of soil physical

**Figure 5.2.11** Soil moisture content in a rill system; Catsop, The Netherlands, 1994
Figure 5.2.12 expected soil moisture profile in ploughed and harrowed soils after low and high intensity rainfall
properties, such as infiltration capacity, roughness of the soil surface and resistance of the soil surface to detachment by drop impact and flowing water (Imeson and Kwaad, 1994). Under wheeltrack sites the infiltration profiles of both cultivation systems are very similar, indicating the dominance of wheeltrack compaction.

The role of water retention for infiltration in a cultivated loess profile
It might be expected that in the ploughed soil, especially in the subsoil of the Ap-horizon, the air-entry value (Schaap, 1996; Wösten and van Genuchten, 1988) should be lower than in a harrowed soil, due to the presence of macropores; the latter are more abundant in the upper 30 cm of the ploughed soil than in the harrowed soil. The pore size distribution is more uniform in the harrowed soil than in the ploughed soil.

Macropores are defined in many ways (Chen and Wagenet, 1992). Beven and Germann (1981) suggest a pore classification based on flow dynamics as a concern for macropore channelling. This concept is useful for the present study. However, Chen and Wagenet (1992) proposed a comprehensive theory of macropore flow. They considered different domains and processes, derived from previous studies on macropore flow. Their definition for macropores is: 'channelling pores of different radii in which the flux density occurring in the minimum sizes of such pores is greater than or equal to the saturated matrix hydraulic conductivity'.

Comparing the water retention characteristics of ploughed and harrowed soil profiles before and after rainfall simulation experiments the following can be concluded. According to the air-entry values, the ploughed soil has more macropores, supporting the hypothesis that conditions for macropore flow are more favourable. After the experiments, the number of macropores in the upper part of the ploughed profile decreased more than in the harrowed soil. The reverse was the case in the lower part of the Ap-horizon. This means that the upper part of the ploughed profile was more compacted than the lower part of the profile during the experiments. This again supports the evidence that the ploughed soil has a weaker structure than the harrowed soil.

In the upper part of the ploughed soil, the pore size distribution (n) changed considerably during the experiments. The large changes in the air-entry value (1/α) and n in the Bt-horizon were unexpected. A disturbance of the plough sole, caused by deeper ploughing, could explain these changes. Lower in the Ap-horizon, just above the Bt-horizon, only some macropores had disappeared in the ploughed soil compared to the harrowed soil in which relatively more macropores were lost.

A detailed study on soil erosion in the loess area of Southern Limburg (de Roo et al., 1995) shows that changes in the structure and consequently the soil physical characteristics of the toplayer (Ap-horizon) are related to tillage.

Large changes of pore size distribution and air-entry value in the Bt-horizon were not expected. However, in the harrowed soil the air-entry value became much lower and in the ploughed soil much higher compared to the initial situation. Another striking point is the change in n-value of the Bt-horizon, contrary to the impermeable function of this horizon. However, this should be treated with caution, because there was a problem with the line fitting procedure.

The water retention capacity of tilled soil decreases with time after tillage (Tiktak, 1983). Imeson and Kwaad (1994) combined this with change of structure of the tilled layer, by which the pore volume of all size classes is reduced in these soils.
The more detailed results from Table 5.2.1b show that in general during all experiments air-entry value is lower in the ploughed soil than in the harrowed soil in the upper part of the profile. During the course of the experiments, it can be seen that the rainfall simulation experiments with a low rainfall intensity had a higher impact on the upper part of the profile in both soils than the rainfall simulation experiments with higher rainfall intensity. The pore size distribution of the harrowed soil was generally more uniform than in the ploughed soil. This implies that there was a less homogeneous distribution of pore size in ploughed than in harrowed soil, due to the destruction of the structure of the loess soil by ploughing. However, in both profiles there was a sequence found from inhomogeneous to more uniform and again to more inhomogeneity. An example is ploughed soil during high intensity rainfall, which changed from 1.18 to 1.24 and decreases to 1.22 after the last experiment. This indicates dynamics that show fluctuations in pore size distribution.

The wetting and drying water retention curves, show that the structure of the soil in and around rills had more small macropores than the soil in the interrill areas (Fig. 5.2.8). The analyses of these curves suggest that the drainage system in the interrill area was dominated by larger (macro)pores than at the rill side. The apparent larger effect of hysteresis in the interrill area supports the conclusion that part of the hysteresis phenomena depends on macropores (Table 5.2.2b).

In the case of natural rainfall on the drainage system of a ploughed soil it was found that the drier the sampled soil, the more water there was released from the soil. This means that the drier the soil the more macropores will be developed. This was caused by change in bulk density by drying or cycles of wetting and drying, which is most clear in the lower part of the Ap-horizon. Concerning the Ap-horizon, the idea is that the (macro)porosity changes, because of rainfall, either in the upper part or in the lower part or both. The topsoil of the Ap-horizon seems to become more compacted, whereas in the subsoil of the Ap-horizon, macropores seem to play a more important role during the period of sampling. The drier the soil the higher the hysteresis effect, however in the topsoil of the Ap-horizon this effect is not seen at pF=0.40, but at higher pF-values (Table 5.2.2a).

**Hydrological processes on a cultivated loess slope**

Combining the field pressure head values during the experiment and the relationship between pressure head and hydraulic conductivity it is concluded that during rainfall and infiltration the hydraulic conductivity ranged from 0.3cm/day to 16cm/day. For ploughed soil these values represent the hydraulic conductivity for the soil matrix, but not for the macropores. The hydraulic conductivity can be used to measure soil water fluxes between the different soil layers to determine the soil water dynamics and vertical drainage pattern in the soil profile (Koorevaar et al., 1983).

It seems that the infiltrated water during the experiments with low intensity rainfall created favourable conditions for generating overland flow during the high intensity rainfall experiments for both ploughed and harrowed soil. This is explained by the infiltration theory, which also counts for badland regoliths (Horton, 1940; Philip, 1957; Chapter 5.1.2). Infiltration capacity, which is given by infiltration rate, decrease during a rain event until a constant value (Horton, 1940). Sorptivity is an important parameter in the infiltration rate equations for instantaneous infiltration (Philip, 1957). Sorptivity becomes smaller as the antecedent water content
increases. This happened during the series experiments, which resulted in a decrease of infiltration capacity and therefore a greater risk for runoff. Possible mechanisms are:

1. After low intensity rainfall the topsoil (0-5cm) of the profile has been saturated, which causes for sequential high intensity rainfall a possibility for saturated overland flow; a possible scenario for harrowed soil.

2. After three experiments with low intensity rainfall the complete Ap-horizon is water saturated which creates very good conditions for rainfall with high intensity to generate saturated overland flow; a possible scenario for ploughed soil.

3. Stability change of the soil aggregates at the surface is caused by preceding experiments. After rewetting the surface, especially by rainfall with high intensity, the lower aggregate stability results in the breakdown of aggregates and slaking of the surface.

4. The surface conditions can also be changed by the impact of raindrops on saturated soil aggregates, depending on the stability of aggregates when saturated. In this case the surface conditions are changed by the impact of high intensity rainfall on a saturated soil.

Scenarios 3 and 4 are possible for both ploughed and harrowed soil. During this study three successive rainfall simulation experiments with low intensity did not generate runoff. According to Ritsema et al. (1996) on a loessial hillslope Hortonian overland flow occurred during natural rainfall. This started after water saturation of the first 5-10cm of the ploughed profile. Deeper in the profile unsaturated conditions still prevailed. This conclusion would give preference to scenario 1 or in case of changes in surface conditions, mechanism 3 or 4 (photo 5.2.2a and b). These last mechanisms probably cause Horton overland flow. However, natural rain showers in the measured periods had 70mm/hr or more peak intensity, which is considerably more than the simulated rainfall during the present research. This means that especially at the lower rainfall intensities prevailing conditions are not necessarily surface conditions, but can be in this case soil structural parameters as suggested by Imeson and Kwaad (1994) or a possible saturation as in scenario 1 or 2 (Chapter 2.2.4 this thesis).

Results from the hydrological balance show that both ploughed and harrowed loess soil profiles, already exposed to a series of low intensity events, are very vulnerable to overland flow if rainfall with high intensity occurs successively (ca. 60mm/hr). It was expected that low intensity rainfall would create conditions for overland flow in harrowed soil. The absence of macropores in harrowed soil would cause quick saturation after start of rainfall of the harrowed layer (upper 5cm), after which overland flow would start. An explanation for difference between results and expectations is that the rainfall intensity is low enough to create a homogeneous infiltration front, which moves slowly to the deeper profile (Fig. 5.2.10a). The high intensity rainfall, however, probably causes changes in soil surface stability, which increases the amount of runoff (Fig. 5.2.10b). Moreover, antecedent soil moisture content is a relevant parameter for soil surface change during rainfall (Photo 5.2.3a & b; Imeson and Kwaad, 1994). If high intensity rainfall is preceded by low intensity rainfall than change in surface is less pronounced and less relevant for infiltration capacity.

The soil moisture profiles of ploughed and harrowed soil show some differences. In general it seems that in the harrowed profile the upper part of the Bt-horizon corresponds better with the points in the Ap-horizon than in the ploughed profile. This indicates a discontinuity in response to infiltration in the latter profile. Low intensity rainfall in the ploughed soil shows clearly more infiltrated water in the lower Ap than at the surface. This indicates possible macropore flow. This effect is less clear in the harrowed soil. After high intensity rainfall, infil-
CHAPTER 5.2

Trated water remains longer in the upper part of the harrowed soil than in the ploughed soil. This is explained by the higher hydraulic conductivity of the macropores in the ploughed soil. After a series of low and high intensity events, soil moisture in the ploughed soil is in the lower part of the profile equal to the upper part. In the harrowed soil, soil moisture decreases with depth after a series of rainfall events. Also in this case soil water infiltrates quicker through the macropores to the lower Ap-profile in ploughed soil than in harrowed soil.

In addition, Stolte et al. (1996) found that differences in hydraulic properties of the top layer of cultivated loess soils cause differences in potential runoff. High intensity rainfall on

Photo 5.2.2a Initial surface conditions of rainfall simulation experiments in ploughed soil, Wijnandsrade, The Netherlands

Photo 5.2.2b Surface conditions after high intensity rainfall in harrowed soil, Wijnandsrade, The Netherlands

trated water remains longer in the upper part of the harrowed soil than in the ploughed soil. This is explained by the higher hydraulic conductivity of the macropores in the ploughed soil. After a series of low and high intensity events, soil moisture in the ploughed soil is in the lower part of the profile equal to the upper part. In the harrowed soil, soil moisture decreases with depth after a series of rainfall events. Also in this case soil water infiltrates quicker through the macropores to the lower Ap-profile in ploughed soil than in harrowed soil.

In addition, Stolte et al. (1996) found that differences in hydraulic properties of the top layer of cultivated loess soils cause differences in potential runoff. High intensity rainfall on
harrowed soil caused a similar trend in runoff as in the ploughed soil (Table 5.2.3a), but with more runoff generation in the third experiment. The abrupt increase in runoff during this experiment could be caused by either changes in surface properties or by a water saturated layer just beneath the soil surface (Fig. 5.2.10b). According to the homogeneous soil moisture profile, mentioned above, an appropriate explanation is the saturation of the soil surface. From the results in the wheeltrack in ploughed soil it is evident that the first experiment with low intensity rainfall contributed to the generation of runoff during the second low intensity experiment. This was possibly caused by changes at the surface, because the increase in runoff was relatively high. The surface already had been changed by the wheel compaction
so that rainfall with a higher intensity (75mm/hr) caused runoff of more than half of the rainfall. During the experiments with high intensity rainfall the runoff was increasing. From this is concluded that compaction and instability of the surface layer is the most important cause of runoff in soil affected by wheel pressure. However, runoff also causes a change of the surface, i.e. slaking, which is a self-improving system.

The situation of the wheeltrack in harrowed soil shows surprising results (Table 5.2.3a). During the low intensity experiments, the first and second experiment showed a similar response in runoff. The experiments with high intensity rainfall showed an increase in runoff from experiment 1HA to 2HB starting with a runoff coefficient lower than during the first experiment with low intensity rainfall. It was expected that if no runoff occurred, this would be the case for experiments with low intensity rainfall, as happened on ploughed soil. A possible factor in this case was the roughness of the surface. When the roughness is very low the plot surface has a low detention storage. According to the ponded surfaces during the experiments, the plot used for the experiments with high intensity rainfall, had a higher detention storage than the plot used for the LI experiments. The surface storage effect possibly overruled the effect of surface changes during the first experiment. Runoff will cause a lower roughness index preparing the plot better for generating overland flow. The situation is described in Figure 5.2.10d. The soil moisture profile did not show a specific difference between low and high intensity rainfall. This means that under these conditions the determining factor was the surface morphology.

Expectations for drainage conditions in a rill system in ploughed soil are that in a rill bottom soil moisture content is higher than in an interrill area, because of the drainage of interrill areas to a rill. Only at one location (B) the interrill area is slightly drier than at other points. At this location the distance between rills is much more (ca. 10m) than at the other locations (ca. 3m). Possibly location B is a drier part of the slope having more internal drainage and less runoff than locations A and C.

5.2.5 Conclusions
The soil water pressure shows that under low intensity rainfall the infiltration front in the ploughed soil moves more quickly downwards than in the harrowed soil (Fig. 5.2.1). In the ploughed soil the water stagnates on a relatively impermeable plough sole.

During high intensity rainfall, the soil water pressure increases in the ploughed soil, similarly as in the harrowed soil. This is probably caused by the impact of the high intensity rainfall on the weaker soil structure at the surface of the ploughed soil.

In the ploughed soil the air-entry value is lower than for the harrowed soil, caused by macropores. The pore size distribution is less uniform and therefore more heterogeneous than in the harrowed soil, probably caused by the bigger pores in the ploughed soil. Conditions for macropore flow are more favourable in ploughed than in harrowed soil. The ploughed soil appeared to have a weaker structure than the harrowed soil. In the Ap-horizon, just above the Bt-horizon, few macropores disappeared in the ploughed soil compared to the harrowed soil, in which relatively more macropores disappeared. In the ploughed soil the air-entry value and the pore size distribution increased with low intensity rain events. This implies a decrease of the pore size and an increase in the uniformity of the pores. Rainfall with a lower intensity has a higher impact on the upper part of the profile in both soils.
than rainfall with a higher intensity. According to the water retention curves, in and around rills, more smaller pores are present than in the interrill areas. From a rill system of a ploughed soil it is shown that the drier the sampled soil the more water is released from the soil, while establishing the water retention characteristic in the laboratory. This means that the drier the soil, the more macropores have been formed. The topsoil of the Ap-horizon seems to become more compacted than the subsoil, which means that macropores play a more important role in the subsoil.

The hydraulic conductivity during rainfall ranged from 0.3cm/day to 16cm/day. After low intensity rainfall the risk for runoff was higher. This can be explained by the saturation of the complete profile, which is, according to this and other studies, the most probable cause of overland flow (Stolte et al., 1996; de Roo et al., 1995; v. Dijk and Kwaad, 1996).

If high intensity rainfall is preceded by low intensity rainfall, than change in surface is less pronounced and has less influence on the infiltration capacity.

The soil moisture profiles of ploughed and harrowed soil after low and high intensity rainfall show decrease in soil moisture with depth in the harrowed soil and a uniform soil moisture front in the ploughed soil. The deeper soil moisture front in the ploughed soil is probably caused by the quick drainage of water through macropores. In the harrowed soil, the homogeneous soil profile causes a homogeneous decreasing infiltration front in depth.

From the results of the experiments in a wheeltrack it is concluded that the effects of compaction dominate the effects of cultivation type. Runoff during the experiments causes more slaking and loss of structure at the surface, which is a self-improving system. From these experiments is also concluded that a high surface roughness, is a determining factor for runoff.

In a rill system in ploughed soil the soil moisture content in a rill is higher than in between rills, which indicates the drainage of water from the higher parts into the rill.
6

Erodibility of badland regoliths and cultivated loess soils

Introduction

Soil erosion depends on the erodibility of soil material and erosivity of the erosive agents as, in this study, water. In the badland area in South-East Spain and in the loess area in Southern Limburg, The Netherlands, field studies were made to investigate the erodibility of the soil material under field conditions. For this purpose sediment discharge was measured during rainfall simulation experiments and these results were related to hydrological properties, such as soil moisture content and water discharge. Soil dynamic properties as studied in Chapter 4 in the laboratory are in this chapter considered under field conditions. The aim of this chapter is to establish if threshold values for erosion are observed during rainfall simulation experiments and under field conditions.
6.1 Erodibility of badland regoliths

This section reconsiders and discusses results of laboratory and field tests of badland regoliths. These results are compared with results from the hydrological experiments of Chapter 5.1. Parameters for erosion, measured during field experiments, are also presented and discussed. An attempt is made to relate the differences in erosion processes, described in Chapter 3 to threshold values of the material properties and the behaviour of the material. A summary of the experimental field conditions is given in Table 6.1.1.

### Table 6.1.1 Characteristics of plots and experiments on badland regoliths

<table>
<thead>
<tr>
<th>badland regolith</th>
<th>slope angle (°)</th>
<th>aspect</th>
<th>plot surface (m²)</th>
<th>experiment no.</th>
<th>rainfall intensity (mm/hr)</th>
<th>total sediment yield (kg/m²)</th>
<th>total runoff (l/m²)</th>
<th>runoff coefficient (fraction of rainfall)</th>
</tr>
</thead>
<tbody>
<tr>
<td>white marls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>N exposed</td>
<td>39</td>
<td>N358</td>
<td>4.1</td>
<td>1</td>
<td>27.5</td>
<td>2.15</td>
<td>14.0</td>
<td>0.70</td>
</tr>
<tr>
<td>S exposed</td>
<td>43</td>
<td>N241</td>
<td>2.8</td>
<td>1</td>
<td>15.0</td>
<td>0.395</td>
<td>1.65</td>
<td>0.15</td>
</tr>
<tr>
<td>SW exposed</td>
<td>48</td>
<td>N235</td>
<td>4.1</td>
<td>1</td>
<td>23.5</td>
<td>0.395</td>
<td>1.80</td>
<td>0.10</td>
</tr>
<tr>
<td>brown marls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S exposed</td>
<td>52</td>
<td>N214</td>
<td>13</td>
<td>1</td>
<td>42.5</td>
<td>1.00</td>
<td>16.0</td>
<td>0.50</td>
</tr>
<tr>
<td>grey marls</td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>S exposed</td>
<td>37</td>
<td>N179</td>
<td>5.5</td>
<td>1</td>
<td>18.0</td>
<td>0.535</td>
<td>0.940</td>
<td>0.70</td>
</tr>
</tbody>
</table>

6.1.1. Field measurements for erosivity and erodibility

Erosivity and erodibility have been detected in the field by various parameters. During rainfall simulation experiments sediment discharge is a measure for both features. In relation to soil moisture content, sediment discharge can be seen as more dependent of either erosivity or erodibility. Soil shear strength, roughness of the surface and crack patterns are field indicators which could say something about the erodibility of the soil and the erosion processes evident at the surface. Finally, rill patterns and their relationships with the above parameters will lead us to a specific type of erosion and morphology of the plots.

According to the chemical soil properties (Table 4.1.1), differences in erosion processes between white and grey marls are likely to be related to these properties. This is also the case for grey and brown marls. Because the brown and white marls seem to have identical chem-
ical properties, differences in erosion processes should be related to other soil properties, such as physico-chemical, physical or mineralogical.

**Sediment discharge**

Table 6.1.1 and Figures 6.1.1a to d give data of sediment discharge during the rainfall simulation experiments on badland regolith. In general sediment concentration is rather irregular prior to saturation.

On white marls the data of the experiments show an average sediment concentration during the experiment of ca. 100 g/l. A good example is seen in Fig. 6.1.1a. The sediment concentration seems to increase irregularly during the first minutes of runoff to a maximum. About 10 minutes later sediment concentration drops, which coincides in some cases with an increase of runoff. From the total of six experiments on the plots of the white marls, the second experiment on the southerly exposed plot shows a strong deviation (Fig. 6.1.1b) from the average value of the sediment concentration. This resulted in a very high total amount of sediment (Table 6.1.1).

On brown marls the pattern of the sediment concentration was very different from the white marls. During the first minutes of runoff a higher sediment concentration was found than during the following part of the experiment (Fig. 6.1.1c). The average sediment concentration was higher than on the white marls. It is obvious (Table 6.1.1) that the total sediment yield was much higher than on the white marls.

On the grey marls the average sediment concentration was the highest compared to the other materials (Fig. 6.1.1d). The total sediment yield was not extremely high, but in relation with the low runoff coefficient it was obvious that the sediment concentration must be high (Table 6.1.1). During the second experiment on the grey marls the runoff and sediment concentration were acting more like white marls (Table 6.1.1). This was possibly caused by the crust formed at the surface after the first experiment.

**Dynamic soil properties and clay mineralogy**

Indicators as soil shear strength, roughness of the surface and crack patterns have been mentioned in Chapter 4.1. Results from the field tests and measurements are used in section 6.1.2 to relate these indicators to field conditions to establish relationships for erodibility. Finally the amount of rills is studied, to find a relationship between erodibility and type of erosion.

The clay mineralogical composition of the badland regolith is given in Table 4.1.5. Grey marls contained the largest amount of the swelling clay mineral smectite (Fig. 4.1.3). Brown marls showed a high swelling capacity because of a combination of a high amount of illite and sodium (Fig. 4.1.3; Table 4.1.1).

A combination of the above described properties probably gives an explanation of the behaviour of the material. Physico-chemical properties, like clay dispersion, shrinkage and swelling and chemical thresholds, are related to the above mentioned properties and to external factors like soil moisture content (Gerits, 1991).
Figure 6.1.1 Runoff and sediment concentration during rainfall simulation experiments, badlands, Spain
6.1.2 Discussion

Aggregation in relation to chemical soil properties
All regolith types, except the brown marls, show a decrease in depth of aggregates smaller than 2mm (Table 4.1.1). In the brown marls this aggregate fraction increased from the surface until the horizon with salt crystals, marked as puffed soil. Because of the high content of sodium salt the soil was very unstable and vulnerable to erosion (Photo 6.1.1). So, stable aggregates were hardly formed. It is also obvious in Table 4.1.2 that this horizon shows a high EC and SARp-value. From this horizon on the amount of aggregates < 2mm decreased in depth. The grey marls show a relatively high amount of small aggregates at the surface, which could indicate a higher susceptibility to erosion and a less stable surface layer or crust. This lack of stability certainly is an explanation for the dominating erosion process of mass movement instead of rill erosion (Photo 6.1.2). It seems that aggregate fractionation was more evident in the brown and grey marls considering the differences in aggregate size between the horizons. The relatively high differences in aggregate fractionation were possibly caused by chemical fractionation. In the brown marls this is obvious as stated before by
considering EC and SARp of the subsurface material. In the grey marls the most obvious chemical fractionation was seen between the crust and subsurface material. The EC and SARp of the crust were much lower than the underlying material.

The amount of water dispersed soil material under natural conditions was lowest for white and brown marls (Table 4.1.3a; ‘water dispersed’, white marls, southerly exposed is an extreme exception). This means that in these regoliths micro-aggregation is highest, compared to grey marls. Which is confirmed by the ‘waterstable aggregates’ (Table 4.1.3a). Micro-aggregates of grey marls appear to be less stable under laboratory conditions.

Texture of white and brown marls was similar. However, grey marls contained more sand and clay than the other regoliths (Table 4.1.3b).

Sediment discharge in relation to soil moisture and chemical runoff properties

Soil moisture content is seen as one of the determining factors for soil erosion in this area. Chemical factors like EC and SARp were used to give an explanation of the erodibility of the regoliths. To compare sediment concentration with soil moisture content, the average characteristics of soil moisture contents of the different measuring points on the slope were calculated.

In the white marl regoliths the infiltration into the soil on the northerly exposed slope was
quickest, which is seen by the convex slope of the soil moisture characteristic (Fig. 6.1.2a). On the south-westerly exposed slope infiltration started only after 12 minutes (Fig. 6.1.2b). Whereas during both experiments on the southerly exposed slope, infiltration is very low and slowly (Fig. 6.1.2c). A slightly positive relationship between soil moisture content and sediment concentration was found in the sides of the rills during the second experiment on the northerly exposed slope. While soil moisture reached its maximum, sediment concentration increased considerably and stabilised further on with some outliers to higher values. Pressure head values showed (Fig. 6.1.3a) that the upper part of the profile (5cm) was saturated from about 3 minutes after start of the experiment. This was not the case on the southerly exposed slope. On the south-westerly exposed slope a positive relationship between soil moisture and runoff was established (Fig. 6.1.2b). Runoff started, while soil moisture increased considerably and reached its maximum. Also a quick saturation of the upper part of the regolith profile was seen by the pressure head values, similar to data on the northerly exposed slope. However, there were too few data points for sediment concentration to find a significant relationship. Sediment concentration appeared to be stable during the experiment. Differences between EC and SARp were highest on the northerly exposed slope (Fig. 6.1.4a). This could indicate a high erodibility and thus higher sediment concentrations than on the other slopes and materials. However, this was not confirmed by the field data.

The infiltration in the brown marls was according to the average curves (Fig. 6.1.5a) higher and quicker than in the white marls, especially during the first experiment. The second experiment was more similar to the white marls, possibly, as mentioned before, by the development of a crust after the first experiment. During the first experiment on brown marls a slightly negative relationship was seen between sediment concentration and soil moisture content in the interrill and rill area (Fig. 6.1.5a). This relationship was caused by the first measured sediment concentrations that were quite high, whereas the following measured values were much lower. Possibly, unconsolidated sediment at the surface, washed away by the first runoff, caused this relationship. Pressure head values of the experiments did not show a completely saturated upper part of the profile (Fig. 6.1.3b). Differences between EC and SARp were much lower than on white marls on the northerly exposed slope (Fig. 6.1.4b) and equal to the south facing white marls. This means that other than chemical factors of the runoff should explain the difference in sediment concentration between brown and white marls. In this case a combination of illite and a sodium-rich environment caused a highly erodible situation (Imeson et al., 1982; Yong and Warkentin, 1975).

The infiltration in the grey marls was highest during the first experiment compared to the first experiments on the other regoliths (Table 6.1.1). The second experiment showed higher runoff and even at some places a maximum of infiltration, which could indicate macro-pore flow (Fig. 6.1.5c; App. III, Fig. 8). No specific relationship was seen between sediment concentration and soil moisture content. The pressure head values during both experiments on grey marls did not show a complete saturation of the upper part of the material (Fig. 6.1.3c). Differences between EC and SARp were very low, so, as posed for brown marls, other than these chemical properties should explain the high erodibility of this material.
(a) white marls, northerly exposed, experiment 2

(b) white marls, southerly exposed, experiment 1

(c) white marls, southerly exposed, experiment 2

Figure 6.1.2 Relationship between soil moisture, sediment concentration and runoff in badland regolith
ERODIBILITY OF BADLAND REGOLITHS

(a) white marls, northerly exposed, experiment 2

(b) brown marls, southerly exposed, experiment 2

(c) grey marls, southerly exposed, experiment 1

Figure 6.1.3 Relationship between soil water pressure, sediment concentration and runoff in badland regolith
CHAPTER 6.1

Figure 6.1.4 Practical sodium adsorption (SARp) ratio and electrical conductivity (EC25) during rainfall simulation experiments, badlands, SE Spain; arrows indicate start and end of runoff.
**Erodibility of Badland Regoliths**

(a) *Brown marls, southerly exposed, experiment 1*

(b) *Grey marls, southerly exposed, experiment 1*

(c) *Grey marls, southerly exposed, experiment 2*

*Figure 6.1.5* Soil moisture related to sediment concentration and runoff during rainfall simulation experiments on badlands, Spain
Soil shear strength and vertical resistance in relation to soil moisture

Both field parameters, soil shear strength and vertical resistance of the surface, were studied in relation to soil moisture in this paragraph.

Soil shear strength and vertical resistance have been measured before and after the simulation experiments (Fig. 6.1.6a and b). Under dry conditions results are an indicator for compaction at the surface and crust formation. All badland regolith materials showed high values for both parameters under dry conditions, except grey marls before the experiments. This means that white and brown marl regoliths form a persistent crust when drying out at the surface. Whereas grey marl regoliths form an ephemeral crust, which disappeared because of shrinkage and swelling after several weeks.

Figures 6.1.6a and b show also the final soil moisture content of an experiment. The soil moisture content of the brown and grey marl regoliths was much higher than of the white marls. This means that, compared with the white marls, the brown marls can contain more...
water before a threshold for erodibility is reached (Fig. 6.1.2a to c and 6.1.5a). This supports the results from the liquid limit tests (Fig. 4.1.1). Which show that brown marl regoliths can contain more water before liquefaction occurs.

Compared with the white marl regoliths, it is likely that grey marls can contain more water before it reaches the erodibility similar to the white marls (Fig. 6.1.5b and c). However, compared with the brown marls, it seems that it reached this threshold at a lower soil moisture content than the brown marl regoliths. This does not agree with the results from the liquid limit tests, which means that in the case of the brown and grey marls the soil structure and macropores play a very important role for the difference in erodibility and consistency of the soil.

**Consistency related to field conditions**

The liquid limit index increased in the order white, brown, grey marls (Fig. 4.1.1). The difference between white and brown marl regoliths was smaller than between brown and grey
This indicates more difference in physico-chemical properties between brown and grey marls than between white and brown marls. This is reflected by the preceding soil chemical results, which have been related to soil consistency (Gerits, 1991). The C5-10-index mentioned in Table 4.1.4 showed a less clear result. The white marls on the southerly and south-westernly exposed slope showed high indices, whereas the white marls on the northerly exposed slope showed the lowest index of all materials. Brown and grey marl regoliths showed indices in between the preceding ones. The grey marls showed a higher stability of the topsoil than the brown marl regoliths. However, because the values were based on only one liquid limit curve and the difference is only 0.8 weight% this result has to be considered with great care. The most stable material appears to be the white marls on south or south-west facing slope. This is not according to the expectations of the results of de Ploey and Mücher (1981), who found a positive relationship between the liquid limit and C5-10-index in cultivated loess soils.

Differences between the liquid limit of the white marls on northerly and southerly exposed slopes were small. Nevertheless the white marl regoliths on the south-westerly exposed slope showed the lowest liquid limit index, whereas the white marls on the northerly exposed slope showed the highest index. These differences can be caused by the different aspect of the slopes, resulting in a different chemical composition of the regolith. However, differences in clay mineralogy cannot be excluded (Table 4.1.5). Considering the other horizons on the northerly exposed slope, the slightly weathered shards showed a higher liquid limit index than the above lying horizons. The subsurface material showed almost a similar liquid limit to the top layer of the regolith. The C5-10-index (Table 4.1.4) showed a clear difference between the north facing slope and the south and south-west facing slopes. The indices of the latter were higher. This could indicate a difference caused by aspect. However, differences in parent material, i.e. texture and clay mineralogy should not be excluded. Considering the differences between the horizons on the north facing slope, the C5-10-index behaved like the liquid limit. This was similar to what de Ploey and Mücher (1981) found. The subsurface material showed a smaller C5-10-index than the surface material. This could be explained by the higher stability of the crust and sub-crust compared to the brittle subsurface material.

There is concluded, from the above results, that the liquid limit and C5-10-index of the upper horizons of all badland materials show a different order of stability. However, for the determined horizon on the white marl regoliths both indices are acting parallel to each other. But the C5-10-index is a stability index for the topsoil and the liquid limit for the subsoil, which means that comparing horizons of the same profile is not according to the possibilities of these indices. The liquid limit increases in the order white, brown and grey marl regoliths. Within the white marls it is the lowest value on the south-westerly exposed slope and the highest on the northerly exposed slope. According to the data, the C5-10-index on the north facing white marl regoliths is the lowest, whereas on the south-west facing slope it is the highest. Brown and grey marls are lying in between. Because of the small differences between the indices, determined with only one liquid limit curve, it is uncertain if the differences are significant. However, it is obvious that the white marls on the south-west facing slope show the highest value. Unclear is what are the distinguishing parameters which explain the results.
of the liquid limit and C₅₋₁₀-index, either the difference in chemical soil properties caused by aspect (radiation) or the parent material, i.e. the clay mineralogy and texture.

(Macro)porosity and bulk density in relation to field conditions
Bulk density is highest for white marls and lowest for grey marl regoliths (Fig. 4.1.4). Analyses of the water retention characteristics showed an increasing sequence of saturated volumetric water content in the order white to brown to grey marls. Also the uniformity of the pore size distribution was lowest for grey marls, which means more variety in pore size (Fig. 4.1.5a to c). The amount of macropores, calculated from the water retention characteristics and bulk density increased in the sequence white to brown to grey marls (Table 4.1.6a).

Differences in dry bulk density of badland regoliths are caused by the following process. Swelling and shrinkage of badland regolith is caused by sequences of wetting and drying. When the regolith is wetted the material swells as a result of the texture and clay mineralogy and the chemical soil properties. This results in a lower dry bulk density. While drying out again the regolith shrinks but the bulk density is kept low, which means that more macropores should be available.

On the northerly exposed slope the rainfall experiments did not have any effect on the dry bulk density, whereas on the other materials the dry bulk density was lower after the rainfall (Fig. 4.1.4). This was expected according to the process described above. Possibly after some time the dry bulk density increased again, because of instability of the soil structure, by which macropores were filled up with fine regolith material.

It is obvious that the dry bulk density decreased from white to brown to grey marls. This was also corroborated by the infiltration capacity or runoff coefficient of the regolith (Table 6.1.1). Brown and grey marl regoliths showed a very low runoff coefficient compared to the white marls. However, the white marls on the south-west facing slope also showed a very low runoff coefficient. This could be explained by the high amount of macropores compared to the other sites on white marls. In soils subject to shrinkage and swelling and crust formation, macroporosity can be an important factor for infiltration.

Considering the process of decrease in dry bulk density it should be expected that the amount of macropores in the samples taken after the experiments was higher than before. This was the case in the white marl regoliths on the south-west facing slope and on the brown and grey marls. The other sites did not show much difference in volume of macropores (Table 4.1.6a).

Swelling and shrinkage capacity in relation to macroporosity
Sodic- and clay-rich soils are very vulnerable to swelling and shrinkage (Imeson et al., 1982). For the badland regoliths this was already noticed in the field, because of the large shrinkage cracks and smaller tension cracks.

Results of the SARAN test for badland regoliths are given in Figures 4.1.6b to d. The grey marls show the highest COLE-index, which means the highest shrinkage and swelling capacity. Brown marls have a lower index and white marls the lowest. This was also expected.
according to the clay mineralogy (Table 4.1.5) and the observations in the field.

This shrinkage and swelling test can also be used to quantify the swelling and shrinkage potential of a soil layer (Bronswijk and Evers-Vermeer, 1990). In that case the assumption should be made that surrounding aggregates in a soil layer do not affect the shrinkage capacity of an aggregate.

Bronswijk and Evers-Vermeer (1990) described the different shrinkage phases for clay-rich soils (Fig. 4.1.6a). In large saturated soil samples structural shrinkage takes place. This is when only large water-filled pores empty and the soil hardly changes in volume. When the large pores are empty the normal shrinkage process starts. During this phase the volume decrease of clay aggregates is equal to water loss. The aggregates remain fully saturated. When air is entering the pores of the aggregates residual shrinkage starts. At this moment water loss is greater than volume decrease. The last phase is zero shrinkage. The soil particles have reached their densest configuration and the volume of aggregates stay constant. Water loss is equal to increase of air volume in the aggregates.

The results from the shrinkage test showed that the dry bulk density of the badland regoliths changed dependent of soil moisture content (Fig. 4.1.6a to d). The lower the soil moisture content the higher is the dry bulk density. White marls showed the lowest variation in bulk density and grey marls the highest. This change in bulk density probably gave deviating results for, for example, field soil moisture content, water retention characteristic and (macro)porosity.

When calculating the volumetric soil moisture content, normally the dry bulk density is used. This was also done when determining the calibration curves for the TDR measurements. This means that in the wetter part of the curve the bulk density that was used was too high and should be lower, so that the volumetric soil moisture content in this part of the curve should be higher. Another problem can be that the used dry bulk density was too low, because of the difficulty of estimating the volume after drying the sample. The calibration curve of the TDR measurements was adapted by using the relation between gravimetric and volumetric soil moisture content of the shrinkage characteristic to find the corrected volumetric soil moisture contents related to the gravimetric soil moisture content (Fig. 4.1.7a to c). These relationships were also used to adapt water retention characteristics.

Another way to find out the importance of macroporosity was to calculate the difference between the dry bulk density of soil core samples and the saturated and dry bulk density of the soil clods used in the SARAN-test (Table 4.1.6b). The amount of macropores was higher by using this method than the preceding method, using the water retention characteristic (Table 4.1.6a). By using the data from the SARAN-test, differences were calculated between soil aggregates and soil core samples. A soil aggregate can swell more than a soil core sample, because of no surrounding soil material. This means that in this case results of macroporosity depend on scale. For the preceding method of determination of the macroporosity a fixed volume of a pF-ring was used. This is a way to avoid the differences in dry bulk density.
ERODIBILITY OF BADLAND REGOLITHS

(a) white marls northerly and southerly exposed

(b) white marls south-westerly exposed

(c) brown marls southerly exposed

(d) grey marls southerly exposed

Figure 6.1.7 Corrected calibration characteristics badland regoliths
Figure 6.1.8 Calibration characteristics badland marls of gravimetric soil moisture
Correction of soil moisture data and water retention characteristics by swelling and shrinkage

Swelling and shrinkage capacity causes dynamic bulk densities in relation to soil moisture content. For both soil moisture values measured by TDR and water retention characteristics, corrections due to these differences in bulk densities were calculated.

soil moisture contents

 Corrections of the soil moisture data, calculated with TDR were made for some measuring points in the badland regoliths, using swelling and shrinkage data described above. Field data of the white marl regoliths fell within the range of the SARAN-test. In this range swelling and shrinkage were behaving almost linear in the range 0 to 0.4 cm³/cm³ volumetric soil moisture content (Fig. 4.1.7a to c). However, the best fit is an exponential relationship for all materials, especially brown and grey marls with higher soil moisture contents. This relationship shows that a small difference in dry bulk density caused a clear difference in the apparent soil moisture content, which cannot be neglected. For south-westerly exposed white marls an exponential relationship was used, which differed slightly from the one for northerly and southerly exposed white marls, because the material behaved slightly different.

The calibration characteristic, giving a relation between travel time of the electromagnetic signal and the volumetric soil moisture content (Fig. 3.2.3), was corrected in the following way. The gravimetric soil moisture content corresponding to the volumetric soil moisture content of the calibration curve was corrected by using the above mentioned relationship between gravimetric and volumetric soil moisture content obtained from the shrink and swell test (Fig. 4.1.7a to c). The corrected characteristics between TDR travel time and volumetric soil moisture content are given in Fig. 6.1.7a to d together with the not corrected characteristic. The difference in soil moisture content for white marl regoliths was about 0.02 cm³/cm³ higher than the original data. For grey marls it was 0.2 cm³/cm³ higher and for brown marls 0.015 cm³/cm³ higher or lower.

Correction of the field data of the badland regolith had been done in a slightly different way. The calibration characteristic for the travel time was constructed with the gravimetric soil moisture data, which are independent of the bulk density of the material (Fig. 6.1.8a to d). The fitted relationship through these data had been used to determine the gravimetric soil moisture content from the measured TDR travel times in the field. For the field data of the white marls only interpolation was used by transferring field measurements with calibration characteristics. For the brown and grey marls the field measurements had to be extrapolated with the calibration characteristics because the field soil moisture data lied outside the range of the laboratory data by which the calibration characteristics had been constructed. The gravimetric soil moisture data were transferred into volumetric soil moisture data by means of the exponential relationships from Fig. 4.1.7a to c. The difference for white marls was between 0.05 and 0.02 cm³/cm³ (Fig. 6.1.9). For brown marls it ranged from 0 cm³/cm³ to 0.2 cm³/cm³ and for grey marls the maximum difference was even 0.3 cm³/cm³ (Fig. 6.1.10 and 11).

For white and grey marl regoliths the corrected data were higher than the original data. This means that by calculating the original values a lower bulk density was used. An expla-
nation is that the bulk density of the bulk sample was measured in the original volume. The bulk density of aggregates does not include macropores as in bulk samples. The conclusion is that for bulk samples the original volumetric soil moisture is the best approximation, whereas for samples without exped macropores, as aggregates, the values corrected for shrink and swell are preferable.

For brown marl regoliths the corrected data were in most cases lower. Which means that for the correction a lower bulk density was used. A physical explanation is that in this material more macropores are available in the aggregates and less macropores in between aggregates. In that case aggregates have more space to swell during a shrink and swell test than in a soil column, which explains the lower bulk density of the corrected data. This is also partly an artefact of the shrink and swell test, which leads to a similar conclusion as for white and grey marls.

water retention characteristics

The change in bulk density because of shrinkage and swelling had, as seen above, some impact on the volumetric soil moisture content and therefore on the water retention charac-
Figure 6.1.10 Soil moisture during experiment 2 on brown marls and corrected values according to shrinkage and swelling test

Figure 6.1.11 Soil moisture during experiment 1 on grey marls and corrected values according to shrinkage and swelling test
teristic. The gravimetric soil moisture contents from the laboratory samples, used for the
determination of the water retention characteristics, were transferred into volumetric soil
moisture contents by using the exponential relationships given in Figures 4.1.7a to c. The cor-
crected volumetric moisture contents are given in Fig. 6.1.12 a to c. It is obvious that for white
and brown marls (Fig. 6.1.12a and b) differences between original and corrected values were
highest between soil moisture value 0.20 cm³/cm³ and 0.35 cm³/cm³. At higher values differ-
ences became smaller. This was caused by the exponential relationship between gravimetric
and volumetric soil moisture content derived from the shrinkage and swelling test. At higher
soil moisture values a limit was reached. This is not visible in Figure 6.1.12c of grey marl
regoliths. The higher the soil moisture values the higher the differences were. In this case the
limit was not reached in the range of these soil moisture values. As the corrected TDR data,
all corrected volumetric moisture contents laid above the original data. This means that the
used dry bulk density for the original data in all cases was too low. This is explained by the
fact that the dry bulk density was used in the original volume as mentioned above. The devi-
ation became higher the wetter the soil, because of the swelling and the decrease of the bulk
density (see Fig. 4.1.6a). However, a limit was reached because of the exponential relation-
ship. This implied also a physical limit of swelling capacity, which is set by saturation of the
regolith material. The deviation in the brown marl regoliths is in this range comparable to the
one in the white marls. However, for the brown marls, the corrected values were higher than
the original values, which was contrary to the TDR data (Fig. 6.1.10). This was caused by the
higher dry bulk density used for TDR data than for water retention characteristics. A similar
problem as with the TDR data raised here. Because the pF-sample is a bulk sample, it con-
tained macropores. These macropores had not been considered in the shrinkage and
swelling test. Therefore, the corrected water retention characteristic was only valid for aggre-
gates and for bulk samples the original characteristic should be used.

6.1.3 Soil surface dynamics influenced by rainfall and soil moisture

Soil surface roughness
No significant development of roughness was seen between the measured periods. However
period 3 showed that two years after the experiments, differences of roughness between the
plots were more significant than in the first measured period. This counts for both indices
(Table 4.1.7a and b).

Crack patterns
The surface area of cracks decreased after the experiments for all materials (Table 4.1.8c).
Two years later the cracks had re-established themselves, except for the grey marls, in which
the surface area of cracks even had been more decreased.

A statistical analysis was made of the changes that had occurred in crack size and crack
density (Table 4.1.8a and b). Significant differences in crack size were recorded for the white
marls (except for the northerly exposed plot), and for the grey marls between the third and
fourth period. On the grey marls there was also a difference between the second and the third period. In the field this was seen by the crust that developed on the grey marls during drying out of the material. The large amount of rainfall during the experiments had a high impact on crust and crack formation. For the differences of crack size between the plots per period

**Figure 6.1.12** Water retention characteristics and corrections according to swelling and shrinkage test, badlands, Petrer, Spain
brown marls appeared to differ from the other materials. In the field this was seen by the extremely wide cracks and rough surface. In the period just after the experiments the white marls differed for crack width significantly as a group from the brown and grey marls as a group. This is explained by the high swelling and shrinkage capacity of the latter two regolith types, which caused the regoliths to react similarly. Two years after the experiments, brown marls differed significantly from the other regoliths. Crack width of grey marls had decreased to a similar size as for the white marls. Crack density was very variable between the periods (Table 4.1.8b). The smaller the crack space, the higher was crack density.

A significant difference was seen between measurements before and after the experiments on all south facing regoliths. Most differences have been shown for brown and grey marls. Which seem to be the most dynamic materials. For white marls no specific pattern was seen.

**Dynamics of rill patterns**

Tables 4.1.9 and 10 show results of statistical analyses of rill characteristics between the experiments. Almost no significant difference in rill width and depth had been measured between periods of experiments.

Field observations showed no clear differences in rill pattern between the periods of experiments for white and brown marls. On the grey marls, mudflow tracks were created during the rainfall simulation experiments (Photo 6.1.3a). These were only surficially visible in the field, two years later (Photo 6.1.3b).

Rill indices shown in Table 4.1.10 support change in rill pattern on grey marls. For rill index 4, the total rill surface area, a decreasing trend on brown marls was seen during the course of the experiments.

All of the rill indices, also partly described in Chapter 4.1.4 illustrate that the rill situation

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**Photo 6.1.3a** Grey marl regolith during second rainfall simulation experiment, Petrer, Spain
returns to an equilibrium stage equal to the situation before a rainfall event. This is demonstrated best by especially rill indices 1 and 2 (Table 4.1.10).

Rill indices 1 and 2 also work for the regoliths in which mass movements are important. It is obvious that in brown and grey marls less rills are present. For grey marls both indices show a return to the equilibrium stage. Rill index 3, which indicated rill volume, did not differentiate between materials (Table 4.1.10). This could mean that the materials susceptible to rill erosion have more superficial rills and less erodible material than the materials to mass movements. These, possibly, have less rills but they are much deeper. This was seen by rill index 4, which showed higher values for the white marls than the other materials (Table 4.1.10). However the values of the grey marls are comparable with the white marls. In the field was seen that the first and last value of the grey marls were caused by only one rill, which means that this rill was enlarged by the rainfall experiment and had not been restored to the original dimensions again after two years.
6.2 Erodibility of cultivated loess soils

Parameters for erosion, measured during field experiments, are presented and discussed in this chapter. The results of the field and laboratory tests have been compared with the results from the hydrological experiments of Chapter 5.2. The differences in processes related to erosion are studied and discussed for the two cultivation types, harrowed and ploughed, mentioned in Chapter 3 and 4. The processes have been related to material properties and behaviour of the material.

6.2.1 Field measurements for erosivity and erodibility

As mentioned in Chapter 6.1.3 a good indicator of field erosivity and erodibility is the sediment discharge in surface runoff. Related to the soil moisture content, it is also useful as an indicator of erosion. This is also the case for loess soil. Soil shear strength and roughness at the surface are also important field indicators of erosion. In loess, naturally occurring cracks and crack patterns are less important for erosion than in badland soils. Cultivation is an underlying cause for rill erosion. Rill patterns are useful indicators of sensitivity to erosion.

Sediment discharge

Both the sediment concentration during runoff and the total sediment yield were monitored during rainfall simulation experiments (Fig. 6.2.1 and 2 and Tables 5.2.3a and b). Relationships were studied between runoff and sediment discharge by considering sediment concentration and sediment yield.

harrowed soil

During the low intensity experiments runoff and sediment were only generated in wheel tracks. For both low intensity experiments, the total sediment yield of the B experiment was higher than the A experiment (Table 5.2.3a). In spite of the similar runoff coefficients, the total sediment yield was slightly lower during experiment 2LI than during experiment 1LI. This could be caused by the formation of a consolidated rill bed in the wheel track. During experiment B of 1LI, it seemed that this rill bed already existed, because the sediment concentration decreased and became less irregular during the experiment (Fig. 6.2.1a). During the following experiment, the sediment concentration increased again and became more irregular (Fig. 6.2.1b). The increase in runoff was rather gradual. A second sediment impulse occurred during experiment 2LIA, after the decrease in sediment concentration of experiment 1LIB.

In spite of the low runoff coefficients during the high intensity experiments, on the wheel track, compared to the low intensity experiments the total sediment yield was similar. In case of the high runoff coefficients during 2HI, the sediment yield was very high compared to 1HI. On the plot without a wheel track, the runoff coefficients were very low, but the sediment yield was similar to that for the low intensity experiments in the wheel track (Table 5.2.3a). During a third repeated high intensity experiment, the sediment concentration increased with the runoff (Fig. 6.2.1c). This indicates a linear relationship between both parameters. However, when high intensity experiments follow on from low intensity experiments, the relationship is
Figure 6.2.1 Runoff and sediment concentration during rainfall simulation experiments on harrowed loess soil
Figure 6.2.2 Runoff and sediment concentration during rainfall simulation experiments on ploughed loess soil
negative: the sediment concentration decreases with increasing runoff (Fig. 6.2.1d). During this last sequence of experiments, the total sediment yield was considerably lower than during the sequence with only high intensity experiments (Table 5.2.3b). It seems that the soil is less erosive when high intensity experiments follow on from low intensity experiments, compared to only a sequence of high intensity experiments.

ploughed soil

During low intensity experiments, runoff was only generated in a wheel track. This occurred during the second experiment (2LI) on the plot (Table 5.2.3a). Compared with the harrowed soil, the runoff coefficient was slightly lower, although the sediment yield was similar. The pattern of the sediment concentration during this experiment was very irregular and was comparable with the first low intensity experiment on harrowed soil.

High intensity rainfall caused runoff in a wheel track in the ploughed soil during two experiments with a repeated experiment (Fig. 6.2.2a and b). During the first high intensity experiment, the runoff was similar to the repeated experiment, however the sediment concentration of the latter was much higher. It seemed that the soil became more erosive after moistening. The runoff coefficient of the repeated experiment of experiment 2HI was the highest of this series, but the total sediment yield was the highest for the repeated experiment of 1HI (Table 5.2.3a). The difference between these two experiments was the rainfall intensity, which was higher for 1HI than for 2HI. This indicates a considerable impact of the rainfall intensity on the erosion of the soil. A comparison with a 1HI experiment on the harrowed soil in a wheel track showed the ploughed soil to have a higher runoff and sediment yield. It has to be noticed that the rainfall intensity for the harrowed soil was lower during this experiment, which also could be a factor explaining the low runoff.

A high intensity experiment on ploughed soil, following three low intensity experiments, produced runoff immediately (Table 5.2.3b), whereas in a series of three high intensity experiments, only the second and the third experiment gave runoff (Table 5.2.3a). The third high intensity experiment gave, after the low intensity experiments, a considerably higher sediment yield than in the series with only high intensity experiments at similar rainfall intensity. This indicates that for ploughed soil when low intensity rainfall precedes high intensity rainfall, the soil is more erodible than when high intensity rain falls immediately on a dry soil. During both high intensity experiments, there was higher runoff for the experiment 3HI (Fig. 6.2.2c and d). Sediment concentrations were similar for both experiments, which means that the total sediment yield for the last experiment, with a higher runoff, was highest (Table 5.2.3b). Another 3HI experiment after low intensity experiments showed a higher runoff and a higher sediment yield. This was possibly caused by a difference in slope.

A conclusion for the harrowed soil experiment is that after low intensity experiments, high intensity experiments are less erosive. For the ploughed soil, the opposite was concluded. This is explained by more runoff in the case of high intensity experiments that follow low intensity ones.
Figure 6.2.3 Vertical resistance before and after the experiments

Figure 6.2.4 Shear strength of the surface before and after the experiments
Soil shear strength
The vertical resistance of the soil surface, measured with a penetrometer varied considerably during the experiments (Fig. 6.2.3). In harrowed soil, the resistance increased after one low intensity experiment and decreased again during the course of the other experiments. Only after combined experiments of low and high intensity the resistance increased again. The resistance in a wheel track was higher than the other values, clearly caused by compaction of the surface layer. In ploughed soil a similar trend was seen. During the course of the experiments vertical resistance did not change significantly, except for the results after three LI experiments, which showed an increase in vertical resistance.

Soil shear strength at the surface showed an increase during the course of the experiments in both harrowed and ploughed soil (Fig. 6.2.4). Initial values of the freshly cultivated soil were zero or less. In ploughed soil, after the first high intensity experiment, the value was higher than after the first low intensity experiment. However, the final soil shear strength of the low intensity experiments had increased considerably more than the final value of the high intensity experiments. In harrowed soil the increase in soil shear strength was higher during the high intensity experiments than during the low intensity experiments. This means that in ploughed soil high intensity experiments act as less stabilising agents than low intensity experiments. In harrowed soil low intensity experiments seemed to act as less stabilising agents. The values in a wheel track did not show clear changes between low and high intensity experiments.

Soil shear strength and vertical resistance at the surface in a rill system spatially varied slightly. Only in a rill was the soil shear strength slightly lower than in the side of a rill and in interrill areas. This is explained by the condition of soil aggregates at the bottom of a rill, affected by flowing water. Vertical resistance was higher in a rill than at the other locations. This compaction was also caused by the flowing water producing an armoured streambed.

During one month in April 1994, every week soil shear strength and vertical resistance were measured at the surface on a ploughed ridge and between ridges. Between ridges soil shear strength and vertical resistance were slightly lower. This was possibly caused by a difference in soil moisture content. During the time of measurement both parameters increased considerably. This was caused by slaking of the ploughed clods because of rainfall. Drying out of the upper slaked soil increases crust formation, which causes a higher soil shear strength and vertical resistance.

Roughness of the soil surface
Changes in roughness of the soil surface can be an indicator of erosion. To measure roughness, two indicators were used, RI1 and RI2 (see Chapter 3.2.2).

Before and after every experiment, the roughness was measured at 4 places on the experimental plots (0.18m²). The average values of these measurements were used to describe changes in roughness (Fig. 6.2.5 and 6). Both indices, however especially index 1 showed a decrease during the course of 1 experiment. In most of the cases at the beginning of the next experiment the values increased again. Variation of both indices was highest dur-
Figure 6.2.5 Roughness index 1 during rainfall simulation experiments in loess

Figure 6.2.6 Roughness index 2 during rainfall simulation experiments in loess
CHAPTER 6.2

(a) index 1

![Image of roughness index 1 graph]

(b) index 2

![Image of roughness index 2 graph]

Figure 6.2.7 Roughness index 1 and 2 in ploughed loess, Wijnandsrade

In low intensity experiments. Differences in variation were highest for index 2. In Figure 6.2.6a and b was seen that height differences were disturbed less by low intensity experiments than by high intensity experiments. Both index 1 and 2 varied more in ploughed soil than in harrowed soil. It seemed that finally rainfall had more impact on the subsidence of a ploughed than of a harrowed surface.

From measurements during one month on a ploughed loess soil, no clear changes in roughness were measured in time. Spatial differences were found between measurements on a ploughed ridge and in between a ridge (Figure 6.2.7a and b). In between a ridge the surface roughness was less. This was probably caused by water flowing into the depression and consequently the development of a flat streambed, when water started to flow.

Roughness measurements in a rill system (Catsop) were carried out at three different locations in an interrill area. These locations showed too much variation.
6.2.2 Discussion

Sediment discharge in relation to soil moisture conditions
When soil aggregates are saturated with water they become less stable. The soil consistency decreases with increasing soil moisture content. A lower consistency results in a higher susceptibility to dispersion and entrainment of the soil particles by flowing water. Therefore the relationship between sediment discharge and soil moisture content in harrowed and ploughed soil profiles was studied.

harrowed soil
The second low intensity experiment on the harrowed soil in a wheel track showed a slightly lower sediment yield than the first experiment, in spite of similar runoff coefficients (Table 5.2.3a). The volumetric soil moisture content of 2LB was higher in the surface layer, which could indicate a consolidated soil surface with a low permeability (Fig. 5.2.3b). A consequent process could be that the surface layer of the streambed will become saturated. By loss of cohesion because of saturation, soil particles will be entrained by runoff. Therefore, sediment concentration will increase again.

The sediment yield of the second high intensity experiment and its repeated experiment on a wheel track was much higher than of the second low intensity experiment, in spite of a similar runoff coefficient (Table 5.2.3a). The soil moisture profile of the high intensity experiment was similar to the lower intensity experiment (Fig. 5.2.3b). In this case, possibly a combination of the energy of the high intensity rainfall and soil moisture content caused increase of sediment detachment.

In case of high intensity experiments after low intensity experiments on a harrowed plot without a wheel track some of the B experiments showed a higher runoff coefficient than the A experiments (Table 5.2.3b). Only in one case this higher runoff coefficient resulted in a higher total sediment yield. In all high intensity experiments, the B experiment suggested more saturation of the profile than the A experiment (Fig. 6.2.8a and Fig. 6.2.9a). The expectation would be that B experiments showed more erosion and thus had a higher sediment yield than A experiments. This was not obvious according to the results for the harrowed profile (Table 5.2.3b).

After only three high intensity experiments the upper part of the profile had a higher soil moisture content than after one high intensity experiment (Fig. 5.2.3a and Fig. 6.2.10). This could indicate a higher erodibility of the soil, when enough runoff was generated. However this is only supported by the B experiment of the second high intensity experiment, which caused a high total sediment yield, despite the low runoff coefficient (Table 5.2.3a).

According to the above results the soil seemed to be less erosive when high intensity experiments followed after low intensity experiments. The soil moisture content at the surface after low and high intensity experiments was slightly lower than after only high intensity experiments. This could result in a higher susceptibility to erosion for the high intensity experiments without preceding low intensity experiments (de Ploey and Mücher, 1981).
ploughed soil

Also in the ploughed soil, only low intensity experiments on a wheel track gave runoff and therefore erosion (Table 5.2.3a). It seemed that with a lower runoff coefficient in the ploughed soil, a similar sediment yield was reached as in the harrowed soil. The soil moisture content after two low intensity experiments on a wheel track in ploughed soil was lower than in harrowed soil (Fig. 5.2.3b). This shows that even at lower soil moisture the ploughed soil is more erodible, which indicates a lower stability of the ploughed soil.

The soil moisture after two high intensity experiments on a wheel track was also somewhat lower than in the harrowed field (Fig. 5.2.3b). This indicated more runoff in the ploughed soil and possibly an armoured channel caused by the high rainfall intensity (Photo 6.2.1 and 6.2.2). In Table 5.2.3a is seen that high intensity rainfall on a wheeltrack in ploughed soil had a higher runoff coefficient than on harrowed soil.

Figure 6.2.8a Soil water pressure during high intensity rainfall simulation experiments on harrowed soil

ploughed soil

Also in the ploughed soil, only low intensity experiments on a wheel track gave runoff and therefore erosion (Table 5.2.3a). It seemed that with a lower runoff coefficient in the ploughed soil, a similar sediment yield was reached as in the harrowed soil. The soil moisture content after two low intensity experiments on a wheel track in ploughed soil was lower than in harrowed soil (Fig. 5.2.3b). This shows that even at lower soil moisture the ploughed soil is more erodible, which indicates a lower stability of the ploughed soil.

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On plots without a wheel track, the sediment yield was higher during high intensity experiments that followed low intensity experiments (Table 5.2.3b). Only high intensity experiments gave a lower sediment yield (Table 5.2.3a). The third high intensity experiment after low intensity experiments showed a reasonably high sediment yield (Table 5.2.3b). Both repeated experiments of 3HI (Fig. 6.2.8b) showed higher pressure heads and more saturation of the soil profile than the preceding experiments, which could indicate a lower consistency and a more erodible soil (Fig. 6.2.9b and c). Comparing both soil moisture profiles of only three high intensity experiments and three high intensity experiments preceded by three low intensity experiments, it is obvious that the upper part of the latter profile showed a higher soil moisture content (Fig. 5.2.3a and Fig. 6.2.10). This indicates also a lower consistency and more susceptibility to erosion.

**Figure 6.2.8b** Soil water pressure during high intensity rainfall simulation experiments on ploughed soil
Figure 6.2.9 Runoff, sediment concentration and soil water pressure during rainfall simulation experiments
Soil shear strength in relation to consistency and aggregate stability

Important processes influencing the response of loess soil to wetting are slaking, welding (Kwaad and Mücher, 1994) and dispersion of the soil aggregates. This response depends on the physical, chemical and mineralogical soil properties. These properties cause on a higher level physico-chemical soil processes, which are related to slaking, welding and dispersion.

The consistency index A (Fig. 4.2.6a) showed a decrease in value during low intensity experiments. This decrease was more in harrowed soil than in ploughed soil. Relating these values to soil shear strength implies that higher soil shear strength does not mean a higher

Photo 6.2.1 Soil surface after a sequence of 2 high intensity experiments on harrowed soil, Wijnandsrade, The Netherlands

Photo 6.2.2 Soil surface after a sequence of 2 high intensity experiments on ploughed soil, Wijnandsrade, The Netherlands
consistency (Fig. 6.2.4). The amount of waterstable aggregates showed smaller aggregates after three low intensity experiments in ploughed soil than in harrowed soil (Fig. 4.2.4). This means that higher soil shear strength is associated with smaller aggregates.

The vertical resistance of the soil surface was thought to be an indicator for compaction of the surface layer. When relating these data to the aggregate size data in Fig. 4.2.4, it seemed that more compaction in the ploughed soil was associated with smaller aggregates in the surface layer (Fig. 6.2.3). More compaction in ploughed soil was consistent with a decrease in the consistency index A. For harrowed soil, no such relation was found (Fig. 4.2.6).

The mechanism of slaking of the clods was studied in relation to the infiltration and erodibility of the soil (Table 6.2.1). It was expected that because of the slaking of the clod exteriors during high intensity rainfall, water would not infiltrate into it quickly. However, erodibility of the soil would become higher because of slaking. Especially in ploughed soils the exteriors of big clods formed by ploughing, with artificial fractions, are very vulnerable to slaking. Erodibility would also become higher if clods were saturated, so for example a combination of wetting at the in- and exterior and in- and external slaking of the clod. In Table 6.2.1 it is seen that the prevailing class for wetness of the big clods in ploughed soil for the first high intensity experiment was 1 (only wet at the outside). This was not the case in harrowed soil. It means that more water had infiltrated into the bigger clods of the harrowed soil than in the ploughed soil. Relating these data to slaking (Table 6.2.1), it was seen that in both, harrowed and ploughed soils, the big clods had slaked surfaces, but that there was no evidence of internal slaking. Low intensity experiments followed by high intensity experiments showed wetting of the clod at in- and exteriors, however only slaking at the exterior. This was for both the bigger and smaller clods.

Relating these data to soil shear strength, no specific relationships were found. In general it appears that with complete wetting and slaking of the clods, soil shear strength becomes
higher (Fig. 6.2.4, Table 6.2.1). A higher vertical resistance with more compaction would be expected to equate with more slaking and less infiltration (Fig. 6.2.3, Table 6.2.1). In the case of the harrowed soil this happened with respect to the slaking of the big clods. In the case of the ploughed soil, the soil moisture decreased while vertical resistance became higher. The slightly lower shear strength in the ploughed soil after 3LI and 3HI experiments than in harrowed soil, agrees with higher sediment discharge from the ploughed soil. This result could not be explained by the wetting or slaking of the clods. Vertical resistance showed a similar result, which meant that the compaction of the ploughed soil is lower than that for the harrowed soil. However, in the case of higher runoff, as is the case in ploughed soil, compaction could be increased. This could mean that vertical resistance also has another interpretation and is not solely a good indicator of erodibility.

### Soil surface dynamics in relation to runoff

Relationships between erodibility and roughness at the soil surface showed that on a rougher wheel track surface of ploughed soil during low intensity experiments less runoff was produced (Table 5.2.3a). However, the sediment yield was similar to the harrowed soil. During the course of the experiments with only high intensity on the wheel track, or low followed by high intensity, more runoff and sediment was generated than in harrowed soil. This agrees with more subsidence of the surface in case of ploughed soil as mentioned before in this chapter. This means that more runoff and more sediment yield can be caused by subsidence and flattening of the surface. However, subsidence of the surface could also be caused by the higher erosion rate during high intensity experiments on ploughed soil.

### Table 6.2.1 Moistness and slaking of clods after rainfall simulation experiments

<table>
<thead>
<tr>
<th>cultivation</th>
<th>type of clods</th>
<th>experiment</th>
<th>1LIB</th>
<th>2LIB</th>
<th>3LIB</th>
<th>1HIB</th>
<th>2HIB</th>
<th>3HIB</th>
<th>3LIB+</th>
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<td>harrowed</td>
<td>1</td>
<td>3</td>
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<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
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<td>3</td>
<td>1</td>
<td>1</td>
<td>3</td>
<td>3</td>
<td>3</td>
<td>3</td>
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</tr>
<tr>
<td>small clods</td>
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<tr>
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<td>3</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td>1</td>
<td>3</td>
<td></td>
</tr>
</tbody>
</table>

0 = not available  
1 = external  
2 = internal  
3 = external and internal
CHAPTER 6.2

Correction of soil moisture data for swelling and shrinkage

Swelling and shrinkage capacity of loess influences soil moisture and water retention data. To correct these data the relationship between gravimetric and volumetric soil moisture content, derived from the shrinkage and swelling test, was used (see Chapter 4.1.3 and 3.2.3):

\[
y = a \left(1 - e^{-bx}\right)
\]

(6.2.1)

in which

\(x\) = gravimetric soil moisture content (g/g)
\(y\) = volumetric soil moisture content (cm³/cm³)

For ploughed and harrowed soil and the various horizons Ap1, Ap2 and Bt, different values were used for a and b.

measurements with TDR

New TDR calibration characteristics were calculated, by using equation 6.2.1, for the improvement of the soil moisture data for both field and laboratory measurements (Fig. 6.2.11). For the translation of the measured travel time by TDR, the relationship found by Topp was used for the not corrected soil moisture data in Chapter 5.2.2 and 5.2.3. The corrected calibration characteristics show a deviation from the Topp curve for most of the horizons (Fig. 6.2.11). For measurement and calculation of the hydraulic conductivity the calibration characteristics of uncultivated Ap1 and Bt were used:

\[
y = a + bx
\]

(6.2.2)

in which

\(x\) = refraction index \(n_a\)
\(y\) = volumetric soil moisture content (cm³/cm³)

with parameters for:
uncultivated Ap1: \(a=-0.181, b=0.130\) and for
harrowed Bt: \(a=-0.167, b=0.118\)

For measurement of the field soil moisture content the characteristic of ploughed Ap1 was used with: \(a=-0.17\) and \(b=0.145\).

No important differences have been detected between the original and the corrected data of the hydraulic conductivity (Fig. 6.2.12).

The field measurements of soil moisture content in a rill system gave an increase, caused by use of the improved calibration characteristic (Fig. 6.2.13). Only the absolute soil moisture contents have changed, whereas the relative differences have increased slightly.

water retention characteristics

Water retention characteristics also have been corrected similarly to TDR data (Fig. 6.2.14a
to c). It was clear for the Ap that the higher the soil moisture contents, the more the differences between the corrected and uncorrected data became. This reflects probably the different shrinkage stages mentioned in the preceding chapter (Fig. 4.1.6a). According to Fig. 6.2.14a and b, the bulk density of the corrected water retention characteristic was higher than the original. This means that during the drying period the clod of the shrinkage test showed a higher bulk density than the pF-sample. At lower soil moisture content bulk density was less important and therefore soil moisture values were almost equal. The bulk density of the pF-sample was lower, because of macropores in the sample. Bulk density determined with the shrinkage test only concerned micropores and smaller internal macropores.

The corrected water retention characteristic of the Bt-horizon showed a lower bulk density at high soil moisture content (Fig. 6.2.14c). The drier the soil clod, the higher bulk density and finally in the driest part, bulk density was higher than the original characteristic. This means that the bulk density of the original characteristic is an intermediate value. The differences show that macropores are not available in the Bt-horizon.

It is obvious that especially for the Ap-horizon scale is an important problem for bulk density and soil moisture. Bulk density of only soil clods was obviously too high, whereas bulk density of a larger pF-sample was too low. Use of bulk density depends on the scale of the process. In case of the water retention characteristic the original bulk density satisfied.

corrections to the macropore data

The values calculated for macroporosity in Table 4.2.6 can be re-evaluated with the results of the shrinkage and swelling test (see Table 6.2.2). Dry bulk density and bulk density at saturation calculated by the swelling and shrinkage test were used to calculate the relative amount of macropores. This was probably a better estimation of the macro-pore volume than the method used in chapter 4. The difference between the dry bulk density determined with
pF-rings and the above mentioned dry bulk density values of the shrinkage and swelling test was used to show the dynamics in macropores. The spatial and temporal dynamics of macropore volume are shown in Table 6.2.2 in dry conditions and during saturation. The values of macroporosity in Table 6.2.2 were of a similar order as those in Table 4.2.6a and b. The only difference is that under both, dry and saturated conditions the absolute amount of macropores was higher. It is clear that under dry conditions, the volume of macropores was higher than under wet conditions. This emphasises the possibility of macro-pore flow under initially dry conditions. Differences in macropores were obvious between the Ap and Bt-horizon (Table 6.2.2). This last horizon showed few macropores. This was also corroborated by the water retention characteristic.

For all horizons, the dry bulk density determined with the shrinkage and swelling test was higher than the range of values of the bulk density determined from the pF-rings. This is explained by two facts. The calculation of the dry bulk density in a pF-ring was made without taking shrinkage into account. This meant that macropores were included as part of the volume, which resulted in a lower bulk density. The determination of the volumetric change was measured for a soil aggregate that had a smaller volume than the pF-ring and in which dynamic macropores could not be formed. It is shown in Table 6.2.2 that even under saturated conditions macropores were available, which probably governed preferential flow.

**concluding remarks: corrections for swelling and shrinkage**

In almost all cases the correction of the soil moisture values with shrinkage and swelling test data, resulted in an increase in soil moisture contents. This was caused in the first place by the scale problem. The soil sample in the pF-ring contained macropores, whereas the aggregate used for volumetric change was not able to create macropores. This resulted in a higher bulk density for the volumetric change test and thus, for a too high bulk density, when bulk
samples were considered. The improved water retention characteristics were valid for aggregates, in which no macropores occurred. This was also the case for the soil water contents measured with the TDR. The original water contents were used in cases where bulk samples were taken.

Probably a better way to estimate the volume of macropores was by calculating the difference between the bulk density measured in a pF-ring and that measured in a soil aggregate. In this case the volume of macropores under dry conditions was estimated. In case of the calculation of macropores by using the difference between measured bulk density in a pF-ring and the estimated bulk density from the water retention characteristic (the method used in Chapter 4.2), many macropores had already disappeared because of swelling of the material.

6.2.3 Erosional balance in soils susceptible to rill erosion

Erodibility and erosion processes in cultivated loess soils have been analysed in this chapter. A summary of results is shown in Figure 6.2.15a and b. Already mentioned in the preceding chapters is that in the ploughed soil, during high intensity experiments in a wheeltrack more runoff was generated than in harrowed soil. This counts also for high intensity experiments after low intensity experiments. For this last experiment also soil moisture content and sediment yield were higher for ploughed soil. This could indicate a decrease in soil consistency, because of high soil moisture content in ploughed soil. This was not corroborated by the soil consistency data. Soil shear strength in the field was, for ploughed soil during this experiment, slightly lower than for harrowed soil. Low intensity experiments in a wheel track, however, showed more runoff in harrowed field, but not more sediment yield. Results from aggregate stability tests showed that after low intensity experiments waterstable aggregates in ploughed
Figure 6.2.14 Water retention data for harrowed loess soil, from original and corrected data
soil were smaller than in harrowed soil (Chapter 4.2.3). Roughness at the surface was higher in ploughed soil than in harrowed soil. Decrease of roughness during experiments occurred more in case of the ploughed soil.

Measurements in a rill system showed slightly lower soil shear strength in the rill bottom than in interrill areas, which indicated a higher susceptibility for erosion in a rill bed.

From the results was concluded that ploughed loess soil is more susceptible to erosion, especially when high intensity rainfall follows low intensity rainfall. Rainfall has more impact on decrease of roughness at the surface in ploughed than in harrowed soil. Combined with higher soil moisture content of the upper part of a profile in ploughed soil this could be a favourable condition for rill erosion.
Figure 6.2.15a Hydrological and erosion parameters of rainfall simulation experiments on harrowed loess soil
Figure 6.2.15b Hydrological and erosion parameters of rainfall simulation experiments on ploughed loess soil
Part III

Synthesis; Erodibility and hydrological response of soils susceptible to rill erosion
The role of dynamic soil properties for the initiation and development of rill erosion

Introduction

In the preceding chapters erosion processes in badlands and agricultural loess soils were studied experimentally in relation to dynamic soil properties, infiltration and drainage. In this part of the thesis, results from the preceding chapters are discussed and evaluated. They are compared with theoretical considerations. Relevant research questions and hypotheses related to the integration of hydrological and erosion processes are evaluated. One question concerns easy to measure field or laboratory parameters that indicate susceptibility to rill erosion. Other relevant research questions relate to how runoff and infiltration processes affect soil erodibility. They are mentioned and considered for both study areas in the separate chapters. These and other research questions and the hypotheses posed in Chapter 1 are further discussed in Chapter 8.
7.1 Response of dynamic soil properties on rainfall and slope water in badlands


In this chapter results from rainfall and infiltration experiments and soil erodibility analyses are integrated to examine in more detail, runoff and sediment production mechanisms on badland regolith materials, characterised by various processes. The following research questions are relevant for these processes in badland:

1. Does crack flow and saturation above an impermeable rock layer occur during and after rainfall?
2. Does slaking and liquefaction of weathered shards occur in a badland area during rainfall and does this contribute to rill initiation and development?
3. How does the drainage pattern develop during and after rainfall in both badland areas affected by rills and mass movements?
4. Which field and laboratory parameters are good indicators for rill erosion and mass movements?

Soil water movement and infiltration are related to research questions 1 and 3. Question 2 is whether slaking and liquefaction of weathered shards occur in a badland area during rainfall and whether this contributes to rill initiation and development. To study research questions 1 and 2 the interaction of sediment discharge, soil moisture, runoff and chemical soil properties has been considered (Bouma and Imeson, 2000).

From earlier research on badlands in Granada Province, Spain (Gerits et al., 1987; Imeson and Verstraten, 1988), it was found that badlands having different morphological and sedimentological characteristics were affected differently by rill erosion and mass wasting processes. Badland regolith types can be divided in two main types, when considering erosion processes, i.e. biancana and calanchi-like badlands. It was often found that in cohesive soil on biancana-like slopes (Alexander, 1982; Soriano et al., 1992; Torri et al., 1994; Calzolari and Ungaro, 1998), mass wasting was so prevalent that proto-rill systems were limited to the larger topographic depressions. On the more calanchi-like slopes (Alexander, 1982; Soriano et al., 1992) parallel rills were commonly present. These differences in the dominant geomorphological processes were, amongst other things, coincident with differences in a number of material properties that were indicative of clay dispersion, swelling and slaking. For example, the liquid limit was higher on the calanchi-like slopes and the macroporosity higher on biancana.

In the following discussion of the experimental results, it is, in general, shown that soil moisture is an indication for erodibility and after a crust has been formed, this crust is a dominant regulation factor for infiltration, runoff and erosion. In the field was observed that on an experimental slope, rills developed after the removal of the regolith. An equilibrium state was reached after two years, when the rill pattern shows the original pattern again. The rill indices showed that the marl regoliths susceptible to rill erosion had more superficial rills and less erodible material than the marls susceptible to mass movement. This was also seen in the
field as frequent shallow rills in white marls and a few deep rills in brown marl regoliths.

To make the process of rill initiation more clear, the results of this study were applied to underpin the selection of indicators. Indicators are needed firstly because of the complexity of the processes on badland slopes, which makes them so difficult to measure and model, and secondly to obtain spatially referenced data that are needed for both modelling and management.

7.1.1 Infiltration in badlands eroded by rill erosion and mass movements

Badlands dominated by rill erosion

On all badland sites dominated by rill erosion, white marl regoliths, northerly, southerly and south-westerly exposed, the upper part of the regolith became saturated during the rainfall simulation experiments. The wetting front was very variable in depth, which indicated an important influence of macropore flow. However, the data did not demonstrate that a saturated layer developed near the bedrock contact, as was expected according to the drainage model. The saturation of the upper layer of the soil means that the driving force for subsurface flow is gravity.

The soil moisture pattern is very irregular around the rill systems. Cracks and macropores clearly have an important influence on infiltration. In the white marls the maximum increase in volumetric soil moisture content was 0.25 m³/m³. In the brown and grey marls this was 0.5 m³/m³ or more. Except for the north facing slope, rills cannot be considered as separate systems in which only water is transported. Especially beneath rills, as under cracks, water infiltrated as macropore flow resulting in a deep infiltration front. For the soil matrix, the actual infiltration front was much deeper than the calculated infiltration front, which could be caused by macropore or crackflow.

Usually, on the white marl regoliths the infiltration rate is constant, if only infiltration through the soil matrix occurs. After ponding of the rainfall at the surface, a sudden increase of infiltration rate takes place because of crack flow. Then, the pattern of the infiltration process in white marls becomes very variable. Soil matrix infiltration and crack flow both occur at the same time. The variability in increase of soil moisture content is similar for the points in all slope units (rill, interrill and rill side). In rills less water has been infiltrated compared to the surrounding points. The effect of hysteresis of the soil water retention curves is highest in the white marls. This is probably caused by the specific regolith properties and pore geometry. However, measurement deviations of soil water content due to the progress of the infiltration front probably cause part of the hysteresis problem.

Relatively more runoff was generated on the sites dominated by rill erosion compared to the sites dominated by mass movements. This indicates more surface drainage on rill-eroded sites. Overland flow on semi-arid sandy soils with a spatially variable soil moisture content was studied by Fitzjohn et al. (1998). They showed that initially relatively dry isolated soil patches generated more discontinuous overland flow than relatively wet soil. Probably rill erosion contributes to the connection of isolated patches and therefore for more runoff. However, subsurface drainage and infiltration happen to be more important on dry surfaces than on wet, partly dried, crusted surfaces. In most cases on the lower part of the slope more water infiltrated than on the higher part of the slope. During the second experimental run, cumulative runoff was higher on all aspects. Runoff started after the cracks start closing. However, the
infiltration profile showed deep infiltration around cracks. This is probably explained by the partial closing of the cracks or sealing of the surface. The widest cracks and very deep rills stayed open, allowing overland flow to infiltrate, probably enhancing pipe erosion (Farifteh and Soeters, 1999). The difference in size of cracks and crack density between the north facing and south and south-west facing slopes dominated by rill erosion caused a difference in runoff coefficient. On the south facing slopes, shrinkage and swelling of the regolith caused wider cracks and a higher crack density than on the north facing slope, because of the high variations in temperature and therefore in soil moisture content. The runoff coefficients on south facing slopes are lower than on the north facing slope because of the higher infiltration capacity, caused by the size of cracks and crack density.

The role of macropores for infiltration of slope water and rainfall is seen by differences between calculations of the depth of the infiltration front and measured depth of infiltration front. Philip's model calculated an infiltration front of 1-3cm after rainfall of 45 minutes (30mm/hr), based on sorptivity and cumulative infiltration. However, the measured infiltration front of infiltrated water after an event of 45 minutes varied from 5 to 10 cm. This means that another mechanism than only the soil matrix is responsible for infiltration, which is probably bypass-flow through macropores.

Badlands dominated by mass wasting

On the badland slopes that are dominated by mass wasting, i.e. south facing brown and grey marl regoliths an infiltration regime, different from the white marls, has been observed. High variety in soil moisture content is obvious in the brown marls. During the first rainfall experiments, in the rill bottom a considerable increase in pressure head was seen. During the second experiment the pressure head in the part of the rill lower on the slope increased to almost saturation, however in the upper part, the pressure head remained constant. Two points on the mass movement surface beneath each other show a similar wetting pattern, which increased to saturation within 20 minutes after the start of the experiment (42mm/hr). During both experiments in the grey marls saturation was reached. The higher points on the slope responded sooner to the rainfall than the lower ones, with exception of the lower points on the slope in the rill bottom, which reacted similarly as the higher points. It seems that subsurface water from the slope is less important in the grey than in the brown marls and probably the white marls. In the rills of the grey marl regoliths surface flow seems to be more important.

Field soil moisture content varied from 0.0 to 0.5 cm$^3$/cm$^3$ for brown marls and less for grey marl regolith. During the experiments a variable wetting pattern was seen in the surface layer. Material dominated by mass movements shows various types of wetting front. Brown marls, which develop wider cracks at the surface, are dominated by subsurface flow. Soil moisture content was very variable in the upper 10cm. However, in the grey marls the infiltration front was more homogeneous. This indicates less importance of macropore flow in this regolith. The spatial pattern of grey marls shows evidence for more infiltration in a rill than in the surrounding surface material. Runoff from wet surfaces is comparable to the sites dominated by rill erosion. In brown marls on the lower part of the plot, the soil moisture content increased more during the experiments. Flow lines converge in this part of the slope, which indicates possible subsurface flow and therefore increase of soil moisture content. For grey marls soil moisture content increased more during the experiments on the upper part of the slope.
These last results show that subsurface flow is more obvious in brown marls than in grey marls. In grey marls slope water infiltrates in the upper part of the slope and percolates towards the lower part of the slope and is discharged as runoff. Kuhn and Yair (2004) found this process in the Zin Valley Badlands in Israel also on sites with a high rill density during low intensity rainfall.

The infiltration rate of brown and grey marls was higher than those of the white marls. The infiltration process in these regoliths was less dependent of the position of the measuring points, e.g. in a rill or in an interrill area, than in the white marls. During the entire experiments the infiltration rate in brown and grey marls was kept high. In brown marls infiltration in a rill was slightly less than at the surrounding points, especially during the second experiment. In grey marls more water infiltrated in the rill bottom than in the interrill area. Flerchinger et al. (1998) show that in case of limited water supply a heterogeneous approach of the watershed addresses more adequately the variability in water balance.

In brown and grey marls hysteresis of the soil water content was not evident, though it was expected especially in these swelling and shrinking soils, due to their specific pore geometry. In the grey marl regoliths, there was even found an opposite effect of hysteresis, probably because of the extremely high swelling capacity of the soil.

Runoff coefficients show that on brown marls even with very high rainfall intensities (42mm/hr) infiltration capacity was still high. On grey marls it was even higher. However, after sealing of the surface, the runoff coefficient on grey marls during another experiment was considerably higher than on the brown marls, even at a lower rainfall intensity (20mm/hr).

Infiltration on brown marls is less dependent of sealing of the surface than on grey marls and white marls. High shrinkage and swelling capacity with very wide cracks is the cause of this process. Grey marls show the most dependency of sealing because of the high shrinkage and swelling capacity and sensitivity to sealing of the smectitic clay minerals.

Infiltration in brown and grey marls depends, like in the white marls, on cracks and macropores. This is supported by the analysis with the Philip’s equation reported in Chapter 5.1.6. Differences between field observations of soil moisture profiles and calculated soil moisture profiles prove the importance of preferential crack flow in these badland materials.

7.1.2 Erodibility of badlands eroded by rill erosion and mass movements
Slaking and liquefaction of weathered shards in a badland area is postulated as being a major factor in rill initiation and development. Research question 2 was approached by studying dynamic regolith properties, such as the liquid limit, C<sub>5-10</sub>-index, shear strength and vertical resistance. These properties are influenced by rainfall, runoff and soil moisture conditions. It was found that the liquid limit of white marl regoliths, showing rill erosion is lower than of brown and grey regoliths showing mass movements. The C<sub>5-10</sub>-index was mostly higher. For the white marls the dry soil shear strength was higher than for the grey marls. Under wet conditions, the soil shear strength of white and brown marls was similar and higher than for grey marls. However, the soil moisture content of the brown marls was found to be higher than for the white marls. This corroborates the higher liquid limit of the brown marls. Vertical resistance resembled soil shear strength.

The electrical conductivity and the Sodium Adsorption Ratio (SARp) show a difference between grey marls at one side and white and brown marls at the other side. Grey marls show extremely low SARp- and EC-values. In brown marl regolith chemical fractionation caused
aggregate fractionation, whereas in grey marls texture this was caused by clay mineralogy and texture. The surface layer of grey marls and the layer under the subsurface layer in brown marls had a very high content of aggregates smaller than 2mm. The material in these regolith layers was not very consistent and therefore less stable and more susceptible to erosion. For grey and brown marls a threshold was exceeded and mass movement was the dominant erosion process.

The shrinkage and swelling capacity is a result of texture, clay mineralogy and soil chemistry. The white marls, in which most rill erosion occur, have a lower shrinkage and swelling capacity than the brown and grey marls in which mass movements are prevalent. This is caused by the high amounts of smectite in grey marls and in brown marls by the high amounts of smectite and high SARp values (Yong and Warkentin, 1975; Imeson et al., 1982).

Corrections for dry bulk density and soil moisture content were made because of shrinkage and swelling tests. However, this was not relevant in all cases. For example soil moisture contents became too high because of the scale differences between shrinkage and swelling of a soil aggregate and of a bulk soil. As a result from the shrinkage and swelling, macroporosity in white marls was lower than in the mass movement areas, i.e. brown and grey marl regoliths. In these areas macroporosity of grey marls was higher than of brown marls.

Sediment discharge from white marls already stabilised after ca. 5 minutes of runoff. This was also the case for the grey marls when a crust had been formed. Sediment concentration from experiments on brown marls was higher than on white marls and lower than on grey marls without a surface crust; it started rather high and decreased towards the end of the experiments.

The interactions between sediment discharge, soil moisture, runoff and chemical soil properties have to be considered in order to study research questions (1) and (2) (Bouma and Imeson, 2000). On the white marl regoliths sediment concentration and soil moisture content are not likely to be correlated positively. Soil moisture content increased slowly while sediment concentration started with high peaks and stabilised during the experiment. The top layer of the regolith was water saturated after ca. 10 minutes. Differences between EC25 and SARp of the runoff were high compared to the other regoliths, which indicated highly dispersive conditions in the white marls. According to the results of the sediment concentrations the white marls are considered less dispersive than the brown marls. This is on the contrary to the EC25 and SARp values of both materials (Bouma and Imeson, 2000). Soil moisture content and soil shear strength as a measure of erodibility show that white marls can exceed erodibility thresholds at lower soil moisture content than materials susceptible to mass movements. Compaction and slaking of the surface layer is more relevant for white marls than for the other materials.

Infiltration in brown marl regoliths is quicker than in white marls. However, after the formation of a crust, infiltration is similar to the white marls. Sediment concentration and discharge show that more erosion takes place. Soil moisture contents are higher than in the white marls. Differences in SARp and EC25 of the runoff are equal or slightly smaller than of the white marls. Consequently, chemical properties are not the only explaining factors. A combination of soil moisture content, clay mineralogy and chemical properties explain better the behaviour of the brown marl regolith.

On grey marls it is even more obvious that the electrical conductivity and the SARp do not explain the high sediment yield. After formation of a crust the behaviour of sediment concen-
tration and runoff is similar to the white marls. Soil moisture contents during the first experiment increases more than in the other materials. In general it is shown that soil moisture content is an indication for erodibility and after a crust has been formed, this crust is a dominant factor for infiltration, runoff and erosion.

From the surface characteristics it is concluded that only small differences in surface conditions, like roughness, crack size and amount of rills, occur after a big event, on badland slopes. These differences disappear after 2 or 3 months. In the field was seen that after a rainfall simulation experiment on an experimental slope from which the weathered regolith was removed, a weathered layer similar to the removed one developed during the following year. White and brown marls on the southerly exposed slope have a higher roughness than the other sites. Brown marls show significant different maximum heights from the other materials. Analyses of the crack pattern show that after an experiment a development of a crack pattern was observed. Brown marl regoliths obviously contain the highest surface area of cracks. Statistical analyses show that brown and grey marls seem to react similar concerning the crack pattern. This could be explained by the mass movement process, which is the main erosion process in these materials. Crack density is caused by the soil properties and also by aspect and slope degree.

As mentioned earlier in this chapter, in the field was seen that on unweathered shards rills were formed by a rainfall simulation experiment. After two years an equilibrium state was reached, when the slope showed its original rill pattern again. The rill indices show that the marls susceptible to rill erosion have more superficial rills and less erodible material than the marls susceptible to mass movement. This was also seen in the field as frequent shallow rills in white marls and a few deep rills in brown marls.

7.1.3 Indicators for soils susceptible to either rill erosion or mass movements

An ideal indicator is a parameter or variable that is easy to measure and which summarises in shorthand the effects of complex processes that are more difficult to measure or observe (Landres, 1992; Harris et al., 1996). In this section the research question about finding indicators for erosion processes is studied. Several studies on badlands have demonstrated that erosion is a physico-chemically controlled process (Bryan et al., 1978; Hodges and Brian, 1982). Other researchers have emphasised the importance of swelling and shrinkage (Calvo et al., 1991). Both physical entrainment and swelling thresholds are affected by the chemical composition of the soil water. Measuring the relevant chemical and mineralogical and soil physical parameters is extremely laborious and it is too expensive in this way to study many samples.

Indicators were considered at two levels (Figure 7.1.1). At the first level erodibility was seen as an indicator for different process domains, either rill erosion or mass movement. The relationship between soil moisture change (soil moisture content and pressure head) and sediment concentration behaviour indicates the erodibility at this level. Indicators that give information about the dependency of different process assemblages for the above relationship are soil behavioural and soil chemical properties. The indicators obtained at the second level were (1) surface sealing and (2) sudden increase of runoff which reflect complicated assemblages of processes; (3) soil consistency which is a dynamic soil property that is indicative of the stability and therefore erodibility of the material; (4) macroporosity, reflecting a complex of chemical soil properties, clay mineralogy and micro climatic conditions, which influ-
ences the hydrological situation; (5) chemical soil properties and (6) clay mineralogy and texture greatly influencing the above phenomena.

The soil behavioural parameters thought to be indicative for regolith erodibility are the macro pore content, the shear strength and vertical resistance of the soil surface, the C_{5-10}\text{-index} and the liquid limit. Indicators that are related to chemical and mineralogical soil properties in these regoliths are pH, EC_{25}, content of calcite, gypsum and organic C and composition of the clay fraction.

In the white marls eroded by rill erosion, the upper 5cm of the regolith became totally water saturated. This was slightly less valid for the regolith eroded by mass movements. However, for this last regolith (brown and grey marls) infiltration fronts were deeper. In all regoliths macropores played an important role. Around deep cracks the infiltration profile was deeper. Referring to research question 1 there is concluded that according to these results there is no saturation front above an impermeable layer. The upper part of the profile is saturated however not the specific part above the hard rock or unweathered shard layer.

The processes of rill erosion and mass movements are separated by threshold values of physical, chemical and physico-chemical soil properties and processes. These properties and processes and their relationships are extremely complex as is seen in this thesis. Complexity of these relationships is made more clear by selecting indicators for characterising the erosion processes. Indicators are also relevant for obtaining spatially referenced data that are needed for both modelling and management.

In this thesis hydrological and geomorphological mechanisms on badland regoliths were studied thoroughly. Conclusions are summarised in the figure below (Figure 7.1.2) in which complex system response is related to field or laboratory indicators.

**Figure 7.1.1 Hypothesis for relationships between indicators and “Process Domains” for badland regoliths**

- (1) surface sealing
- (2) increase runoff
- (3) soil consistency
- (4) macroporosity
- (5) chemical soil properties
- (6) clay mineralogy and texture

CHAPTER 7.1
7.1.4 Relationships indicative for various processes related to erodibility observed during the experiments

The sediment concentration and sediment yield are usually considered as indicators for erodibility. The highest values are at sites showing mass movements (Figure 7.1.2). A clear development was seen on the grey marls, where after the formation of a surface crust, the erodibility decreased and flow paths started to develop. A similar response was seen during both runs on the white marls. Increase of runoff caused erosion dominated by flow hydraulics at the surface and decrease of erodibility of the material (Figure 7.1.2). During these experiments the increase in runoff coincided with sealing of the surface. After this, the runoff started to be concentrated in rills and on flow paths.

The difference between EC<sub>25</sub> and SAR<sub>p</sub> of the soil solution normally is an indicator for erodibility (Figure 7.1.2). However in this study it was not positively related to erodibility of the marl regoliths. The difference between these parameters was highest for white marls, which

<table>
<thead>
<tr>
<th>Indicators</th>
<th>System Response</th>
<th>Type of erosion</th>
</tr>
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<tbody>
<tr>
<td>erodibility</td>
<td>mass movements</td>
<td>erosion dominated by mass movements</td>
</tr>
<tr>
<td>high SAR and low EC of soil solution</td>
<td>dispersion</td>
<td></td>
</tr>
<tr>
<td>smectite content</td>
<td>erodibility</td>
<td></td>
</tr>
<tr>
<td>macroporosity</td>
<td>infiltration</td>
<td></td>
</tr>
<tr>
<td>sudden increase of runoff</td>
<td>erodibility</td>
<td>rill erosion dominated by flow hydraulics at the surface</td>
</tr>
<tr>
<td>surface sealing</td>
<td>erodibility</td>
<td></td>
</tr>
<tr>
<td>soil shear strength</td>
<td>erodibility</td>
<td></td>
</tr>
<tr>
<td>vertical resistance</td>
<td>erodibility</td>
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</tbody>
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Figure 7.1.2 Relationships between indicators, system response and type of erosion in badland areas (for explanation see text)
showed the lowest erodibility and lowest for grey marls which showed the highest erodibility. This does not agree with the high erodibility of the materials suffering from mass wasting. For grey marls the amount of smectite and texture is the determining factor for shrinkage and swelling and therefore for erodibility. For brown marls it is, as mentioned before, the combination of smectite with a relatively high sodium content (Figure 7.1.2).

Dynamic soil properties as soil shear strength and vertical resistance of the soil surface show that the higher the values the lower the erodibility, according to the sediment concentration (Fig. 7.1.2). Macroporosity is a driving factor for infiltration. The higher is the infiltration the higher erodibility (Fig. 7.1.2).

The C5-10-index and the liquid limit index do not show a uniform relationship with sediment concentration. The relationships seem to be too complex for these indices to be a good indicator for erodibility.

It was emphasised that the results of the experiments for this study were collected during one month. Only surface characteristics were measured one year before and two years after the experiments. Temporal differences in morphology or style of process interactions, as mentioned by Schumm (1956) in the Pert Amboy badlands, were not taken into account. In badlands in Vallcebre, Pyrenees (Regüés et al., 1995), freezing-thawing cycles are an important agent for physical weathering. This is in contrast to the Petrer badlands. Moreover, photographs taken in the Petrer badlands (Calvo and Harvey, 1996) show a seasonal change in surface morphology. However, differences between years were considerably less than those between seasons. Calvo and Harvey (1996) found during longer term cycles, depending on climatic conditions, a differentiation in style of process interaction. In this study differences between materials were determined within one season. In other seasons or under other climatic conditions different process assemblages might be active.

A scale problem resulting from differences in plot size is a difference in the timing of runoff measured. However, from the moment runoff left the plot in rill flow, in most cases it took about 15 minutes before rill and interrill flow were observed on the entire plot. No specific differences were seen in this case for different sizes of plots.

7.1.5 Processes affecting the relationship between soil moisture content and sediment concentration

A general feature in the results is that the sediment concentration and the soil moisture contents, prior to saturation, are very irregular. This is not due to the pre-wetting, as this only affected a very small part of the plot. During both rainfall simulations on the white marls, the sediment concentration continued to increase after water saturation was reached.

This indicated that aggregates were losing their cohesion, preceding entrainment. Gerits (1991) concluded that a rapid rise in sediment concentration during rainfall simulation experiments on similar badland material was caused by physico-chemical thresholds, exceeded by the system. During both runs on white marls, after a short period, the sediment concentrations dropped and remained constant until the end of the experiment. This was also true for the second run on the grey marls. Initial surface conditions for the white marls and for the second run on the grey marls were similar, namely a fairly smooth crusted surface containing shrinkage cracks. This could explain the similar response of both regoliths.

After the sediment concentration drops, the runoff remains high or increases. At this moment the indicators 'soil moisture' and 'sediment concentration' cross a threshold and the
Fig. 7.1.3a Schematised behaviour of soil moisture content and sediment concentration in badland regolith experiencing rill erosion; a threshold is crossed after which the erodibility increases and the mechanism of the erosion process changes.

**LEGEND**

- \(\text{---} \) = soil moisture content
- \(\text{---} \) = sediment concentration
- \(\text{-------} \) = threshold for erosion mechanism

Fig. 7.1.3b Schematised behaviour of soil moisture content and sediment concentration in badland regolith experiencing mass movements; no threshold is crossed during the experiment and the sediment concentration pattern is kept irregular.
problem becomes more complex because flow hydraulics will play a more important role, because of the relatively high amount of runoff (Figure 7.1.3a). Factors like bed shear stress and resistance of the soil to mechanical erosion are interacting with the chemical and physico-chemical processes causing erosion. Differences between runoff of the first and second run are comparable for white and grey marls. However, the different reaction of the sediment concentration indicates a different and complex response of the regoliths. During the experiments on white and grey marls it was observed that the surface was almost completely sealed, which resulted in a crusted surface after drying. An explanation for this fast surface sealing is the high amount of the swelling clay mineral smectite (Table 4.1.5), which accelerates the liquefaction of the material. This increase in surface sealing is also shown by the runoff coefficient, which was higher for the second run on the white and grey marls. This phenomenon could be compared with the last stage of the mechanism for runoff generation on shale slopes in the Dinosaur badlands, Canada, described by Hodges and Bryan (1982). In spite of the difference in material and climate, the sediment concentrations and EC\textsubscript{25} of the runoff in the Dinosaur badlands (Bryan et al., 1984) were in the same range as those described in this study. The rill model developed in smectite-rich badland regoliths by Gerits et al. (1987) and Imeson and Verstraten (1988), was considered for a badland surface that was not completely sealed at the start of rainfall. Saturation occurred locally along flow paths in the regolith. This could be a stage preceding the saturation of the total upper soil profile and closing of the surface. Hodges and Bryan (1982) and Bryan and Hodges (1984) found that in wet antecedent moisture conditions complex changes occur in the character of shale surfaces.

When considering the total sediment yield and the runoff coefficients (Table 6.1.1) almost all materials show a higher runoff coefficient and sediment yield during the second run. The sediment concentration, except for the brown marls, appears to be similar or lower than during the first run, which means that proportionally less sediment is transported when more runoff is generated. This indicates that in the first part of the experiments water infiltration and the response of the soil to infiltration are important for sediment detachment. Later on, when flow hydraulics play an important role, mechanical erosion at the soil surface is caused by flow properties of the runoff. This is supported by Torri et al. (1994) who concluded from experiments on an Italian biancana-like badland that the runoff detachment rate was limited by the infiltration rate of the water front into the regolith. The runoff coefficient of the first experiment on the grey marls was extremely low, whereas the sediment concentration was relatively high. Yair et al. (1980) found on a comparable material in the Zin valley badlands in Israel, that the infiltration rate and sediment concentration of this material on south facing slopes was very high and the sediment was transported in the form of pulsatory viscous mudflows.

The total sediment yield and the sediment concentration is the highest for the second experiment on the grey marls, however also for the brown marls the sediment yield is relatively high. This implies that the grey and brown marls are the most erodible of the three badland materials. This means that material experiencing mass movements is more erodible than the material undergoing rill erosion. Gerits (1991) found the opposite, i.e. that erosion rates on a badland site with rill erosion were much higher than on a badland site with mass movements. However, the stabilising factors on the latter were algae on the surface. This was not the case in the Petrer study area.
The high peaks of the sediment concentration at the beginning of the experiments can be explained, as already mentioned, by the aggregates losing their cohesion during infiltration and subsequent entrainment. Part of the sediment can be supplied from loose sediment on the aggregate surfaces. However, not much evidence of large amounts of loose sediment on the surface was seen before the experiments. From the results in Figures 6.1.2, 6.1.3 and 6.1.5 can be seen that the correspondence between the time of saturation of the soil aggregates and the sediment concentration is significant for the white marls and for the second run on the grey marls, in which saturation is reached relatively quickly (Figure 7.1.3a). In the other materials and experiments it seems that the infiltration depth (15 cm) is too large for the soil moisture content and sediment concentration to be simply related (Figure 7.1.3b). Other parameters, mentioned later in this Chapter, seem to be important for these materials. Because of the thicker regolith layer and the higher infiltration capacity in the grey and brown marls, more water is able to infiltrate in the regolith profile. However, if the time of saturation is reached (which did not happen during the experiment) a thicker part of the regolith profile could become more unstable than in the white marls and therefore could cause a higher increase in sediment concentration at threshold conditions than is the case in white marls.

7.1.6 Relationship between dynamic soil properties and erodibility
The indicators selected to summarise relationships between soil moisture content and sediment concentration behaviour are shown in Figure 7.1.1.

The shear strength and vertical resistance of the material depend strongly on the amount of infiltrated water. The preceding results suggest that the soil water content at the surface of the white marls reaches saturation, which is not the case for the grey and brown marls. Combining these results with the values in Figures 6.1.6a and b, it can be seen that even at saturation, the white marls still have a higher shear strength and vertical resistance than the grey and brown marls. This means that the upper part of the white marls is more stable than the upper part of the brown and grey marls. Comparing this result with differences in macroporosity in Table 4.1.6a and b, suggests that the higher the macroporosity the more unstable the badland regolith type (Imeson, 1986). Macroporosity is an indicator for the swelling and shrinkage capacity of a soil. The higher this capacity is, the higher the infiltration capacity. The higher the infiltration capacity is the lower the possible stability of the soil. The swelling capacity is determined by the texture and clay mineralogy (Chapter 7.1.7). Brunori et al. (1989) found that soil detachability is linked to soil shear strength. This is also shown by the sediment concentrations, which are the highest for the materials with the lowest shear strength value.

The C5-10-index and the liquid limit were measured from remoulded soil samples, so the effects of macropores were not considered. The liquid limit is the lowest for the white marls, so that the material in a remoulded condition is more unstable than the grey and brown marls. This means that the white marls are the first material reaching the liquid limit upon wetting. When this result is compared to its shear strength and the vertical resistance, it means that less water has infiltrated during the experiments in the white marls compared to the brown and grey marls. This is also shown by the runoff coefficients of the materials (Table 6.1.1). The C5-10-index and liquid limit of the badland regoliths are not positively related. This is in contrast with the positive relationship between C5-10-index and liquid limit in loess soils (De Ploey and Müncher, 1981). However, differences between C5-10-indices are small and all values are
above 3, suggesting a stable soil (De Ploey and Mücher, 1981). This indicates that this index has to be used at a different level of scale in clay-rich badland soils in which dispersion and swelling are more important than slaking. This is a very interesting problem that needs to be studied further.

7.1.7 Relationship between chemical and mineralogical soil properties and erodibility

The chemical parameters SARp and EC25 are strongly related to the erodibility of the badland regolith (Kamphorst and Bolt, 1978; Gerits, 1991). Especially, the combination of a high SARp value and a relatively low EC25 in a soil solution causes swelling and dispersion of the soil material. This was obvious during experiments in the white and brown marls. However, the relationships are highly complex and different processes affect different scales (Hodges and Bryan, 1982). This is illustrated by the grey marls, which show higher sediment concentrations, but smaller differences between SARp and EC25 values than in the white and brown marls.

Other parameters also could play an important role in explaining erodibility. One of these parameters is the amount of swelling clay minerals, like smectite, which is much more important in the grey than in the white and brown marls. These clay minerals cause a high swelling and shrinkage capacity resulting in an unstable badland regolith, with a high macroporosity. A high amount of sodium in a smectite-rich environment also causes an increase of swelling capacity (Yong and Warkentin, 1975), which probably happened in brown marls. An important parameter responsible for the higher stability of the white marls could be the high amount of calcite. The calcium carbonate particles are physically inert and can produce a waterstable silt fraction (Imeson and Verstraten, 1989), which results in a decrease of erodibility.

7.1.8 Conclusions

The indicators of erodibility seemed to have various values for the different process domains of rill erosion and mass wasting. Notably, the relationship between soil moisture change and the behaviour of sediment concentration was found to be a direct indicator for erodibility. This relationship can be used to find soil moisture threshold values for the increase of the erodibility. The indicators mentioned in the lowest level of Fig. 7.1.1 are able to explain the thresholds in the above relationship, except for the C5-10-index and the liquid limit, which do not show consistent relationships with the erodibility of these regolith materials.

Regarding the other relevant research questions mentioned in the beginning of this chapter the following conclusions can be drawn. From this specific study it is concluded that in general, when different erosion processes, i.e. rill erosion and mass movements are compared, relatively more sediment is eroded from badland areas susceptible to mass movement. The regolith susceptible to rill erosion is sealed after saturation, which also happens to regolith containing a high amount of smectite and suffering from mass movements, when the surface has been changed by a preceding rainfall experiment. Apparently, before saturation of the surface layer dynamic soil properties play a major role in the erosion process, whereas after saturation and increase of the runoff the increasing importance of flow hydraulics results in an even more complex erosion process in these badland areas.
7.2 Response of dynamic soil properties on rainfall in cultivated loess areas

Relationships between soil water and soil properties of loess soils are explained in this chapter. Indicators for thresholds for erodibility and related erosion processes in this soil are mentioned. Results of this study of loess soil are discussed to find answers for the following research questions:

1. Does macropore flow and saturation above an impeding plough sole occur during and after rainfall?
2. Does slaking and liquefaction of soil aggregates occur in a cultivated loess area during rainfall and does these disintegration processes contribute to rill initiation and development?
3. How does the drainage pattern develop during and after rainfall on cultivated loess soils affected by rills?
4. Which field and laboratory parameters are good indicators for rill erosion?

7.2.1 infiltration and hydrological processes in harrowed and ploughed soil

The following hypothesis was tested for cultivated loess soils in this thesis. In freshly ploughed loess soils, rill initiation is favoured by water saturation in the topsoil, above a relatively impermeable layer, as the plough sole, and by preferential flow through macropores. Research questions related to infiltration in cultivated loess soils are questions 1 and 3. According to the above hypothesis it is expected that in ploughed loess soil with low intensi-

![Figure 7.2.1a Expected infiltration profile in ploughed soil after rainfall with different rainfall intensities](image-url)
ty rainfall, water quickly will infiltrate to the impermeable plough sole, whereas high intensity rainfall reacts similar to harrowed soil (Fig. 7.2.1a and Fig. 7.2.1b). Infiltration was studied in ploughed and harrowed soil profiles in order to study this hypothesis and learn more about favourite conditions for rill initiation and development.

Soil water pressure can indicate saturation of a soil layer. The measured soil water pressure shows that under low intensity rainfall the infiltration front in the ploughed soil moves more quickly downwards than in the harrowed soil (Fig. 5.2.1). These results corroborate the results of the soil moisture content. This is in the ploughed soil highest just above the Bt-horizon after both high and low intensity rainfall. The water stagnates on a relatively impermeable layer, the so-called plough sole. In the harrowed soil more water is kept in the topsoil, especially after high intensity rainfall experiments. Difference between low and high intensity in ploughed soil is that high intensity rainfall creates a less deeper soil moisture front.

The soil moisture profiles of ploughed and harrowed soil after low and high intensity rainfall show decreasing soil moisture in depth in harrowed soil and increasing soil moisture in depth for ploughed soil (Figure 7.2.2a and b). The deeper soil moisture front in the ploughed soil is probably caused by the quick drainage of water through macropores. In harrowed soil, the more homogeneous soil profile causes a homogeneous decreasing infiltration front with depth.

After low intensity rainfall, a greater risk for runoff was developed by high intensity rainfall, especially in ploughed soil. This can be explained by saturation of the complete profile, by slaking of the surface causing Horton overland flow or by raindrop impact causing breakdown of aggregates and slaking. Complete or partly saturation of the soil profile is, according to this and other studies, the most probable cause of overland flow. This agrees with scenario 1 and 2 from Chapter 5.2.4. If high intensity rainfall is preceded by low intensity rainfall than change of

Figure 7.2.1b Expected infiltration profile in harrowed soil after rainfall with different rainfall intensities
the surface conditions is less pronounced and less relevant for infiltration capacity.

From the results of the experiments in a wheel track on ploughed soil it is concluded that compaction and instability of the surface layer is the most important factor for runoff in soils affected by wheel pressure. Runoff during the experiments, also outside a wheel track, caused a streambed and more slaking and loose of structure at the surface, which is a self-improving system.

7.2.2 Erosional balance in ploughed and harrowed loess soils

Erodibility and erosion processes in cultivated loess soils are analysed in this section. A summary of results is shown in Figure 7.2.3a and b. Research question 2 refers to erodibility of the loess soil. Already mentioned is that in the ploughed soil, during high intensity experiments in a wheel track more runoff was generated than in harrowed soil (Table 5.2.3a). This counts also for high intensity experiments after low intensity experiments. For this last experiment also soil moisture content and sediment yield is higher for ploughed soil (Fig. 6.2.15a and b). This could indicate a decrease in soil consistency, because of high soil moisture content in ploughed soil. This was not corroborated by the soil consistency data. Soil shear strength in the field was, for ploughed soil during this experiment, slightly lower than for harrowed soil. Low intensity experiments in a wheel track, however, show more runoff in har-
rowed field, but not more sediment yield. Results from aggregate stability tests show that after low intensity experiments waterstable aggregates in ploughed soil are smaller than in harrowed soil (Chapter 4.2.3). Roughness at the surface is more in ploughed soil than in harrowed soil. Decrease of roughness during experiments is more in the case of the ploughed soil.

Measurements in a rill system show slightly lower soil shear strength in a rill than in inter-rill areas, which indicates a higher susceptibility for erosion.

From the results is concluded that ploughed loess soil is more susceptible to erosion, especially when high intensity rainfall follows low intensity rainfall. Rainfall has more impact on decrease of roughness at the surface in ploughed than in harrowed soil. Combined with higher soil moisture content of the upper part of a profile in ploughed soil this could be a favourable condition for rill erosion.

7.2.3 Indicators for cultivated loess soils susceptible to rill erosion

Indicators are defined as mentioned in section 7.1.3, i.e. a parameter or variable that is easy to measure and which summarises in shorthand the effects of complex processes that are difficult to measure or to observe (Landres, 1992; Harris et al., 1996).

Complex processes are the erosion processes in harrowed and ploughed loess soils. Evidence and explanation has been searched for different types of rill erosion in these loess soils. From this study the following indicators are found to show evidence of soil erosion under two different types of cultivation (Figure 7.2.4).

Indicators were, similar to those of the badlands in section 7.1.3, considered at two levels. The first level shows the erosion process which can lead to different process domains,
Figure 7.2.3a Relationships between dynamic soil properties, infiltration and erosion in cultivated loess soil (for explanation see text)
i.e. rill erosion caused by water saturation combined with destabilisation of the soil aggregates and rill or sheet erosion caused by surface runoff and partly infiltration. The type of erosion process is determined by the relationship between saturation and infiltration of the soil profile and stability of the soil aggregates. This relationship is specified in Chapter 2.3.3 for cultivated loess soil. At the second level indicators, which determine the relationship are mentioned in Figure 7.2.4. Antecedent soil moisture content gives an idea about previous saturation of the soil aggregates or sensitivity to slaking and welding. Rainfall intensity is an important factor determining either surface erodibility or saturation of the soil profile. Macroporosity is a measure for infiltration and possible subsurface flow. Slaking and welding at the surface can cause Horton overland flow and more evidence for rill erosion at the surface. Consistency is a measure for the stability of soil aggregates, which indicates the susceptibility to subsurface soil erosion. Roughness of the soil surface is a measure for overland flow and therefore the possibility for rill or sheet erosion at the surface. The two cultivation systems that were studied, i.e. harrowed and ploughed loess soil, are considered to create the different conditions, which initiate rill erosion at the surface or in the lower part of the Ap-horizon.
7.2.4 Relationships indicative for various processes related to erosion processes

The relationship between the stability of the soil aggregates and infiltration and water saturation of a cultivated loess soil is important to find answer for research question 2 (Fig. 7.2.3a). Rainfall intensity is seen as a driving factor for this relationship. Therefore, it can be used as an indicator for erosion processes. The other indicators are also mentioned in Figure 7.2.3a and their relationship with the system response is given.

Low intensity rainfall results in ploughed soil in saturation of the Ap-horizon and a discontinuity in soil moisture distribution between Ap and Bt. This saturated soil in combination with a decrease in consistency is indicative for subsoil erosion and possibly deeper rill erosion. This means erosion caused in the deeper Ap, which can result in rill erosion. During high intensity rainfall a similar soil moisture front is seen, however more water is kept in the topsoil. In harrowed soil a continue soil moisture distribution is seen during both intensities, with more water in the topsoil. No relationship is seen with decreasing consistency of the subsoil, which indicates surface erosion.

High intensity rainfall on saturated soil, because of preceding low intensity rainfall, causes more sediment discharge on ploughed than on harrowed soil. Difference between both systems is that in ploughed soil the total Ap is saturated, whereas in harrowed soil only the topsoil is saturated. A consequence is that in ploughed soil a greater risk is for deep rill erosion because of the relatively deep saturated soil. In harrowed soil, only the topsoil is saturated, which indicates a risk for surface rill erosion. Römkens et al. (2001) found more soil loss during showers with increasing intensity. However they did not vary soil cultivation, which

![Figure 7.2.4 Relationships found between indicators and “Process domains” for cultivated loess soils](image-url)
is apparently an important factor.

Surface conditions affect infiltration and runoff. Roughness of the surface in ploughed soil is highest of the both systems. It causes more infiltration and therefore less runoff. High intensity on harrowed soil causes decrease of the surface roughness and therefore more runoff and sediment discharge. However, high intensity rainfall on saturated soil has no effect on the surface roughness and consequently has lower runoff and sediment discharge. Römkens et al. (2001) found that initially smooth surfaces might yield less soil loss than initially rough ones. This is another indication that soil structure and cultivation could be important factors.

The air-entry value of the lower part of the Ap-horizon (Ap2) is a differentiating factor between harrowed and ploughed soil. For fresh ploughed soil the indicator is lower than 15 (-cm) and for fresh harrowed soil it is higher than 15 (-cm) (Table 5.2.1a). The system response of the ploughed soil is an increase in macropores of the Ap2, which increases the risk of deep rill erosion. In harrowed soil macropores are stable and the amount in the Ap is lower than 5%. This 5% is the threshold between ploughed and harrowed soil (Table 4.2.6a). A low air-entry value corresponds in general with a high macroporosity (Wösten and Van Genuchten, 1988).

In soils with increasing macroporosity and high infiltration capacity the risk of decrease of consistency of the subsoil is higher. In that case the risk for deep rill erosion is higher.

Change in surface conditions can give completely different results as is shown in case of the plots on wheel tracks (Figure 7.2.3b). Disturbance by wheel pressure causes a higher vertical resistance and therefore a higher runoff in both systems, except for low intensity rainfall in ploughed soil. This situation increases the risk on surface rill erosion or sheet erosion.

Ploughed soil has a rougher surface than harrowed soil, also in a wheel track. Soil moisture at the surface after low and high intensity rainfall is lower than in harrowed soil. Surface erodibility is higher during both intensities in ploughed loess soil. This is seen by a higher sediment discharge, even at a lower runoff during low intensity rainfall. These results increase the risk on surface rill erosion.

Harrowed loess soil shows less sediment discharge and therefore a lower surface erodibility. This indicates a higher risk for sheet erosion, especially if wheel tracks are not too deep.

7.2.5 Relationship between dynamic soil properties and erodibility

Dynamic soil properties influence the erodibility of loess soil. These relationships are explained in this section based on results of this thesis and on studies from literature (Kwaad and Mücher, 1994; Imeson and Kwaad, 1990; de Ploey and Mücher, 1981; Rauws and Govers, 1988).

Air-entry value and pore size distribution were derived from water retention characteristics. The air-entry value of the harrowed and ploughed loess soil has a relationship with macropores. The more macropores are available in a soil, the lower its air-entry value. Water retention characteristics show in Table 5.2.1a and b the dynamics of the air-entry values in ploughed and harrowed soil during the experiments. Initially ploughed soil has a lower air-entry value than harrowed soil. During the experiments the air-entry value increased more in the topsoil of the ploughed soil than those of the harrowed soil. In the subsoil the situation is contrary to the topsoil. It means that the ploughed topsoil is weaker than the harrowed topsoil. The dynamics of the macroporosity (Table 4.2.6a to c) follow the dynamics of the air-entry value in most cases. However, in ploughed soil the increase in macropores in the Ap
does not agree with an increase in air-entry value (Table 5.2.1a). The results of the air-entry value showed that compared to harrowed soil relatively more macropores are kept in the ploughed subsoil. The increase of macropores agrees with hypothesis 2, i.e. in freshly ploughed soils macropores are available for preferential flow. However, the increase of air-entry value in ploughed soil, which is a slower increase than for harrowed soil, showed that the relationship between macropores and air-entry value is more complex than assumed.

Pore size distribution only showed a difference between harrowed and ploughed soil (Table 5.2.1a and b). In general the values for harrowed soil were higher than for ploughed soil. This means that harrowed soil has a more uniform pore size distribution than ploughed soil, which is explained by a more equal distribution of micro-, meso- and macropores in harrowed than in ploughed soil. In ploughed soil more macropores should be available, which is shown by the non-uniform pore size distribution.

For harrowed loess soil water retention curves were corrected for shrink and swell (Figure 6.2.14a to c). The differences between the original and corrected characteristics are explained in Figure 7.2.5. The original curve belongs to the pF-ring sample. The other curves belong to a clod sample for the shrink and swell test. The corrected Bt-characteristic shows at higher soil moisture content a lower bulk density (point A compared to point B in Figure 7.2.5). This means that for a clod sample compared to a pF-ring sample the first one shows more swelling at higher soil moisture content. At lower soil moisture content, dry bulk density is higher than for the original one, which shows more shrinkage than the pF-ring sample. The figure shows that the dry bulk density of the pF-sample is an average value of the Bt. The corrected Ap-curve shows a higher bulk density (point C compared to point B in Figure 7.2.5), which decreases more with lower soil moisture content than the original curve, but does not cross it. It means that the clod always has a higher dry bulk density than the pF-ring sample. This is explained by the amount of macropores in the pF-ring sample. From this is concluded that the corrected curves show that the Ap-horizon has more macropores than the Bt-horizon.

Vertical resistance and soil shear strength increased during low intensity experiments in ploughed soil, which corresponded with an increase in smaller waterstable aggregates (Figure 4.2.4). This relationship was not observed in harrowed soil. It showed sensitivity for soil degradation during slaking and welding of the surface of a ploughed loess soil. During increase of the vertical resistance, soil moisture content of the soil clods decreased in ploughed soil. Which supports the theory of decrease of infiltration after slaking of the aggregates. In the case of low intensity experiments followed by high intensity experiments in ploughed soil, soil shear strength and vertical resistance were lower than in harrowed soil. Slaking of the soil clods was only seen at the outside. Soil moisture content of the soil clods increased contrary to only low and high intensity experiments. These results show that high intensity rainfall after low intensity rainfall in ploughed soil causes a very erosive situation.

Consistency was determined with undisturbed soil clods. Liquid limit and C5-10-index were derived from remoulded soil samples. This means that contrary to these last parameters soil structure played a role in the consistency indices (Table 4.2.4). The trend that is seen for index A is comparable to index B. In ploughed soil, consistency decreased during the experiments especially in Ap2 and in harrowed soil in Ap1 and Ap2. This could be related to the higher soil moisture content in the topsoil of harrowed soil, which destabilised the structure and therefore decreased the consistency. In ploughed soil the structure of the soil aggregates
in Ap2 decreased because of the higher soil moisture content deeper in the profile. Consistency of the soil clods in the Ap in ploughed soil in general was lower than in harrowed soil. However, consistency still decreased during the experiments. Soil moisture content of the soil clods at the surface during the experiments was lower than in harrowed soil. More soil clods in the ploughed soil showed only slaking at the outside of the clod, which means soil degradation in ploughed soil at a very small scale.

Liquid limit and C5-10-index show sensitivity for erosion of the remoulded soil. For harrowed and ploughed soil the liquid limit of the Ap was equal. However C5-10-index showed a lower value for the Ap of ploughed soil. This means that the ploughed Ap is more vulnerable to slaking (de Ploey and Müncher, 1981). Differences between trends in consistency of ploughed and harrowed soil aggregates showed that soil structure is an important factor for sensitivity to erosion.

Vertical resistance at the surface of the wheel track plots was higher than the other plots, during the low intensity experiments. During high intensity experiments vertical resistance of both types of plots was equal. The determining factor for infiltration and runoff was surface morphology, i.e. wheel track. Infiltration profiles were comparable in both cultivation types. However, erodibility was higher for the wheel track in ploughed soil. Soil moisture contents at the surface were lower for ploughed wheel tracks during both intensities. In case of the low intensity rainfall this could be caused by infiltration by by-pass flow. However, in case of the high intensity, runoff was higher and possibly the infiltration capacity was lower by consolidation of the soil surface.
7.2.6 Processes affecting the relationship between soil moisture content and risk on rill erosion

In Figure 7.2.3a and b an indication is given of the type of expected erosion for a specific type of cultivation and rainfall intensity. Especially the experiments with low intensity rainfall followed by high intensity rainfall verify a hypothesis mentioned in Chapter 1. This is the high vulnerability for erosion of freshly ploughed loess soil when rain falls on a highly saturated soil profile.

Low intensity rainfall followed by high intensity rainfall on harrowed loess soil shows erosion processes, mentioned as scenario 1 in Chapter 5.2.4. The low intensity rainfall caused a continuing decreasing soil distribution with depth. The following high intensity rainfall caused a quick saturation of the topsoil and therefore quick runoff. The surface change was less relevant for infiltration capacity than during only high intensity rainfall. Vertical resistance was higher and therefore less infiltration took place. Compared to only high intensity rainfall the situation of low and high intensity rainfall was less erosive. Soil moisture content at the surface was lower, therefore less saturation of the topsoil occurred with less loss of consistency and less erosion than during only high intensity rainfall. From this situation is expected that sheet erosion will develop or superficial rill erosion after eventually saturation of the topsoil.

Scenario 2 was also mentioned in Chapter 5.2.4 as the situation for ploughed soil during high intensity rainfall preceded by low intensity rainfall. The infiltration front of high intensity rainfall after low intensity rainfall was quicker and less deep than during low intensity rainfall. The soil profile was saturated, by which overland flow had formed. Change of the surface conditions was less relevant for the infiltration capacity than for only high intensity rainfall. Also runoff and sediment discharge were higher than during only high intensity rainfall. This higher erodibility was related to higher soil moisture content of the soil clods at the surface and higher soil moisture in the topsoil. This was also reflected in the soil shear strength and vertical resistance of the soil surface, which were lower than in harrowed loess soil. It also counted for the consistency of the soil aggregates in Ap1 and Ap2. Normally high intensity rainfall has a high impact on decrease of roughness of the surface. However, after low intensity rainfall high intensity rainfall had a low impact on surface roughness. The combination of a saturated soil profile, high soil moisture content in the topsoil and lower consistency and surface parameters gives a higher risk on deep rill erosion as mentioned in the hypothesis in the beginning of this chapter. Stolte et al. (1997) found a higher erodibility for crusted loess soils than for cracked loess soils. This was however based on a large-scale catchment study, which was not directly related to consistency and structure of soil clods.

Research question 3 mentioned in the beginning of this chapter is answered by using the results of this Ph.D. study. This question is:

How does the drainage pattern develop during and after rainfall on agricultural loess soils affected by rills?

Scanning curves for water retention of samples in a rill system gave an indication of the relative amount of macropores. In a rill and in the side of a rill smaller pores seemed to be more important for drainage than in between two rills (Fig. 5.2.8). This indicates a more compact structure in and around a rill. In the interrill area macropores seemed to play a more important role. In the field situation soil moisture was relatively high in the rill bottom. In the interrill area soil moisture was relatively low (Fig. 5.2.11).

These results give a positive result for the idea of a rill system in ploughed loess soil as a
CHAPTER 7.2

Rainfall can infiltrate quickly in the interrill area, because of macropores. Possibly it infiltrates sideward to a rill, where an accumulation of soil moisture occurs, which is drained by the rill.

7.2.7 Conclusions

Rainfall on ploughed loess soil infiltrates quickly in the Ap and shows a discontinuity in infiltration front between Ap and Bt-horizon. Macroporosity because of ploughing and increase of macroporosity causes probably by-pass flow deeper in the horizon. Infiltrated water in harrowed soil, on the contrary, is kept more in the topsoil. This is explained by a lower macroporosity in the Ap.

The effect of water on the dynamic soil properties was studied. A conclusion is that soil clods at the surface of ploughed loess soil are more sensitive for slaking and probably welding than harrowed loess soil. This agrees with the results of sediment discharge and consistency that ploughed soil is more susceptible to erosion than harrowed soil. This is corroborated by the experiments of high intensity rainfall after low intensity rainfall. In this situation the soil is more erodible than after only high intensity rainfall. For harrowed soil a contrary conclusion is drawn. High intensity rainfall after low intensity rainfall is less erosive than only high intensity rainfall. Even in a wheel track is runoff on ploughed soil more erodible than on harrowed soil. The effect of rainfall on ploughed soil surface is also shown by the higher impact of rainfall on decrease of roughness of ploughed soil than of harrowed soil.

These conditions of ploughed soil combined with a higher soil moisture content in top- and especially subsoil have a higher risk for deep rill erosion during or after high intensity rainfall. Harrowed soil shows less susceptibility to erosion and combined with higher soil moisture in the topsoil sheet erosion or shallow rill erosion is more probable.

Around a rill system soil moisture accumulates in and under a rill. Macroporosity is higher in the interrill area. This indicates that drainage by by-pass flow from the interrill area to the rills can occur. In that case rills can act as drains for subsurface but also for surface water.
8

Evaluation of the drainage model for rill initiation and development

Introduction

The overall aim of this thesis is to investigate critical conditions for the initiation and development of rills in badland regoliths and in cultivated loess soils. This chapter discusses the conceptual rill initiation and development model against the background of the results already presented. In addition, the processes that lead to rill erosion in badlands are compared with those in the loess soils. Similarities and differences between both areas are considered. Furthermore recommendations are made for future research.
8.1 Conceptual drainage model for badland regoliths

This chapter attempts to provide answers to the following questions raised in section 1.2:

1. Does saturation and subsequent crack flow develop above an impermeable rock layer during and after rainfall?
2. Does slaking and liquefaction of soil aggregates occur in badland regoliths during rainfall and does this contribute to rill initiation and development?
3. How does the runoff pattern develop during and after rainfall?
4. Do the results of rainfall simulation experiments corroborate the projections of the rill drainage model for soils with strongly dynamic soil properties?

8.1.1 Drainage of badland regoliths

The upper part of the white marl regolith becomes water saturated during the rainfall simulation experiments. The depth of the wetting front was very irregular, presumably because of the influence of macropores formed by shrinkage cracks. However, no saturation of the regolith above an impermeable layer was recorded. According to the drainage model derived from Hooghoudt (Ritzema, 1994) and Donnan (1946), no infiltration should be expected beneath a rill. Only in the northerly exposed white marl regoliths no infiltration occurred beneath rills. Elsewhere, infiltration occurred in rill channels. This meant that the rill bottom is not necessarily eroded down to the bedrock. This was also frequently seen in the field (Photo 5.1.1).

In the brown marls, there is more preferential flow through macropores than in the white and grey marls because of the many cracks in this material (Photo 5.1.2). The upper part of the regolith does not become completely saturated, but the soil moisture content is highly variable. The regolith of the grey marls shows a rather homogeneous infiltration front, more than for the brown and white marls. This means that macropores are of minor importance for infiltration. The upper part of the grey marl regolith becomes completely saturated and even 'oversaturated', after which the surface regolith layer starts to flow.

On the white marls, more runoff is generated than on the brown and grey marls. However, as crusts develop during rainfall, runoff generation on all of the materials becomes similar. Considering research questions 1 and 3, it is obvious that the infiltration capacity of the brown and grey marls is higher than of the white marls. Macropore flow appears to be an important infiltration process in especially the white and brown marls. Infiltration during the second experiment on the grey marls was higher than during the first experiment according to the soil moisture measurements. However, runoff is higher during the second experiment. This difference shows a scale problem between point and slope scale measurements. A probable explanation is that runoff through the saturated regolith material, occurred during the second experiment. This could be deduced from both the soil moisture and runoff measurements.

8.1.2 Behaviour of the badland regolith in relation to drainage and erosion

The water stability of (macro and micro) aggregates is highest for the white marls. This can be directly related to the presence of rills (e.g. the white marls are dominated by rill erosion and the brown and grey marls by mass movements).

On the white marls, the sediment yield seems to be related positively to the soil moisture values but the relationships are statistically weak. This is not obviously the case for the other
materials where other properties and parameters are involved.

The brown and grey marls need to contain more water before they reach the same level of erodibility as the white marls. This is also seen in the liquid limit values, which are lowest for the white marls and the highest for the grey. The dry bulk density of the badland regoliths shows an increasing order from grey to brown to white marls, supporting the observation that the grey and brown marls can retain more water than the white marls. However, field measurements as soil shear strength, vertical resistance and sediment concentration showed that the grey marls reach the threshold of erodibility equivalent to the white marls at a lower soil moisture content than brown marls. This result is contradictory to the results of the liquid limit index. An explanation is that the liquid limit was determined with a remoulded soil sample, indicating that in case of the brown and grey marls the soil structure and macropores play a very important role for the difference in erodibility and consistency of the soil.

Swelling during the rainfall simulation experiments and shrinkage after drying of the material caused formation of cracks. Porosity became higher and therefore dry bulk density lower. This is the case during field experiments on almost all regolith materials. Possibly after some time the bulk density increases again, because of instability of the soil structure. In most badland regolith types macroporosity is also higher after the rainfall simulation experiments. Differences in porosity between badland regolith types were reflected by the infiltration capacity, which was high for the brown and grey marls and lower for the white marls. The grey and brown marls also have a higher shrinkage index than the white marls. Therefore, it is concluded that porosity and shrinkage and swelling highly influence hydrological characteristics as infiltration capacity and macropore or subsurface flow.

Referring to research question 2, slaking and liquefaction occur predominantly at the surface where the grey marls even show signs of flow. The brown marls show a lower degree of slaking and liquefaction at the surface, resulting in wider cracks and higher infiltration rate. In the subsurface part of the profile no liquefaction or slaking was observed. The most important factor for infiltration in badland soils appears to be liquefaction and slaking at the surface and, for subsurface flow, (macro)porosity.

Most differences of crack patterns were seen on the brown and grey marls. These results indicate the dynamic behaviour of the regoliths. After the exceptionally high intensity of experimental rainfall, all materials showed a difference. However, two years after the experiments, cracks had re-established themselves, except for the grey marls.

In general there is little difference in index 3, rill volume, between the regoliths. This means that on the white marls, showing an abundant amount of rills, superficial rills are present on less erodible material. Whereas on the brown and grey marls more profound or wider rills are present on more erodible material. Only on the grey marls was a permanent difference in rill pattern seen two years after the experiments. On the other regoliths the rill network returned to their initial equilibrium stage.

Considering research questions 3 and 4, only for the grey marls the development of a rill system was observed. For the other materials the existing rill system was used for runoff.

The relationship between soil moisture content and sediment concentration is a good indicator for the erodibility of the badland regolith. In case of the presence of rill erosion at the surface and a stable crust there is a positive relationship between soil moisture content and sediment concentration. In case of mass movement and an unstable crust, this relationship was not found during the experiments. These differences between the materials are
explained by surface sealing, sudden increase of runoff, macroporosity, chemical soil properties and clay mineralogy.

Conclusions are that relatively more sediment was eroded from badland areas susceptible to mass movements, i.e. brown and grey marls. Areas susceptible to rill erosion are sealed after saturation of the upper layer and possibly therefore less sediment is eroded. Apparently, before saturation of the surface layer dynamic soil properties play a major role in the erosion process, whereas after saturation and increase of the runoff, the increasing importance of flow hydraulics results in an even more complex erosion process in these badland areas.

8.1.3 Explanation of the water balance on badland slopes
Measuring subsurface flow is very complicated. The methods used were not able to measure subsurface flow directly. The different components of runoff measured are explained in the chart below.

\[
\text{rainfall (P)} = W + O1 + M1 + R + M2
\]  

\(W\) = water infiltrated in soil matrix
\(O\) = total overland flow (\(O1 + O2\))
\(O1\) = overland flow into rill
\(M1\) = flow through macropores into rill
\(R\) = rainfall directly into rill
\(M2\) = infiltrated macropore flow into soil matrix
\(C = M1 + M2\)

**Figure 8.1.1 Water movement components on a badland slope**

The water balance is:

\(\text{rainfall (P)} = W + O1 + M1 + R + M2\)  \hspace{1cm} (8.1)

in which

\(W\) = water infiltrated in soil matrix
\(O\) = total overland flow (\(O1 + O2\))
\(O1\) = overland flow into rill
\(M1\) = flow through macropores into rill
\(R\) = rainfall directly into rill
\(M2\) = infiltrated macropore flow into soil matrix
\(C = M1 + M2\)
\( P \) is known as the amount of rainfall  
\( W + M_2 \) is known as the measured soil moisture content  
\( O_1 + M_1 + R \) is known as the total discharge  
\( R \) can be calculated  
\( M_1 + M_2 = \) overland flow into cracks + rainfall directly into cracks

Two cases are considered during the experiments:  
1. Before the cracks are closed  
2. After most of the cracks have closed

Considering equation 8.1 for situation 1, overland flow into the rill is very small. So the total discharge is equal to \( M_1 + R \). This hypothesis is true if rill discharge started before overland flow into a rill. For situation 2 macropore flow should be relatively low, as most of the cracks have closed. This hypothesis can be tested by comparing the time when overland flow started, the time when the cracks closed and the rill discharge characteristic.

The occurrence of macropore flow in a rill is seen as a critical evidence for applying the drainage model. This means that parameters \( O_1 \) (overland flow into rills) and \( R \) (directly into rills) have to be estimated. If the total discharge is known, then macropore flow into a rill, \( M_1 \), can be calculated. However, observations and measurements of overland flow were too uncertain to calculate \( O_1 \). Instead of calculating all parameters, calculations were made using the water balance equation.

During situation 1, macropore flow into rills was not observed. During situation 2 macropore flow was more likely to occur in brown and white marls, southerly exposed, because in these materials cracks did not close during the experiments. These materials are the most appropriate for subsurface flow through cracks and in some specific cases subsurface flow towards rills.

The parameters for the experiments were calculated and are shown in Table 8.1.1. The total water balance is either positive or negative. If positive, it means that more water had infiltrated and was discharged as runoff than had actually been applied as rainfall. This could be explained by water being accounted for more than once in equation 8.1. This happens in the case of the macropore flow, draining into a rill which could also be measured as soil moisture by TDR sensors. On the northerly exposed white marls and on the grey marls this evidently happened. This could indicate macropore flow draining into the rills. On grey marls mudflows were observed at the surface. Especially the high soil moisture content shows that the soil moisture content of these mudflows was measured and probably later also recorded as runoff.

In case of a negative hydrological balance, part of the rainfall was not measured. The water possibly flowed as subsurface flow downslope and was not caught as runoff. This was expected in the situations of white and brown marls on the southerly or south-westerly exposed slopes. These materials, especially the brown marls, showed very wide cracks, generating macropore flow or deep infiltration into the regolith.

Another flow component could be overland flow, draining downslope and not draining into a rill. In such case the surface area used to calculate runoff was too large. In the case of a positive balance the calculated surface is possibly too small.

In conclusion and in spite of the uncertainties it does seem likely that the drainage model
8.1.4 Relationship between pore volume and dynamic soil properties in badland regolith

The erosion process in the badland marls was explained in Chapter 2 as a process dependent on water flow and dynamic soil properties. This process is summarised in differential equation (2.9):

\[
\frac{dP_b}{dF_b} = C_b \times P_b
\]

(2.9)

in which

- \( P_b \) = pore volume of reference/initial situation of badland regolith (m\(^3\)/m\(^3\))
- \( P_b \) = pore volume of badland regolith, dependent of shrink and swell, dispersion, erodibility, soil moisture and water flux (m\(^3\)/m\(^3\))
- \( F_b \) = water flux as bypass flow in cracks and macropores (m/s)
- \( C_b \) = constant, dependent of physico-chemical thresholds and chemical parameters of the regolith related to change in soil moisture content; inverse velocity (s/m)

The value for \( C_b \) was calculated for the badland regolith types. Dry bulk density values before and after rainfall simulation experiments were used to calculate the pore volume. The average rainfall intensity of both experiments was used as flux. The following values were calculated:

- White marls northerly exposed: \( C_b = 0 \) s/m
- White marls south-westerly exposed: \( C_b = 0.104 \) s/m
- Grey marls: \( C_b = 0.142 \) s/m
- Brown marls: \( C_b = 0.300 \) s/m

\( C_b \) depends of the dynamic soil properties as macroporosity and physico-chemical properties. \( C_b \) is highest for brown marls, which could be explained by the high shrink and swell charac-

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**Table 8.1.1 Parameters (in litres) of hydrological balance of badland experiments**

<table>
<thead>
<tr>
<th>Badland type</th>
<th>experiment</th>
<th>rainfall (l)</th>
<th>soil moisture (l)</th>
<th>rainfall into rill (l)</th>
<th>runoff (l)</th>
<th>total water balance (l)</th>
</tr>
</thead>
<tbody>
<tr>
<td>White marls N exposed</td>
<td>1</td>
<td>not determined</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>67.0</td>
<td>13.2</td>
<td>1.26</td>
<td>68.6</td>
<td>14.7</td>
</tr>
<tr>
<td>White marls S exposed</td>
<td>1</td>
<td>25.9</td>
<td>4.80</td>
<td>0.229</td>
<td>4.65</td>
<td>-16.4</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>65.6</td>
<td>9.15</td>
<td>0.580</td>
<td>24.8</td>
<td>-31.6</td>
</tr>
<tr>
<td>White marls SW exposed</td>
<td>1</td>
<td>72.6</td>
<td>36.1</td>
<td>0.672</td>
<td>7.45</td>
<td>-29.0</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>not determined</td>
<td></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Brown marls S exposed</td>
<td>1</td>
<td>411</td>
<td>273</td>
<td>12.9</td>
<td>46.3</td>
<td>-91.6</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>411</td>
<td>117</td>
<td>12.9</td>
<td>104</td>
<td>-189</td>
</tr>
<tr>
<td>Grey marls S exposed</td>
<td>1</td>
<td>73.4</td>
<td>124</td>
<td>3.42</td>
<td>5.18</td>
<td>56.2</td>
</tr>
<tr>
<td></td>
<td>2</td>
<td>86.4</td>
<td>126</td>
<td>11.9</td>
<td>58.1</td>
<td>97.2</td>
</tr>
</tbody>
</table>

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could be applied to the brown marls.
teristics and the wide cracks in the soil surface. Probably this value also shows a higher likelihood of macropore flow. Grey marls show a lower value and white marls the lowest. This is reflected in the field observations that white marls show less macropore flow, because of slaking at the surface. Grey marls show also slaking of the surface, but the material behaves differently to the brown and white marls.

Probably the drainage model only applies to the brown marls, because its surface does not slake completely and macropore flow is generated from the surface into cracks.

8.1.5 Drainage model for rill erosion

Summarising the above it appears that on the white and brown marls more macropore flow is generated than on the grey marls. However, the drainage model of rill initiation could not be applied to both, the white and grey marls. In both materials the upper layer of the regolith becomes water saturated during rainfall. However, according to the drainage model the layer just above the unweathered shards should be water saturated.

Probably the drainage model is applicable to the brown marls, because macropore flow seems to be more important in this material than soil matrix flow. However the experiment was too short to form a water saturated layer deeper in the profile.

A contradiction was seen for the processes in the grey marls. The total runoff increased during the second experiment. On the other hand, measured data showed that infiltration under the rill also increased. It means that surface or subsurface water flow towards the rill was observed and more water was discharged than during the first experiment. This could indicate processes explained by the drainage model. However, as it was also observed in the white marls, the upper layer of the profile was water saturated and even started to flow.

From the above results and observations, it was concluded that the drainage model presented in Chapter 2 should be adjusted as follows:

The upper layer of the regolith becomes water saturated before the lower part of the profile. This is combined with macropore flow infiltrating in the soil matrix deeper in the profile. Finally, the surface layer of the regolith starts to flow and mass movements take place, due to a loss of consistency (Fig. 8.1.2a and b). This mechanism is different from the hypothesis that because of the loss of consistency of the saturated layer deeper in the profile, soil aggregates collapse and a rill initiates, which was explained in the drainage model presented in Chapter 2.

8.2 Conceptual drainage model for loess

In this chapter the research questions raised in section 1.2. are addressed. These are:

1. Does saturation and subsequent macropore flow occur above a relatively impermeable plough sole or Bt-horizon during and after rainfall?
2. Does slaking and liquefaction of soil aggregates occur in ploughed loess soil during rainfall and does this contribute to rill initiation and development?
3. How does the runoff pattern on cultivated loess soil develop during and after rainfall?
4. Do the results of rainfall simulation experiments corroborate the projections of the rill drainage model for soils with strongly dynamic soil properties?

8.2.1 Hydrology in cultivated loess soils
In ploughed soil water infiltrates more quickly during low intensity rainfall than in harrowed soil. The infiltrated water seems to stagnate on a relatively impermeable layer. High after low intensity rainfall shows a decrease in soil moisture with depth in harrowed soil and a uniform
soil moisture profile in ploughed soil. This is also explained by a quicker drainage through macropores. Considering research question 1, macropore flow is likely to occur in ploughed soil. A stagnation of water on the plough sole or Bt-horizon seems to occur, however saturation of the lower Ap is not evident.

Conditions for macropore flow are more favourable in ploughed than in harrowed soil. More macropores are available in the lower Ap just above the Bt-horizon. In the upper part of the ploughed Ap more macropores disappear because of the lower consistency of the soil aggregates. Low intensity rainfall shows a higher impact on the water retention characteristics of the upper part of the profile of both soils than high intensity rainfall.

In the interrill areas of ploughed soil more macropores are available than in and around rills. The drier the soil, the more macropores are formed. In the subsoil of the Ap-horizon, macropores seem to play a more important role.

After low intensity rainfall, the risk for runoff is higher in especially ploughed soil, because of saturation of the profile. Saturation of the profile is in the situation of preceding low intensity rainfall the most probable cause for overland flow. This is part of the answer to research question 3. High intensity rainfall preceded by low intensity rainfall causes a less pronounced change in surface and less influence on the infiltration capacity, so change in surface is not likely to cause runoff.

The effects of compaction in the topsoil as in a wheeltrack dominate the effects of cultivation type. Runoff during the experiments causes more slaking and loss of structure at the surface, which leads to more runoff, showing a positive feedback. A higher surface roughness accounts for less runoff.

In a rill system in ploughed soil, the soil moisture content in a rill bottom was slightly higher than in the interrill areas, which indicated the drainage of water from the higher parts into a rill. This shows for research question 3 that in a rill system drainage to a rill is probable.

8.2.2 Erodibility of cultivated loess soils

High intensity after low intensity rainfall on a ploughed soil produces a higher sediment yield than on harrowed soil. This could indicate a decrease in soil consistency because of high soil moisture content in ploughed soil. However, this is not corroborated by the soil consistency data. Waterstable aggregates from the ploughed soil are smaller than in the harrowed soil, which could indicate higher susceptibility to erosion. In a rill system soil shear strength was slightly lower in a rill bottom than in the interrill areas, which indicated a higher susceptibility for erosion in a rill bed.

Ploughed soil shows a higher roughness of the surface than harrowed soil, but also more decrease of roughness during the experiments.

Ploughed soil has a higher susceptibility to erosion than harrowed soil, especially when high intensity follows low intensity rainfall. Combined with a higher soil moisture content of the top and subsoil of a ploughed profile, more favourable conditions for deep rill erosion during or after high intensity rainfall will occur. It was concluded that for ploughed soil, clods at the surface are more sensitive to slaking and welding than for harrowed loess soil. This supports the results of a higher sediment discharge and a slightly lower soil shear strength.

For harrowed soil a contrary conclusion was drawn. High intensity after low intensity rainfall is less erosive than only high intensity rainfall. Combined with a higher soil moisture content in the topsoil, sheet erosion or shallow rill erosion is more probable.
Following from the above, the answer to research question 2 is that ploughed loess soil clods are more susceptible to slaking and welding and therefore show a lower soil shear strength than harrowed loess soil clods. It could create favourable conditions for rill erosion.

In a rill system, macroporosity is higher in the interrill area than around a rill. This could indicate that drainage by by-pass flow from the interrill area to the rills occur. In that case the answer to reasearch question 4 is that rills can act as drains for subsurface and for surface water.

8.2.3 Hydrological balance of small plots on cultivated loess soils

In this section a summary is given of the hydrological balance of the ploughed and harrowed loess plots. This balance shows evidence for macropore flow in especially ploughed loess profiles.

During a low intensity rainfall experiment of about 60 minutes (20mm/hr) no runoff was observed on both harrowed and ploughed soil. Figure 8.2.1a shows the various components of the hydrological balance. All rainfall (P) infiltrates (I) into the profiles. In ploughed soil more water infiltrates to measured point 2 at about 25cm depth. In harrowed soil water infiltrates continuously through the profile, which shows a decreasing infiltration profile. The lowest measured point in the Bt-horizon is not affected by the infiltrated water in ploughed soil, however it seems to be related to the higher measured points in harrowed soil. It shows that during low intensity rainfall increased infiltration or macropore flow occurs in ploughed soil.

During high intensity rainfall (50mm/hr) runoff occurs on both profiles (Fig. 8.2.1b). Runoff on harrowed soil is higher than on ploughed soil. The infiltration profile in ploughed soil is similar to the situation of low intensity. Measured point M2a is higher than M1a, so water infiltrates quickly through the profile until the Bt-horizon. In harrowed soil the infiltration profile is more continuous.

High intensity rainfall after low intensity rainfall also gives a remarkable difference between harrowed and ploughed soil (Fig. 8.2.1c). For harrowed soil the infiltration profile is similar to low intensity. However, runoff occurs, so infiltration is lower than during low intensity rainfall. On ploughed soil more runoff occurs than on harrowed soil. More water has infiltrated to the lower Ap (M2a) compared to harrowed soil. Which is again an indication for macropore flow in the ploughed soil.

8.2.4 Relationship between pore volume and dynamic soil properties in cultivated loess soils

The erosion process caused by macropore flow in cultivated loess soil was explained in Chapter 2 as a process dependent on water flow, slaking, welding and loss of consistency. This process is summarised in differential equation (2.10):
EVALUATION OF DRAINAGE MODEL

**Figure 8.2.1a Hydrological balance of low intensity rainfall in cultivated loess soils**

\[
\frac{dP_i}{dF_i} = C_i \times P_i
\]  \hspace{1cm} \text{(2.10)}

in which

- \( P_i \) = macropore volume of reference/initial situation, which is a result from cultivation, i.e. ploughing or harrowing (m³/m³)
- \( P_s \) = macropore volume of cultivated loess soil, dependent of slaking, welding, loss of consistency, soil moisture content and macropore flow (m³/m³)
- \( F_i \) = water flux as bypass flow in macropores (m/s)
- \( C_i \) = constant, dependent of ability to slake, thresholds for consistency and antecedent soil moisture content as a controlling factor for slaking and dispersion; inverse velocity (s/m)

In the cultivated loess profiles differences in bulk density before and after experiments are low, however differences in macropore volume are present (Table 4.2.6a to c). This means that probably in this type of soil and on the scale of these experiments a redistribution of pore volume takes place during rainfall. However, macropores are available and in some cases an
CHAPTER 8

**Figure 8.2.1b** Hydrological balance of high intensity rainfall in cultivated loess soils (for explanation symbols see legend Fig. 8.2.1a)

**Figure 8.2.1c** Hydrological balance of high intensity rainfall after low intensity rainfall in cultivated loess soils (for explanation symbols see legend Fig. 8.2.1a)
increase in macropore volume is evident.

To calculate constant $C$ for the various cultivation types, the average rainfall intensity of the A and B experiments was used as a flux. Differences in macropore volume were calculated with $P$ (pore volume) as the situation before the experiments. The rainfall intensity of the last A & B experiment was used. The results of the calculations of $C$ are not very clear. In the upper layer of the Ap the most positive $C$-values were found for harrowed soil. These positive $C$-values mean that the amount of macropores increase in the Ap1 of the harrowed soil during rainfall, and not in the Ap1 of the ploughed soil. Negative values were not mentioned because they mean a decrease in macropore volume or water flux, which was not interesting for the aim of this research. This happened for the wheel track experiments. The following positive $C$-values were found:

Harrowed soil, Ap1: 1 low intensity exp.: $C = 1.37 \text{s/m}$
3 low intensity exp.: $C = 0.893 \text{s/m}$
1 high intensity exp.: $C = 1.12 \text{s/m}$
3 high intensity exp. $C = 0.468 \text{s/m}$

Ploughed soil, Ap1: 3 high intensity exp.: $C = 0.117 \text{s/m}$
Ap2: low + high intensity exp.: $C = 0.448 \text{s/m}$

$C$-values of harrowed soil in Ap1 are higher than $C$-values of ploughed soil. So, the difference in pore volume in the upper part of the Ap in harrowed soil is probably higher than in ploughed soil. This was also observed by the analysis of other data. Only in the Ap2-horizon of the ploughed soil a positive $C$-value was found. Which means that the dynamics of the macropores in the Ap2-horizon in ploughed soil are higher than in harrowed soil. A remarkable fact is that these dynamics are observed after low intensity followed by high intensity. From this and other data is concluded that ploughed soil is very vulnerable to soil erosion, either surface or subsurface, when short high intensity rainfall occurs after a long period of low intensity rainfall.

8.2.5 Drainage model for infiltration in and runoff on cultivated loess soils

Considering the rill erosion model on loess soil, posed in Chapter 2, a few adjustments should be made to make it more appropriate for cultivated loess soils (Figure 2.1b). Evaluating the results mentioned before in this Chapter two situations previous to rill erosion are explained.

Figure 8.2.2a shows a ploughed loess profile in which macropores are most abundant in the lower Ap (Ap2). However because of the bigger clods caused by ploughing macropore flow occurs through the upper and lower Ap. The macropore flow infiltrates in the lower Ap and stagnates because of a discontinuity in structure by the Bt or a probable plough sole. This results in a moist upper layer and a more wet lower Ap above the Bt-horizon. Finally, however this was not proved by the experiments, the more wet or saturated soil aggregates lower in the profile loose their consistency and cause an instable soil profile, which will risk deep rill erosion. This can especially occur when low intensity rainfall is followed by high intensity rainfall. Low intensity causes in this situation already saturated soil aggregates, which are very vulnerable to erosion and especially the high energy of high intensity rainfall.
For loess soil that was only freshly cultivated by harrowing in the upper 5 cm, the following model was developed (Fig. 8.2.2b). The profile of this soil is dominated by soil matrix flow and not by macropore flow. During rainfall, a continuously decreasing infiltration front is observed. The upper layer of the Ap is saturated and the lower part of the Ap is moist after the experiments. The boundary of lower Ap and Bt-horizon shows a more undulating layer than in ploughed soil. The lower Ap has a more diffuse transition into Bt-horizon. The saturated layer at the surface indicates that this situation shows a higher risk for sheet erosion or shallow rill erosion. This can especially occur during high intensity experiments on relatively dry soil. High intensity after low intensity rainfall shows less vulnerability to erosion because of the pre-wetting and stable structure of the soil profile.

A third model is derived from this research, i.e. an existing rill system in ploughed loess soil (Fig. 8.2.2c). When rills have already been formed in ploughed loess soil the following processes take place. In the interrill area macroporosity is higher than under and around the rills. This causes a higher macropore flow in the interrill area during rainfall. The lower soil moisture content in the interrill area than the soil moisture content around the rills gives evidence for a drainage direction from the interrill area to the rills. This is part of the model on which this research was based (Fig. 2.2b). However, evidence was not found for the process of initiation of a rill mentioned in this model.

**Figure 8.2.2a** Freshly ploughed soil; risk for deep erosion
Both models for badland and loess soils have been evaluated and adjusted in the preceding chapter. Considering research question 4 and the 3 hypotheses mentioned in section 1.2 it is interesting to find out in which area and in what situation the rill model from which the research was derived is valid.

The theoretical model of Gerits et al (1987), here mentioned as the drainage model, has been applied to both the badland and loess situations. In section 8.1.5 it was shown that the drainage model is not valid for the white marls (experiencing rill erosion) and for the grey marls, (experiencing mass movements and mud

**Figure 8.2.2b** Freshly harrowed soil; risk for sheet erosion and shallow rill erosion (for explanation see legend Figure 8.2.2a)

**Figure 8.2.2c** Rill system developed in ploughed soil (for explanation see legend Figure 8.2.2a)
flows). The drainage model could be applied to the brown marls (experiencing mass movements and slight rill erosion). However, this was not completely verified by the experiments.

The conclusion from section 8.2.5 is that the drainage model can be partly applied to freshly ploughed loess soil in which there is no evidence of rill erosion yet. On the other hand is the model also appropriate for a rill system developed in ploughed loess soil. However, the process of rill initiation mentioned explained in the drainage model could not be proved in this study.

From the above is concluded that the drainage model is appropriate for ploughed loess soil with a few adjustments for the process of rill initiation. According to the gaps in the studied processes experiments in future research could be adjusted to find the missing processes. For the badland regoliths, the drainage model is not applicable and needs many adjustments.

8.4 Conclusions and recommendations

The general aim of this research was:
To investigate critical conditions for the initiation and development of rill erosion (in soils containing many macropores above an impeding layer) in representative marl regoliths and cultivated loess soils.

The formulated hypotheses were:
• Rill initiation in badland areas is enhanced by the water saturation of the topsoil with many macropores above an impeding layer and by the occurrence of crack flow.
• In freshly ploughed loess, rill initiation is favoured by water saturation in the topsoil, by an impeding layer (plough pan) and by preferential flow through macropores.
• Rill development can be explained by considering them as drains. There is a feedback caused by the relationship between soil moisture content and shear strength dynamics.

General conclusions from this research are:
1. Rill initiation in badland areas is enhanced by water saturation of the top layer of the regolith profile. Only in badland regolith, suffering from mass movements, with a considerable high crack density and showing deep cracks, macropore flow could play a role in rill initiation.
2. It has not been demonstrated by the research that rills in badland regolith can be considered as drains. By modifying the experiments it could be possible to study if this is also valid for badland regolith experiencing mass movements.
3. In freshly ploughed loess soils, macropore flow probably occurs and contributes to the saturation of the soil aggregates in the lower Ap-horizon. This process can increase the risk for deep rill erosion. However, in more shallow cultivated loess soils, like harrowed loess, a risk for sheet erosion and shallow rill erosion is caused by the saturation of the surface layer of the Ap-horizon.
4. Measurements in and around a rill system in ploughed loess soil show that rills could be considered as drains. However, some further research is needed, because these measurements are not absolutely conclusive.
5. Possible critical conditions for the initiation of rill erosion in badland regoliths and cultivated loess soils are especially found in the macropore volume, the antecedent soil moisture content, the rainfall intensity and in the various dynamic soil properties.

It is recommended that the missing processes mentioned in the preceding chapter will be the subject of further research. These are the subsurface processes that lead to rill initiation. Similar experiments to those used in this study could be slightly modified to find the answers to the remaining questions of rill initiation. Possibly, newly developed, measurement methods could possibly be used to detect subsurface processes without disturbance.

The macropore model explained in Chapter 2 and sections 8.1.4 and 8.2.4 needs to be developed by other experiments and measurements. The constant $C$, which is calculated for the experiments in badland regolith and cultivated loess soils, is not stable during the infiltration process. This is caused by start and change of runoff and therefore infiltration and also probably not linear dynamics of pore volume during the experiments.

It would be very useful to put the discovered processes into a three-dimensional model in time. Especially subsurface processes have to be represented, which are connected to erosion processes at the surface. According to field experience rill erosion does not occur only because of the hydraulic conditions of overland flow exceeding specific thresholds, but in some cases it already initiates before these critical values are attained. This implies that various processes can initiate rill erosion. Following Horton’s ‘hydrophysical’ approach (Horton, 1945) many researchers studied hydraulic rill characteristics and modelled them (Govers, 1991; Rauws, 1987; de Ploey, 1989; Elliot and Laflen, 1993; Gilley et al., 1993; Gilley et al., 1990; Govers and Rauws, 1986; Govers, 1992; Rose et al., 1983). Other researchers have found more importance of the interaction of soil and water. Their models of rill erosion have incorporated chemical and physico-chemical processes (Gerits, 1991; Gerits et al., 1987; Imeson and Verstraten, 1988; Torri et al, 1987). During the last decade more spatial conditions have been built in rill erosion models (Favis-Mortlock et al., 1998; Nearing et al., 1989; Wright and Webster, 1991). To get more knowledge about the exact processes which cause the initiation of rills and the prediction of the development of the rills and the rill system, modelling of chemical, physical and physico-chemical processes and integrating these in a spatial system is a potentially important tool. Boogaart (1996) compared different algorithms for spatial modelling. He found a dependency for the developed landscape of flow routing algorithms and the initial situation. There is more need to find quantitative relationships between model and landform parameters and geomorphological processes.

Possible spatial models or model environments suitable for modelling of rill initiation are the model of Wright and Webster (1991) and the model environment of PCRaster (Wesseling et al., 1996). Catchment modelling in loess was done with a physically-based PCRaster model, LISEM (Stolte et al., 1997). However, it was not used in this study because of the smaller scale experiments. Especially the macropore model, part of the drainage model and the hydrological balance of badland regolith and cultivated loess soil are important to relate to each other. The spatial modelling of these processes will give more insight in the relationship of subsurface processes to surface erosion processes.
Detailed experimental studies of small scale soil erosion processes are not only of scientific value. They can also be used to improve the efficiency and effectiveness of soil conservation and protection practices (Geelen et al., 1996). Soil erosion is now recognised as one of the major threats to sustainable land use, both with respect to farmland and agro-pastoral areas (DG-Env, 2002). Slowly, the enormous off-site damage being caused by soil erosion is being appreciated. When this thesis was conceived, one of the biggest perceived research gaps concerned the relative lack of data and information regarding the influence of dynamic soil properties on erosion. This is still the situation today. This area of research has remained under-investigated because of the technical difficulties encountered. This thesis successfully managed to observe and monitor how the dynamics of soil behaviour affected or influenced the initiation of rills. Some of the implications for soil conservation that emerge when dynamic soil properties are taken into account are illustrated in the next paragraphs.

Firstly there are implications in relation to the planning of soil conservation measures and determining when and where they are needed. The rill initiation mechanisms identified in this thesis, for example, show that rill erosion can be expected at much lower threshold rainfall intensities than is expected from the assumptions of Horton’s model of rill initiation. Research indicated that on farmland critical factors are soil compaction and the waterstable properties of soil aggregates. This Ph.D.-research suggests that to reduce the risk of erosion a good strategy is to improve soil structure and reduce compaction. It also implies that patterns of rill erosion sensitive areas can be inferred from easy to measure indicators.

The second set of implications concerns the importance of soil erosion pathways for the movement of phosphorous and other chemicals that contaminate drinking or surface water. Knowledge regarding this is vital in order to plan drinking water treatment and measures to improve surface water quality and ecology as directed by the Water Framework Directive of the EU. This thesis has identified completely different pathways from those that are normally described in the literature and therefore has great relevance for many water quality issues. The soil should be managed to ensure that the ploughed soil does not develop conditions that can allow rills to form. For example the connectivity of subsurface macro-pores should be guarded against. Grass strips that are used to intercept overland flow probably also reduce the risk of this occurring (v. Dijk et al., 1996). However, there is a good case for not allowing woody vegetation on grass strips as this could eventually favour increased connectivity.

The idea of comparing rill erosion processes in two considerably different areas was to learn from the similarities and differences in soil and material properties and processes. Similarities appeared to be especially soil physical properties, such as macropore volume and the susceptibility of the material to slaking and therefore erosion. This high erodibility was, however, in the badlands caused by a high shrinkage and swelling capacity and in the cultivated loess...
soils by ploughing the topsoil. Also in the badlands, chemical and physico-chemical properties played an important role, whereas in loess soils they did not seem to be a determining factor. Considering the consequences of rill erosion processes, they have a higher off-site effect in the loess area than in the badland area. In the loess area rill erosion causes a loss of the fertile layer and this is transported to the lower areas, into the villages and choking the drain system. This increases the risk and hazard of flooding. In the badland area, off-site effects are less important, because there are fewer people and the eroded material is not transported very far because of the isolated valleys. However, on-site problems create difficult conditions for the farmer. Therefore, non-agricultural land use functions are recommended for these areas.

Badland area
Because areas of badlands in marls have extremely erodible regoliths in which rill erosion or liquefaction can occur, it would seem risky to use such areas for intensive farming. Nevertheless, in large areas of Spain and Italy this is being done. These areas are increasingly being used for irrigation or for growing wheat and in both cases massive rill erosion and off-site flooding are occurring.

Although it might seem obvious that badland areas are not suitable for farming, traditional agricultural land use practices seem to be sustainable on the flat valley bottom and terrace areas. However, on these flat areas and artificially made terraces mentioned above, the exploitation of olive trees is possible but not lucrative and there is always the risk of tunnel erosion in the dispersive soils. The regolith properties (high amounts of salts, and physical properties that inhibit plant growth) mean that these areas should not be cultivated but that the restoration of the semi-natural vegetation cover should be encouraged.

In some ways badland areas are very resilient systems; once they are formed they are hard to change. Nevertheless, the land reshaping going on today is threatening the continued existence of many badland areas. Although this may work for a few years, this thesis would suggest that reshaping is a high risk activity that in time will lead to mass movements and the development of new gully systems. It is better to promote other functions in these areas, such as for example nature conservation, extensive grazing and sustainable tourism. An example of this is the badland area near Almería in South-east Spain, which already was declared a nature reservation.

When soil profiles develop on the lime rich soils from which salts have been leached, soils can develop excellent physical properties and have high amounts of organic carbon. As they now contain almost no organic matter, they have a great potential to sequestrate carbon.

How important is offsite damage?
A large part of the badland area is clearly experiencing mass movements and has a very high rate of sediment production. It does not necessarily follow that there is a high off-site impact.

A conclusion of this thesis is that after exceeding certain thresholds of flow hydraulics, the sediment concentrations in the rills surprisingly decreases. This could mean that the transport capacity of the runoff increases and that the runoff has the ability to erode the stream bed.
downstream from the badland area. However, the experimental results are based on simulat-
ed rainfall events, with a ten-year return period. Unfortunately, during the field study of this
research no real large events were observed that enabled their impact to be directly
observed.

Supporting evidence for a very high rate of erosion is provided by the very high rates of
weathering and weathered regolith removal. Observations showed that after removing the
regolith, a new regolith layer with rills at the surface and sediment production was developed
again within a period of a few months. It is obvious from this result that the regolith layer is
usually in a critical condition that cannot be influenced easily by measures to control erosion.
The rate of erosion is therefore in practice limited by the amount of rainfall and rate of weath-
ering.

Although the rate of erosion is high, the risk of damage to society of a ten-year event is pos-
sibly low, as the offsite damage would not affect many people. An event with a one-hundred
year return period could have a very large impact. In the loess region in South-Limburg ero-
sion is a much more serious problem and a ten-year event is important.

Loess area
On the cultivated loess areas of South-Limburg, soil erosion is a serious issue. As already
mentioned, there is concern about both the on-site loss of fertility and the off-site damage to
other cultivated or urban areas and the choking of drainage systems. Loss of soil fertility is
recognised today as a general long-term consequence of decades of land degradation in
which the cultivatable soil layer is reduced in thickness by erosion. Fertile loess soils were
formerly much more extensive in South-Limburg and occurred on areas that now have very
clayey or sandy soils that are naturally less productive.

Soil erosion in the area increased after the big re-allotments in this area in the 1960’s and
1970’s (Dorren and Imeson 2005). Research into the causes of soil erosion in South-Limburg
done by many people during the last decades eventually resulted in the introduction of more
sustainable practises (Hoofdproductschap Akkerbouw, 2003). The findings from this research
also contributed to these improvements.

This thesis concluded that areas, which had been ploughed in the autumn and harrowed
in spring, had a higher risk of sheet erosion. In contrast, areas, which had been ploughed in
spring and immediately harrowed, had a higher risk of serious rill development.

The erodibility of soil, freshly ploughed in the spring, is greater than that of soil, ploughed
earlier in the autumn. Erodibility is even greater when the soil has been previously saturated
by a low intensity shower. Soil aggregation and structure are better for a freshly harrowed soil,
than for a freshly ploughed one. This is an important conclusion for sustainable land use.
There is much discussion at the moment about the relative advantages of winter ploughing.
On the one hand if there is frost in winter, it can lead to a better soil structure. On the other
hand it often results in more erosion. The research here would suggest that it is better not to
plough soils in the late winter, when there is a higher risk for saturation by rainfall, but to
plough and harrow them in spring, just before sowing of the crops. The distribution of soil
moisture in the soil profile is very closely affected by the effect of ploughing on the distribu-
tion of macropores. The more macropores in the lower Ap, the more rapid infiltration there is
to this part of the soil. Considering soil, ploughed in autumn, it was evident that the macropores that were produced had largely disappeared again in spring. The gradual disappearance of macropores means that the risk of rill erosion by subsurface flow decreases. This means that during a period of half a year a soil property can recover again. However, this improvement is compensated for by a greater risk on rill erosion by overland flow.

Wheel tracks have long been recognised as important for rill initiation. Research in this thesis showed that in both cultivation systems, wheel pressure had a similar influence in soil erosion and soil physical and dynamic properties. The conclusion is that wheel pressure always encourages rill development.

**Combating erosion in South Limburg, The Netherlands**

During the last five years, several measures have been taken to reduce erosion and in general these should have had a positive influence on reducing rill erosion, which is a major source of flood runoff (Hoofdproductschap Akkerbouw, 2003). Especially the reduction of winter ploughing and the use of catch crops are beneficial. However, cold and wet autumn weather always brings with it the risk that the soil structure will be damaged in a way that increases the risk of rill erosion. Nevertheless, by increasing the organic matter content of the soil and reducing the amount of compaction, critical conditions for rill erosion are likely to occur much less frequently today than they did before the new regulations came into effect. Improving soil quality and soil health is a good strategy for combating soil erosion in Limburg.

**Land consolidation versus farming**

In a recent paper Dorren and Imeson (2005) showed how the recent history of soil erosion and conservation in South Limburg could be explained by a loop in an adaptive cycle that links policy to research. The true trigger of the soil erosion problem in south Limburg was the re-allocations that took place during the 1970’s. This was not appreciated at the time and research was initiated to identify the causes of the problem and to find solutions. As a result of this research and the implementation of soil conservation measures developed in Germany, soil conditions were improved in the 1990’s to the extent that the problems have largely gone away. Soil erosion might have stopped by itself due to the resilience of the land. Although public perception was that the farming practices were responsible, in practice it was not the normal farming practices that were too blame but the treatment of the land by the authorities during the farming reallocation work.

**Importance of soil structure to soil resistance against external forces**

An important example of the devastating force of subsurface flow on soil structure, and therefore on society, is the recent flooding of New Orleans in September 2005, after hurricane Katrina. One of the reasons of the collapse of dikes and dams was the subsurface erosion process of piping. In The Netherlands piping caused weakening of the dikes, and therefore a high-risk situation, during the river floods of 1993 and 1995. Another case in The Netherlands was the unexpected collapse of a dike in the village of Wilnis. The problem in this case was drying out of the peat soil, which caused a weakening of the soil structure and therefore of the dike. These facts suggest that studying soil structure, subsurface erosion and preferential flow are of vital interest for society.
Summary

Soil erosion can be a major problem in hilly and mountainous areas in both temperate and drier climates. Many soils are suffering from concentrated surface flow in shallow channels (known as rills), entraining and transporting enormous amounts of sediment. The process of rill erosion is controlled by rainfall and slope water and occurs on soils with specific properties when specific thresholds are exceeded. This thesis studies the initiation and development of rills influenced by certain specific soil properties, such as soil structure and consistency. The initiation of rills is a very complex process as not only are rainfall and slope water conditions important, but also the way in which the soil or regolith changes their properties in response to wetting during rainfall. Two areas were selected for studying rills. These are a natural badland area in Southeast Spain and a cultivated loess area in South-Limburg, The Netherlands. Similarities between these areas are their susceptibility to rill erosion and their high macroporosity in the topsoil above a relatively impermeable layer. The general aim of this study is to investigate critical conditions for the initiation and development of rill erosion in regoliths and soils with a high macroporosity in their topsoil, e.g. marl regoliths and cultivated loess soils. The most important research question is whether rill initiation and development is enhanced by the infiltration of water and specific dynamic soil properties.

A general introduction of the research is given in Chapters 1 to 3.

The subjects of rill erosion and modelling initiation and development of rills are introduced in Chapter 1. The approach of the study is mainly experimental, however, research questions and experiments were derived from a conceptual drainage model.

The drainage theory for rill erosion combined with dynamic soil properties is explained in Chapter 2. This theory is derived from the drainage theory of Hooghoudt and Donnan. An important aspect is the presence of a (semi-) impermeable layer. Specific (top)soil properties that are mentioned are the amount of micro- and macropores, shrinkage and swelling of the soil and soil consistency. An equation was established to describe the dynamics of these soils influenced by infiltration of slope and rain water.

The field areas are described in Chapter 3, as are the methods of laboratory, field and data analyses. The badland area in Southeast Spain is a naturally actively eroding area, with a Mediterranean climate. In this area three different regoliths were studied. One material is suffering from mainly rill erosion and two other materials from mainly mass movements. Soil erosion in the cultivated loess area in Southern Limburg, with a temperate climate, is enhanced by various human activities, in particular those related to soil cultivation practices, e.g. ploughing.

In part II, Chapters 4 to 6, the results of the laboratory and field experiments are presented and discussed.

The dynamic properties of the badland regoliths, discussed in Chapter 4 reveal that there are three types of material, namely white, brown and grey marls. The white marls have the lowest shrink and swell capacity and the grey marls the highest, however creating high
macroporosities in all materials. Surface features of erosion and mass wasting are predominantly rill and pipe erosion on the white marls and mass movements on the brown and grey marls. The unweathered regolith could behave like an impermeable layer. The cultivated loess area has the typical decalcified loess soils of the region. Two types of cultivated soil profiles were studied, one recently ploughed and the other recently harrowed. As could be expected, the ploughed soil had a higher volume of macropores. The loess profile consists of an Ap and a Bt horizon. In the ploughed profile a plough sole could function as a semi-impermeable layer.

The results of rainfall simulation experiments are presented in Chapter 5. In the badland regoliths infiltration of rainfall and slope water occurred on almost all measurement points on the experimental slopes. The upper part of especially the white marl regolith profile was completely saturated with water during the experiments. White and brown marls showed a fluctuating wetting front in depth, which indicated an important contribution of macropore flow. This is in contrast with the grey marl regolith that had a more homogeneous wetting front. On the white marls relatively more runoff was generated, indicating a lower infiltration capacity than in the other regoliths.

In ploughed loess soils, the conditions for macropore flow appeared to be more favourable than in the harrowed soil. The ploughed soils had a weaker structure than the harrowed soils. Soil moisture data indicate the presence of a discontinuity, by a relatively impermeable layer, in the ploughed soil. However, such a layer could not be identified in the harrowed soil. This difference is even more pronounced under higher intensity rainfall. High intensity rainfall has a less marked effect on the soil surface if it is preceded by low intensity rainfall and therefore also for the infiltration characteristics. However, low intensity rainfall creates favourable conditions for runoff generation during high intensity rainfall. The effects of compaction at the surface in a wheeltrack dominate the effects of tillage type. Water retention curves show that in and around rills in ploughed loess soil more smaller pores are present than in the interrill areas. Evidence of drainage from higher parts of the slope into a rill is seen by the spatial soil moisture distribution.

Results of the soil erodibility parameter analysis are presented in Chapter 6. Soil shear strength, consistency, roughness at the surface, aggregation and sediment discharge are compared with the soil moisture data. The grey marls appear to produce the most erodible material and the white marls relatively the least. This means that the material mainly suffering from rill erosion is less erodible than the other materials on which mass movements are predominant. The differences show that soil structure and macropores play a very important role in influencing the erodibility of these materials. The amount of the clay mineral illite, combined with a high sodium content is also responsible for the erodibility of the brown marl regolith. For the grey marl regolith a high smectite content plays an important role for the erodibility.

Ploughed loess soils appeared to be more susceptible to erosion than harrowed loess soils. This is especially the case when high intensity rainfall follows low intensity rainfall. Rainfall has more impact on the decrease of surface roughness in ploughed than in harrowed soils. Combined with a higher soil moisture content of the upper part of a profile in ploughed soils, this could be a favourable condition for rill erosion.

The results mentioned above were used to improve the drainage model and the macropore theory mentioned in Chapter 2.
Part III contains a synthesis of the results of the experiments and describes the erodibility and hydrological response of the badland regoliths and cultivated loess soils.

In Chapter 7 the results are discussed to find answers to the relevant research questions derived from the objectives mentioned in Chapter 1. Relationships between soil water and soil and regolith properties are explained in this chapter. Also indicators for thresholds of erodibility and related erosion processes are discussed.

For badland regoliths the indicators of erodibility appeared to have various values for the different process domains of rill erosion and mass wasting. A direct indicator for erodibility of badland regoliths was found to be the relationship between soil moisture change and the behaviour of sediment concentration. This relationship can be used to find soil moisture threshold values for the increase of the erodibility. The indicators mentioned in Chapter 7.1, i.e. surface sealing, increase of runoff, soil consistency, macroporosity, chemical soil properties and clay mineralogy and texture are able to account for the thresholds in the above relationship. This is not valid for the C5-index and the liquid limit for the soil consistency, which do not show consistent relationships with the erodibility of these regolith materials. In general, relatively more sediment is eroded from badland areas susceptible to mainly mass movements than to mainly rill erosion. A regolith that is susceptible to rill erosion becomes sealed after water saturation, which also happens to regolith containing a high amount of smectite, after a preceding rainfall event. Apparently, before the saturation of the surface layer, dynamic soil properties play a major role in the erosion process, whereas after saturation and increase of the runoff, the increasing importance of flow hydraulics results in an even more complex erosion process in these badland areas.

In ploughed loess soils, rainfall infiltrates quickly into the Ap-horizon. A discontinuity in the infiltration front is seen between the Ap and Bt-horizons. Macroporosity, because of ploughing and increase of macroporosity probably causes by-pass flow deeper into the Ap-horizon. Infiltrated water in the harrowed soil, on the contrary, remains more in the topsoil. This is explained by a lower macroporosity in the Ap. Ploughed soil appears to be more sensitive to slaking and probably welding than harrowed soil. These conditions of ploughed soil combined with a higher soil moisture content especially in the subsoil create a higher risk for deep rill erosion during or after high intensity rainfall. Harrowed soil shows less susceptibility to erosion and combined with higher soil moisture in the topsoil, sheet erosion or shallow rill erosion is more probable. Around a rill system soil moisture accumulates in and under a rill. Macroporosity is higher in the interrill area. This indicates that drainage by by-pass flow from the interrill area to the rills can occur.

Evaluation of the model in Chapter 8 shows that the drainage model is appropriate for ploughed loess soil, with a few adjustments being needed for the process of rill initiation. According to the gaps in the studied processes, experiments in future research could be performed to allow the missing processes to be found. For the badland regolith, the drainage model is not applicable and would need too many adjustments.

In the badland area it appears that on the white and brown marls, more macropore flow is generated than on the grey marls. In white and grey marls the upper layer becomes water-saturated during rainfall. Probably, the drainage model is applicable to the brown marls, because macropore flow seems to be more important in this material than soil matrix flow. However, the experiment was too short to form a water saturated layer deeper in the profile. In combination with rills as surface features, the drainage model should be adjusted as fol-
The upper layer of the regolith becomes water saturated above the lower part of the profile. Macropore flow infiltrates in the soil matrix deeper in the profile. Finally, the surface layer of the regolith starts to flow and mass movements take place, due to a loss of consistency. This mechanism is different from the hypothesis that because of the loss of consistency of the saturated layer deeper in the profile, soil aggregates collapse and a rill initiates.

Considering the drainage model for loess soils, a few refinements have to be made to make it more appropriate. In ploughed loess, macropores are most abundant in the lower Ap. Infiltrated water flows as macropore flow into the lower Ap and stagnates on a plough sole or a more compacted Bt-horizon. Finally, the more wet or saturated soil aggregates lower in the profile lose their consistency and cause an instable soil horizon, with the risk of deep rill erosion. Antecedent low intensity rainfall causes in this situation already saturated soil aggregates that are very vulnerable to erosion and especially during high intensity rainfall.

Harrowed loess soils are dominated by soil matrix flow. The upper Ap is saturated and the lower part of the Ap is moist after rainfall. This lower Ap has a more diffuse transition with the Bt-horizon, compared to a ploughed profile. A continuously decreasing infiltration front is seen after infiltration. The saturated layer at the surface indicates that there is a higher risk for sheet erosion or shallow rill erosion. Pre-wetting of the profile by low intensity rainfall causes a lower vulnerability to erosion. A third model describes an existing rill system in ploughed loess soil. In the interrill area macroporosity is higher than under and around rills. This causes a higher macropore flow in the interrill area during rainfall. The lower soil moisture content in the interrill area than the soil moisture content around the rills, gives evidence for a drainage direction from the interrill area to the rills.

General conclusions from this research are:
1. Rill initiation in badland areas is enhanced by water saturation of the top layer of the regolith profile. Only in badland regoliths, suffering from mass movements, with a considerable high crack density and showing deep cracks, macropore flow could play a role in rill initiation.
2. It has not been demonstrated by the research that rills in badland regolith can be considered as drains. By modifying the experiments it could be possible to study if this is also valid for badland regolith experiencing mass movements.
3. In freshly ploughed loess soils, macropore flow probably occurs and contributes to the saturation of the soil aggregates in the lower Ap-horizon. This process can increase the risk for deep rill erosion. However, in more shallow cultivated loess soils, like harrowed loess, a risk of sheet erosion and shallow rill erosion appears to be caused by the saturation of the surface layer of the Ap-horizon.
4. Measurements in and around a rill system in ploughed loess soil show that rills could be considered as drains. However, some further research is needed, because these measurements are not absolutely conclusive.
5. Possible critical conditions for the initiation of rill erosion in badland regoliths and cultivated loess soils are especially found in the macropore volume, the antecedent soil moisture content, the rainfall intensity and in the various dynamic soil properties.
Implications for policy

In the Epilogue recent problems connected to this Ph.D. research are mentioned. Soil erosion is now recognised as one of the major threats to sustainable land use by the EU. This thesis successfully managed to observe and monitor how the dynamics of soil behaviour affected or influenced the initiation of rills. It also suggests that a good strategy to reduce the risk of erosion is, to improve soil structure and reduce compaction. The importance of soil erosion pathways for contamination of drinking or surface water is seen in order to plan drinking water treatment and measures to improve surface water quality and ecology, as directed by the Water Framework Directive of the EU.

For a specific area as the badland area near Petrer, Spain, it is better to promote functions such as nature conservation, extensive grazing and sustainable tourism.

The results of the study in the cultivated loess area lead to a better understanding of the impact of cultivation practices on erodibility of the soil in combination with soil moisture content and dynamic soil properties. This Ph.D. research suggests that it is better not to plough soils in the late winter, when there is a higher risk for saturation by rainfall, but to plough and harrow in spring, just before sowing of the crops.

Finally the importance of studying subsurface flow is emphasised by the recent flooding in New Orleans and in The Netherlands the flooding in Wilnis and high-risk situations during the river floods of 1993 and 1995. In these situations dikes were weakened because of subsurface flow and piping.
Samenvatting

Bodemerosie is een belangrijk probleem in geaccidenteerde streken in gematigde en drogere klimaten. Veel bodems in deze gebieden zijn onderhevig aan rillerosie, waarbij oppervlaktewater geconcentreerd in ondiepe geulen (rills) enorme hoeveelheden sediment losmaakt en transporteert. Het proces van rillerosie wordt bepaald door neerslag en hellingwater en vindt plaats op bodems met specifieke eigenschappen en bij het overschrijden van bepaalde drempelwaarden. Dit proefschrift beschrijft het ontstaan en de ontwikkeling van rills als gevolg van deze specifieke bodemeigenschappen, zoals bodemstructuur en consistentie. Het ontstaan van een rill is een zeer complex proces, omdat niet alleen neerslag en hellingwater een belangrijke rol spelen, maar ook de verandering van de bodem als gevolg van bevochtiging en infiltratie. De onderzoeksgebieden zijn een natuurlijk geërodeerd badlandgebied (letterlijk ‘slecht land’) in Zuidoost Spanje en een gecultiveerd akkerlandgebied op löss in Zuid Limburg. De belangrijkste overeenkomsten tussen deze gebieden zijn de grote gevoeligheid voor rillerosie en de hoge macroporositeit in de bovenste bodemlaag, boven een relatief ondoorlatende laag in het profiel. De algemene doelstelling van dit proefschrift is het onderzoeken van kritische condities voor het ontstaan en de ontwikkeling van rillerosie in een aantal veelvoorkomende mergelsoorten en in gecultiveerde lössgebieden. De belangrijkste onderzoeksvraag is of het ontstaan en de ontwikkeling van rills wordt versterkt door infiltratie van water in combinatie met specifieke dynamische bodemeigenschappen.

In Hoofdstuk 1 tot en met 3 wordt een algemene inleiding van het onderzoek gegeven. De onderwerpen rillerosie en het modelleren van het ontstaan en de ontwikkeling van rills worden geïntroduceerd in Hoofdstuk 1. Het onderzoek is voornamelijk experimenteel. De onderzoeksvragen en experimenten zijn afgeleid van een conceptueel drainage model. In Hoofdstuk 2 wordt deze drainagetheorie in combinatie met dynamische bodemeigenschappen uitgelegd. Deze theorie is afgeleid van de Hooghoudt en Donnan theorie voor drainage. Een belangrijk aspect hierbij is de aanwezigheid van een relatief ondoorlatende bodemlaag. Specifieke bodemeigenschappen die van belang lijken te zijn voor rillerosie zijn het volume micro- en macroporiën, de krimp- en zwelcapaciteit en de consistentie van de bodem. Een vergelijking is opgesteld voor de dynamiek van de bodem afhankelijk van hellingwater en neerslag.

De resultaten van de veld- en laboratoriumexperimenten worden gepresenteerd en bespro-ken in deel II.


In Hoofdstuk 5 worden de resultaten gepresenteerd van de regensimulatie experimen-ten. In het badlandmateriaal infiltreerde de neerslag en het hellingwater op bijna alle meet-punten van de plots. Vooral de bovenste laag van de witte mergels was volledig verzadigd met water. Het infiltratiefront in de witte en bruine mergels was variabel in diepte, wat een aanwijzing kan zijn voor preferente stroming door macroporiën. In de grijze mergels was een homogener vochtfront te zien. De runoff was relatief hoog op de witte mergels en de infiltratiecapaciteit dus lager dan op de andere materialen.

In de geploegde löss bleken de omstandigheden voor preferente stroming door macropo-riën gunstiger te zijn dan in de geëgd löss. De aggregaatstructuur was slapper in het geploegde profiel dan in het geëgd profiel. Vochtmetingen lieten zien dat er waarschijnlijk een relatief ondoorlatende laag in het geploegde profiel aanwezig was. Dit was niet het geval in de geëgd bodem. Het structuurverschil tussen geploegd en geëgd wordt nog duidelijker tijdens neerslag met hogere intensiteit (60mm/hr). Het effect van de hoge neerslagintensiteit op het oppervlak en de infiltratie wordt minder na regen met een lagere intensiteit (20mm/hr). Neerslag met lage intensiteit creëert gunstige omstandigheden voor runoff tijdens hoge intensiteitbuien. Het effect van compactie aan het oppervlak in een wielspoor overheerst het effect van bodembewerking. Waterretentiecharacteristieken van geploegde löss in een rillsysteem laten zien dat er meer kleine poriën in en rond de rills aanwezig zijn dan in de interrillgebieden. De ruimtelijke vochtverdeling laat zien dat er waterstoming kan zijn van de hogere delen van de helling naar de rills.

De resultaten van de erodibiliteitsparameters worden gepresenteerd in Hoofdstuk 6. Veld- en laboratoriummetingen van de bodem (schuifweerstand, consistentie, ruwheid van het oppervlak, aggregatie en sediment afvoer) worden gerelateerd aan het bodemvocht. De grijze mergels lijken het meest gevoelig voor erosie en de witte mergels het minst. Dit betekent dat materiaal onderhevig aan rillerosie minder gevoelig voor erosie is dan materiaal onderhevig aan massabeweging. De verschillen tussen de materialen laten zien dat bodemstructuur en het volume macroporiën van groot belang zijn voor de erosiegevoeligheid van deze materialen. In het bruine materiaal is de combinatie van het kleiminaal illiet en een hoog natriumgehalte ook van belang voor de erodibiliteit. In de grijze mergels speelt een hoog smectietgehalte een belangrijke rol.

Voor de gecultiveerde lössbodems geldt dat de geploegde bodems gevoeliger zijn voor erosie dan de geëgd bodems. Dit is vooral het geval als neerslag met een hoge intensiteit

SAMENVATTING
volgt op neerslag met een lagere intensiteit. Verder heeft neerslag meer invloed op de afname van de bodemruwheid in geploegde dan in geëgde bodems. In combinatie met een hoger vochtgehalte in het bovenste deel van het profiel kunnen de bovenstaande omstandigheden zeer gunstig zijn voor rillerosie.

De besproken resultaten zijn gebruikt om het drainagemodel en de theorie over de rol van macroporiën (*Hoofdstuk 2*) te verbeteren.

**Deel III** omvat een synthese van de resultaten en beschrijft de erosiegevoeligheid en de hydrologie van het badlandgebied en het gecultiveerde lössgebied.

*Hoofdstuk 7* bespreekt de resultaten van het onderzoek met als doel de onderzoeksvragen uit *Hoofdstuk 1* te beantwoorden. De relaties tussen bodemwater en eigenschappen van bodem en verweringsmateriaal worden verklaard. Ook worden indicatoren voor drempelwaarden van erosiegevoeligheid en hieraan gerelateerde erosieprocessen besproken.

Voor het badlandmateriaal blijkt dat de indicatoren verschillende waarden hebben voor de verschillende erosieprocessen, nl. rillerosie en massabeweging. Een directe indicator voor erosiegevoeligheid van badlandmateriaal lijkt de relatie tussen de verandering in bodemvochtgehalte en het gedrag van het sediment. Hieruit kunnen drempelwaarden van bodemvocht worden gehaald die de toename van de erosiegevoeligheid voorspellen. De indicatoren die deze drempelwaarden kunnen verklaren zijn dichtslaan van het oppervlak, toename van de runoff, consistentie van de bodem, macroporositeit, chemische bodemeigenschappen en kleimineralogie en textuur. De C5-10-index en de liquid limit laten geen consistentie relatie zien met de erosiegevoeligheid. In het algemeen erodeert er meer sediment van badlandmateriaal gevoelig voor massabeweging dan van materiaal gevoelig voor rillerosie. Materiaal dat gevoelig is voor rillerosie slaat dicht nadat het verzadigd is. Dit gebeurt ook met zeer erosiegevoelig badlandmateriaal met een hoog smectietgehalte na een voorafgaande regenbui. Het blijkt dat voorafgaand aan de verzadiging van de bodem en toename van de runoff spelen hydraulische eigenschappen van de runoff een belangrijke rol, wat resulteert in een nog complexer erosieproces.


De evaluatie (*Hoofdstuk 8*) van het drainagemodel laat zien dat het model na een aantal aanpassingen voor het ontstaan van rills geschikt is voor geploegde lössbodems. In toekomstig onderzoek is het van belang de ontbrekende processen te onderzoeken. Het draina-
gemodel is voor het badlandmateriaal niet toepasbaar zonder zeer veel aanpassingen.

In het badlandgebied komt de meeste stroming door macroporiën voor in het witte en bruine badlandmateriaal. In het witte en grijze materiaal wordt de toplaag verzadigd tijdens de regenexperimenten. In het bruine badlandmateriaal is stroming door macroporiën van groter belang dan stroming door de bodemmatrix. Dit kan betekenen dat het drainagemodel wel van toepassing is op dit materiaal. Maar om dit te bepalen waren de experimenten te kort, want er ontstond geen verzadigde laag boven het onverweerde materiaal. Voor het materiaal onderhevig aan rillerosie kunnen de volgende aanpassingen worden gedaan. De toplaag van het materiaal raakt verzadigd en water infiltreert verder in het profiel als stroming door de bodemmatrix en macroporiën. Uiteindelijk begint de toplaag te vloeien en komen er massabewegingen op gang als gevolg van consistentieverlies. Dit mechanisme wijkt of van de hypothese, waarin dieper in het profiel aggregaten verslepen en hun consistentie verliezen, waardoor een rill ontstaat.


**Conclusies** van dit onderzoek zijn:
1. Het ontstaan van rills in badlandgebieden wordt versterkt door de waterverzadiging van de toplaag van het verweringsmateriaal. Preferente stroming door macroporiën kan alleen een rol spelen bij het ontstaan van rills in badlandmateriaal onderhevig aan massabeweging met een zeer hoge dichtheid van scheuren, die relatief diep zijn.
2. Het onderzoek wijst niet uit dat rills in badlandmateriaal kunnen worden beschouwd als drains. Door de experimenten aan te passen kan worden uitgezocht of het drainagemodel geldig is voor badlandmateriaal onderhevig aan massabeweging.
4. Metingen in en rond een rillsysteem op geploegde löss laten zien dat rills zouden kunnen worden beschouwd als drains. Verder onderzoek is echter nodig, omdat deze metingen niet voldoende bewijs leveren.

5. Kritische condities voor het ontstaan van rillerosie in badlandgebieden en gecultiveerde lössbodems worden bepaald door het macroporiënvolume, het initiële vochtgehalte, de neerslagintensiteit en de verschillende dynamische bodemeigenschappen.

**Aanbevelingen voor het beleid**

In de [Epiloog](#) worden recente problemen aangestipt die te maken hebben met dit onderzoek. De EU ziet bodemerosie als één van de belangrijkste bedreigingen voor duurzaam landgebruik. Dit promotieonderzoek laat zien hoe de dynamiek van het bodemgedrag het ontstaan van rills beïnvloedt. Er komt uit naar voren dat het verbeteren van de bodemstructuur en het voorkomen van compactie een goede strategie is voor afname van de kans op erosie. Voor drink- of oppervlaktewatervervuiling is het van belang om de impact van bodemerosie in een gebied te kennen om drinkwater te zuiveren en de kwaliteit van het oppervlaktewater en de ecologie te verbeteren, zoals wordt bepaald door de EU Kaderrichtlijn Water.

Voor een specifiek gebied, zoals het badlandgebied bij Petrer in Spanje zijn natuurbeheer, extensieve begrazing en duurzaam toerisme, geschiktere functies.

De resultaten van het onderzoek in gecultiveerde lössbodems leiden tot een beter begrip van de invloed van bodembewerking op de erosiegevoeligheid van de bodem in combinatie met bodemvocht en dynamische bodemeigenschappen. Uit het onderzoek komt naar voren dat het beter is niet te ploegen aan het eind van de winter als de bodem waterverzadigd is, maar te ploegen en te eggen vlak voor inzaai.

Resumen

La erosión de los suelos puede ser un importante problema en zonas de montaña y con pendientes, tanto en climas templados como en secos. Muchos suelos están afectados por la arroyada superficial concentrada en canales someros (conocidos como rills), que arrancan y transportan enormes cantidades de sedimento. El proceso de la erosión por rills está controlado por la lluvia y la pendiente del flujo y ocurre en suelos con propiedades específicas cuando determinados umbrales son superados. Esta Tesis estudia la influencia de ciertas propiedades de los suelos, como la estructura del suelo y la consistencia, sobre el inicio y desarrollo de los rills. El inicio de los rills es un proceso muy complejo dado que no solo cuentan las condiciones de lluvia y pendiente, sino también el modo como el suelo y la regolita cambian sus propiedades en respuesta a la humectación durante la lluvia.

Para el estudio de los rills se han seleccionado dos áreas: Una zona de abarrancamientos (badlands) en el Sudeste de España y una zona cultivada sobre depósitos de loes en el Sur de Limburg, Países Bajos. El propósito general de este estudio es investigar las condiciones críticas para el comienzo y desarrollo de la erosión por rills en suelos cultivados en loes y regolitas sobre margas representativos.

Una introducción general de la investigación se ofrece en los capítulos 1 a 3. Los temas relativos a la erosión por rills y la modelización de su inicio y desarrollo se introducen en el Capítulo 1. La aproximación al estudio es principalmente experimental. Las cuestiones de investigación y los experimentos se han derivado de un modelo conceptual del drenaje.

En el Capítulo 2 se explica la teoría del drenaje en combinación con las propiedades dinámicas del suelo. Esta teoría se deriva de la teoría del drenaje de Hooghoudt y Donan. Un aspecto importante es la presencia de una capa (semi-) impermeable. Las propiedades específicas del suelo que se mencionan son: la cantidad de micro- y macroporos, la expansión y contracción del suelo y su consistencia. Una ecuación ha sido establecida para describir la dinámica de los suelos estudiados, influenciada por la infiltración del agua de lluvia y escorrentía.

Las zonas de campo se describen en el Capítulo 3, así como los métodos de laboratorio, de campo y análisis de datos. La zona de badlands en el Sudeste de España es una zona de erosión activa natural, con un clima Mediterráneo. En esta área se han estudiado tres tipos de regolita. Un material estaría afectado por erosión en rills y los otros dos por movimientos en masa. La erosión del suelo en la zona de cultivos del loes del Sur de Limburg, con un clima templado, esta afectada por diferentes actividades humanas, en particular aquellas relacionadas con prácticas agrícolas.

En la parte II se presentan y discuten los resultados de los experimentos de campo y laboratorio.
Las propiedades de la regolita de los badland, mencionadas en el Capítulo 4 revelan que hay tres tipos de material, denominados margas blancas, marrones y grises. Las margas blancas tienen la menor capacidad de expansión y contracción y las grises la mayor. Los rasgos de la superficie de erosión y denudación son predominantemente erosión en rills y pipes en las margas blancas y movimientos en masa en las marrones y grises. La regolita no meteorizada puede ser vista como una capa impermeable. La zona de cultivos en loes tiene los suelos loesicos descalcificados típicos de la región. Se han estudiado dos tipos de perfiles de suelo cultivados, uno labrado recientemente y el otro recientemente rastrillado. Como podría esperarse el suelo labrado tiene un mayor nivel de macroporos. El perfil de loes consiste en un horizonte Ap y un Bt. En el perfil labrado una suela de arado funciona como una capa semi-impermeable.

Los resultados de experimentos de simulación de lluvia son presentados en el Capítulo 5. En las regolitas de badlands la infiltración del agua de lluvia y escorrentía ocurre prácticamente todos los puntos de medida en las laderas experimentales. La parte superior del perfil, especialmente en las margas blancas, se satura de agua completamente durante los experimentos. Las margas blancas y marrones mostraron un frente húmedo de profundidad variable, el cual indica una importante influencia del flujo de macroporos. Esto contrasta con la regolita de las margas grises que tiene un frente húmedo mucho más homogéneo. En las margas blancas se generó relativamente más escorrentía, mostrando una capacidad de infiltración inferior a las otras regolitas.

En los suelos de loes labrados las condiciones para el flujo de macroporos parecen ser más favorables que en los rastrillados. El suelo labrado tiene una estructura más débil que el rastrillado. Los datos de humedad el suelo indican la presencia de una discontinuidad, por una capa relativamente impermeable en el suelo labrado. Sin embargo esta capa no se ha podido identificar en el suelo rastrillado. Esta diferencia es mucho más pronunciada con intensidades de lluvia mayores. La lluvia de alta intensidad tiene un efecto menos pronunciado sobre la superficie del suelo si esta precedida de una de menor intensidad y por tanto, también por alas características de la infiltración. Sin embargo, las lluvias de baja intensidad crean condiciones favorables para la generación de escorrentía durante intensidades elevadas. Los efectos de compactación de la superficie en las rodadas dominan sobre los efectos del tipo de laboreo. Las curves de retención hídrica muestran que en las zonas labradas del loes, en los rills y alrededor de estos, hay poros más pequeños que en las áreas entre rills. La evidencia de drenaje desde las partes altas de la ladera hacia un rill se ha visto a partir de la distribución especial de la humedad del suelo.

Los resultados de los análisis de la erodibilidad del suelo se presentan en el Capítulo 6. Las medidas de campo y laboratorio (resistencia a la cizalla, consistencia, rugosidad de la superficie, agregación y descarga de sedimentos) se comparan con los datos de humedad del suelo. Las margas grises se presentan como el material más erosionable y las blancas como el menos. Esto significa que el material afectado por erosión en rills es menos erosionable que otros materiales en los que los movimientos en masa son predominantes. Las diferencias muestran que la estructura del suelo y los macroporos juegan un papel muy importante, influenciando la erodibilidad de estos materiales. La cantidad de illita en los minerales de arcilla, combinada con un elevado contenido en sodio es también responsable de la erodibilidad de la regolita de las margas marrones. Para las margas grises el elevado contenido en smectita juega un elevado papel en su erodibilidad.
De los resultados de las medidas de campo y laboratorio y de la erodibilidad en los suelos labrados del loes, se concluyó que estos suelos son los más susceptibles a la erosión. Esto es especialmente así cuando lluvias de fuerte intensidad suceden a otras de menor intensidad. La lluvia tiene más impacto sobre el descenso de la rugosidad superficial en los suelos labrados que en los rastrillados. En combinación con una mayor humedad de la parte superior de un perfil labrado puede ser la condición favorable para la erosión en rills.

Los resultados mencionados arriba han sido usados para mejorar el modelo de drenaje y la teoría de macroporos destacados en el Capítulo 2.

La Parte III contiene una síntesis de los resultados de los experimentos y describe la erodibilidad y la respuesta hidrológica de las regolitas de badlands y suelos cultivados en loes.

En el Capítulo 7 se discuten los resultados del estudio buscando respuestas a las preguntas de investigación relevantes derivadas de los objetivos mencionados en el Capítulo 1. Las interrelaciones entre el agua del suelo y las propiedades del suelo y la regolita se explican en este capítulo. También se discuten los indicadores de umbrales de erodibilidad y los procesos de erosión relacionados.

Para las regolitas de los badlands los indicadores de erodibilidad parecen tener varios valores para los diferentes procesos de erosión en rills y denudación en masa. Un indicador directo de la erodibilidad de la regolita de los badland es la relación entre cambio en la humedad del suelo y el comportamiento de la concentración de sedimentos. Esta relación puede usarse para encontrar los valores umbral en la humedad del suelo que incrementan la erodibilidad. Los indicadores mencionados en el Capítulo 7.1, por ejemplo sellado superficial, incremento de la escorrentía, consistencia del suelo, macroporosidad, propiedades químicas del suelo, mineralogía de las arcillas y textura, son aptos para influir sobre los umbrales en la relación descrita arriba. Esto no es válido para el índice C₅₁₀ y el límite líquido de la consistencia del suelo, el cual no muestra relaciones consistentes con la erodibilidad de estos materiales de regolita. En general, mayor cantidad de sedimentos es removida en las áreas de badlands susceptibles de movimientos de sedimentos que de erosión en rills. Una regolita que es susceptible a la erosión en rills se sella tras la saturación, lo que también ocurre en una regolita con alto contenido en smectita, tras un evento de lluvia precedente. Aparentemente, antes de la saturación de la capa superficial. Las propiedades dinámicas del suelo juegan un papel mayor en el proceso de erosión, mientras que tras la saturación y incremento de la escorrentía, la creciente importancia de la hidráulica del flujo supone un aún más complejo proceso de erosión en estas zonas de badlands.

En los suelos de loes labrados la lluvia se infiltra rápido en el horizonte Ap. Una discontinuidad en el frente de infiltración ha sido observada entre el horizonte Ap y el Bt. La macroporosidad y el incremento de esta al labrar causa probablemente un flujo de by-pass hacia una mayor profundidad en el horizonte. El agua infiltrada en el suelo rastrillado, por el contrario, permanece mas en la parte alta del suelo. Esto se explica por una baja macroporosidad en el horizonte Ap. El suelo labrado es así más sensible al compactación y probable sellado que el rastrillado. Estas condiciones del suelo labrado, combinado con un mayor contenido en humedad en el subsuelo crean un mayor riesgo de erosión en rills profundos durante o tras lluvias de alta intensidad. El suelo rastrillado muestra menor susceptibilidad a la erosión y combinado con mayor contenido en humedad en la parte superior, hacen que la arroyada difusa y la erosión en rills poco profundos sean más probables. Entorno a un sistema
de rills la humedad del suelo se acumula en y debajo los rills. La macroporosidad es mayor en la zona entre rills. Esto indica que el drenaje por flujo de by-pass entre la zona entre rills y el rill puede ocurrir.

La evaluación de modelo en el Capítulo 8 muestra que el modelo de drenaje es apropiado para los suelos de loes labrados, y poco reajuste es necesario para el proceso de inicio de rills. De acuerdo con las lagunas en los procesos estudiados, experimentos en investigaciones futuras pueden ser definidos para permitir encontrar los procesos perdidos. Para las regolitas de los badland el modelo de drenaje no es aplicable y necesitaría de muchos ajustes.

En la zona de badlands parece que en las margas blancas y marrones se genera mayor cantidad de flujo en macroporos que en las grises. En las margas blancas y grises la capa superior se satura durante la lluvia. Probablemente, el modelo de drenaje es aplicable a las margas marrones, puesto que el flujo en macroporos parece ser más importante en este material que el flujo matricial. Sin embargo el experimento fue demasiado corto para formar una capa saturada en profundidad. En combinación con rills como rasgos superficiales el modelo de drenaje debe ser ajustado del siguiente modo. La capa superior de la regolita se saturá por encima de la parte inferior del perfil. El flujo en macroporos se infiltra in la matriz del suelo en profundidad en el perfil. Finalmente, la capa superficial de la regolita comienza a fluir y ocurren movimientos en masa debido a una perdida de consistencia. Este mecanismo es diferente de las hipótesis por la perdida de consistencia del nivel saturado dentro del perfil, los agregados del suelo colapsan y se inician los rills.

Considerando el modelo de drenaje para los suelos en loes unos pocos refinamientos se han hecho para hacer el modelo más apropiado. En un perfil de suelo labrado los macroporos son más abundantes en la parte inferior del horizonte Ap. El agua infiltrada fluye como flujo en macroporos en el Ap inferior y se estanca en la suela de arado u horizonte Bt mas compactado. Finalmente, los agregados más húmedos y saturados en la parte baja del perfil pierden su consistencia y causan un horizonte instable en el suelo, con el riesgo de erosión en rills profunda. Una lluvia antecedente de baja intensidad crea agregados ya saturados que son muy vulnerables a la erosión y especialmente a la lluvia de alta intensidad. El suelo de loes rastillado está dominado por el flujo matricial. El horizonte Ap superior se saturá y el inferior esta húmedo tras la lluvia. El Ap inferior tiene una difusión más difusa hacia el horizonte Bt en comparación con el suelo labrado. Un frente de infiltración decreciente puede ser observado. La capa superficial saturada indica que hay un mayor riesgo de erosión por arroyada difusa y rill someros. La pre humectación del perfil por lluvias de baja intensidad causa una menor vulnerabilidad a la erosión. Un tercer modelo describe un sistemas de rills existente en suelos de loes labrados. En las zonas interrills la macroporosidad es mayor que por debajo y alrededor de los rills. Esto causa un mayor flujo por macroporos en el área entre rills durante la lluvia. La menor humedad del suelo en la interrill área que alrededor de los rills proporciona evidencia de una dirección de drenaje de la interrill área hacia los rills.

Las Conclusiones generales de esta investigación son:

1. El inicio de los rills en las zonas de badlands esta potenciado por la saturación de la capa superior del perfil de regolita. Solamente en regolitas de badlands afectadas por movimientos en masa con una considerable densidad de grietas y mostrando grietas profundas, el flujo en macroporos puede tener un papel en el inicio de los rills.
2. No se ha demostrado en esta investigación que los rills en la regolita de los badlands puedan ser considerados como drenes. Modificando los experimentos sería posible estudiar si esto es válido para regolitas afectadas por movimientos en masa.

3. En el suelo recientemente labrado el flujo en macroporos ocurre probablemente y contribuye a la saturación de los agregados en la parte baja del horizonte Ap. Este proceso puede incrementar el riesgo de erosión por rills profundos. Sin embargo, en suelos cultivados menos profundos, como los del loes rastrillados, el riesgo de erosión por arroyada difusa y rills someros es causado por la saturación de la capa superficial del horizonte Ap.

4. Las medidas en y alrededor de un sistema de rills en el suelo de loes labrado muestran que los rills pueden ser considerados como drenes. Sin embargo, se necesita de más investigación al no ser estos datos absolutamente concluyentes.

5. Se han encontrado condiciones posiblemente críticas para el inicio de la erosión en rills en los badlands y suelos cultivados en relación al volumen de macroporos, la humedad antecedente, la intensidad de la lluvia y en diferentes propiedades dinámicas.

**Implicaciones para la política**

En el *epilogo* se mencionan problemas recientes conectados con esta investigación. La erosión del suelo es reconocida ahora como uno de los mayores desafíos para el uso sostenible de la tierra en la UE. Esta Tesis se ha manejado con éxito para observar y monitorizar como la dinámica del comportamiento del suelo afectado o influenciado por la erosión en rills. También sugiere que una Buena estrategia para reducir el riesgo de erosión es mejorar la estructura del suelo y reducir la compactación. La importancia de los caminos de la erosión del suelo para la contaminación de las aguas es vista en relación a la planificación del tratamiento de aguas potables y medidas para la mejora de la calidad de las aguas superficiales, tal como esta contemplado en la Directiva Agua de la UE.

Para una zona específica como los badlands próximos a Petrer (España) es mejor promover funciones tales como conservación de la naturaleza, ganadería extensiva y turismo sostenible.

Los resultados del estudio en la zona cultivada en loes nos llevan a una mayor comprensión del impacto de las prácticas agrícolas sobre la erodibilidad de los suelos en combinación con la humedad del suelo y sus propiedades dinámicas. La investigación sugiere aquí que es mayor no labrar los suelos y rastrillarlos en primavera, justo antes de la siembra.

Finalmente la importancia del estudio en relación al flujo subsuperficial está enfatizada por las recientes inundaciones en New Orleans y la inundación de Wilnis en los Países Bajos y las situaciones de alto riesgo durante las inundaciones de 1993 y 1995. En estas condiciones los diques fueron debilitados debido al flujo subsuperficial y el piping.
References


REFERENCES


REFERENCES


REFERENCES


REFERENCES


REFERENCES


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NEN5791 Bodem. Onverzadigde zone. Bepaling van de waterdoorlatendheidskarakteristiek en de waterretentiekarakteristiek met de verdampingsmethode volgens Wind.


REFERENCES


Appendices
### Appendix I A Aggregate Size Distribution of a harrowed loess profile

#### Aggregate Size Distribution of the aggregate fraction < 2mm (weight%)

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### Appendix 1B Aggregate Size Distribution of a ploughed loess profile

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<td>n.a.</td>
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<td>11</td>
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</tr>
<tr>
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<td>n.a.</td>
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<td>15</td>
<td>12</td>
<td>10</td>
<td>2</td>
<td>18</td>
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<td>n.a.</td>
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<tr>
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<td>8</td>
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</table>
Appendix II

Figure 1 Initial soil water pressure, white marls, northerly exposed
(a) (b) (c)

Figure 2 Soil water pressure during experiments on white marls, northerly exposed
(a) (b) (c)

(a) (b) (c)
Appendix II (continued)

Figure 3 Initial soil water pressure, white marls, southerly exposed

(a) Initial soil water pressure, white marls, southerly exposed

(b) Initial soil water pressure, white marls, southerly exposed
Appendix II (continued)

Figure 5 Initial soil water pressure, white marls, south-westerly exposed

(a) Wsw1

(b) Wsw2

Figure 6 Soil water pressure during experiments on white marls, south-westerly exposed

(a) side of rill

(b) rill and interrill area
Appendix II (continued)

Figure 7 Initial soil water pressure, brown marls, southerly exposed
(a) (b)

Bs1

Bs2

Figure 8 Soil water pressure during experiments on brown marls, southerly exposed
(a) (b)

Bs1

Bs2

side of rill

rill and interrill area
Appendix II (continued)

Figure 9 Initial soil water pressure, grey marls, southerly exposed
(a) (b)

Figure 10 Soil water pressure during experiments on grey marls, southerly exposed
(a) side of rill
(b) rill and interrill area
Appendices

Appendix II (continued)

Figure 11 Initial soil water content, white marls, northerly exposed

(a) (b)

Figure 12 Soil water content during experiments on white marls, northerly exposed

(a) (b)

Vw1

soil water content (cm³/cm³)

Wn2

soil water content (cm³/cm³)

Vw2

soil water content (cm³/cm³)

EH(1)

RH

EH(2)

IH

EH(3)

EH(4)

EL(1)

RL

EL(2)

IL

EL(3)

EL(4)

location on slope

soil water content (cm³/cm³)

Vw1

volumetric soil moisture content (m³/m³)

Wn2

volumetric soil moisture content (m³/m³)

Vw2

volumetric soil moisture content (m³/m³)

time after start experiment (min.)

EH(1)

EH(2)

EH(3)

EH(4)

EL(1)

EL(2)

EL(3)

EL(4)

RL

IL

R(1)

R(2)

R(3)

R(4)

time after start experiment (min.)

Vw1

Vw2

rill and interrill area
Appendix II (continued)

Figure 13 Initial soil water content, white marls, southerly exposed

(a) (b)

Figure 14 Soil water content during experiments on white marls, southerly exposed

(a) side of rill

(b) rill and interrill area
Appendix II

Figure 15 Initial soil water content, white marls, south-westerly exposed

(a) (b)

Figure 16 Soil water content during experiments on white marls, south-westerly exposed

(a) side of rill

(b) rill and interrill area
Appendix II (continued)

Figure 17 Initial soil water content, brown marls, southerly exposed

(a) 

(b) 

Figure 18 Soil water content during experiments on brown marls, southerly exposed

(a) 

(b) 

Bs1

Bs2

() 

location on slope

soil water (cm³/cm³)
Appendix II (continued)

Figure 19 Initial soil water content, grey marls, southerly exposed
(a) 
(b)

Figure 20 Soil water content during experiments on grey marls, southerly exposed
(a) 
(b)
Appendix III Soil moisture content, according to TDR measurements, during rainfall simulation experiments and their fit functions, Petrer, Spain

Figure 1 White marls, northerly exposed, experiment 2

(a) (b) (c) (d) (e) (f) (g) (h) (i) (j)

<table>
<thead>
<tr>
<th>EH(1)</th>
<th>Soil moisture</th>
<th>reciprocal model: (a = 0.0505, b = 11.3)</th>
<th>linear fit: (a = 0.170, b = 4.67 \times 10^{-5})</th>
</tr>
</thead>
<tbody>
<tr>
<td>time after start experiment (min.)</td>
<td>volumetric soil moisture content (m(^3)/m(^3))</td>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>0</td>
<td>0.25</td>
<td>0.15</td>
<td>0.1</td>
</tr>
<tr>
<td>EH(2)</td>
<td>Soil moisture</td>
<td>reciprocal model: (a = -0.0139, b = 2.3 \times 10^{-5})</td>
<td>linear fit: (a = 0.0555, b = 7.59 \times 10^{-6})</td>
</tr>
<tr>
<td>time after start experiment (min.)</td>
<td>volumetric soil moisture content (m(^3)/m(^3))</td>
<td>0</td>
<td>0.05</td>
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<td>0</td>
<td>0.25</td>
<td>0.15</td>
<td>0.1</td>
</tr>
<tr>
<td>EH(3)</td>
<td>Soil moisture</td>
<td>quadratic fit: (a = 0.103, b = 1.25, c = 0.247)</td>
<td>reciprocal logarithm: (a = 2.46, b = 1.82)</td>
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<tr>
<td>time after start experiment (min.)</td>
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<td>0.05</td>
</tr>
<tr>
<td>0</td>
<td>0.25</td>
<td>0.15</td>
<td>0.1</td>
</tr>
<tr>
<td>EL(1)</td>
<td>Soil moisture</td>
<td>logistic model: (a = 0.126, b = 0.767, c = 0.146)</td>
<td>reciprocal model: (a = 0.00389, b = 5.84)</td>
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<tr>
<td>time after start experiment (min.)</td>
<td>volumetric soil moisture content (m(^3)/m(^3))</td>
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<td>0.05</td>
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<td>0</td>
<td>0.25</td>
<td>0.15</td>
<td>0.1</td>
</tr>
<tr>
<td>EL(2)</td>
<td>Soil moisture</td>
<td>reciprocal quadratic: (a = 10.1, b = -0.00812, c = 8.64 \times 10^{-6})</td>
<td>hyperbolic fit: (a = 0.125, b = 1.21)</td>
</tr>
<tr>
<td>time after start experiment (min.)</td>
<td>volumetric soil moisture content (m(^3)/m(^3))</td>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>0</td>
<td>0.25</td>
<td>0.15</td>
<td>0.1</td>
</tr>
<tr>
<td>IH</td>
<td>Soil moisture</td>
<td>quadratic fit: (a = 0.0591, b = 0.00259, c = -4.04 \times 10^{-5})</td>
<td>reciprocal logarithm: (a = 0.626, b = 2.38)</td>
</tr>
</tbody>
</table>

| RL | Soil moisture | linear fit: \(a = 0.0359, b = 5.41 \times 10^{-6}\) | reciprocal model: \(a = -0.136, b = 12.7\) |
| time after start experiment (min.) | volumetric soil moisture content (m\(^3\)/m\(^3\)) | 0 | 0.05 | 0.1 | 0.15 | 0.2 | 0.25 |
| 0 | 0.25 | 0.15 | 0.1 | 0.05 | 0 |
| IL | Soil moisture | reciprocal model: \(a = -0.0355, b = 7.3 \times 10^{-5}\) | hyperbolic fit: \(a = 0.125, b = 1.21\) |
| time after start experiment (min.) | volumetric soil moisture content (m\(^3\)/m\(^3\)) | 0 | 0.05 | 0.1 | 0.15 | 0.2 | 0.25 |
| 0 | 0.25 | 0.15 | 0.1 | 0.05 | 0 |
Appendix III

Figure 1 (continued)

(k) 

Figure 2 White marls, southerly exposed, experiment 1

(a) 

(b) 

(c) 

(d) 

(e) 

(f) 

Figure 2 (continued)

(k)
Appendix III

Figure 2 (continued)

(i) (j) (k) (l)

Figure 3 White marls, southerly exposed, experiment 2

(a) (b) (c) (d)
Appendices

Appendix III

Figure 3 (continued)

(g) (h)

Figure 4 White marls, south-westerly exposed, experiment 1

(a) (b)
**Appendix III**

**Figure 4 (continued)**

(e)  (f)

(g)  (h)

(i)  (j)

(k)  (l)

**Figure 5** Brown marls, southerly exposed, experiment 1

(a)  (b)
APPENDICES

Appendix III
Figure 5 (continued)

(c) (d) (e) (f) (g) (h) (i) (j) (k) (l)

soil moisture
reciprocal quadratic; \(a = 3.55, b = 0.00933, c = -0.00559\)
logarithmic fit; \(a = 0.570, b = -0.00761\)

soil moisture
reciprocal fit; \(a = -0.00550, b = 2.00\)
logarithmic fit; \(a = 1.60, b = 0.0368\)

soil moisture
reciprocal quadratic; \(a = 2.96, b = -0.0725, c = 0.00104\)
reciprocal logarithm; \(a = 1.58, b = 0.0409\)

soil moisture
logistic model; \(a = 0.526, b = 14.0, c = 0.140\)
logarithmic fit; \(a = 0.570, b = 0.00933\)

soil moisture
linear fit; \(a = 0.358, b = 0.00412\)
linear fit; \(a = 0.395, b = 8.47 \times 10^{-5}\)

soil moisture
reciprocal quadratic; \(a = 2.89, b = -0.0930, c = 0.00132\)
reciprocal logarithm; \(a = 1.04, b = 0.0693\)

soil moisture
logistic model; \(a = 0.526, b = 14.0, c = 0.140\)
reciprocal logarithm; \(a = 1.01, b = 0.250\)
Appendix III (continued)

Figure 6 Brown marls, southerly exposed, experiment 2

(a) (b) (c) (d) (e) (f) (g) (h) (i) (j)
Appendix III

Figure 6 (continued)

(k) (l)

Figure 7 Grey marls, southerly exposed, experiment 1

(a) (b)

(c) (d)

(e) (f)

(g) (h)

(i) (j)

(k) (l)
Appendix III

Figure 7 (continued)

(i) (j)

Figure 8 Grey marls, southerly exposed, experiment 2

(a) (b)

(c) (d)

(e) (f)
Appendices

Appendix III

Figure 8 (continued)

(g) Soil moisture

(h) Soil moisture

(i) Soil moisture

(j) Soil moisture

(k) Soil moisture

(l) Soil moisture

soil moisture reciprocal quadratic; a=4.40, b=-0.0609, c=0.000323

soil moisture reciprocal quadratic; a=5.44, b=-0.0587, c=0.000266

soil moisture logistic model; a=0.663, b=5.22, c=0.0749

soil moisture reciprocal quadratic; a=2.93, b=-0.253, c=0.00734

soil moisture reciprocal quadratic; a=0.230, b=0.0210, c=0.000321

soil moisture reciprocal logarithm; a=2.58, b=0.0461
Curriculum Vitae

Nienke Adriana Bouma was born on April 10, 1966 in Utrecht. After half a year the Bouma family moved to Meppel, where Nienke started her primary education, followed by high school education in 1978 at the RSG Meppel. At the age of 16 she moved to Heiloo and graduated from high school (RSG Noord-Kennemerland, Alkmaar) in 1984. She started studying Physical Geography and Soil Science that same year at the University of Amsterdam. After two years of studying she stayed one year in Norway and contacted soil scientists at the Norwegian Institute of Land Inventory (NIJOS) in Ås, to arrange a landscape ecological research. This research was carried out one year later, entitled 'change in vegetation patterns affected by clear cutting and skiing'. In 1989 she did a traineeship of four months in soil chemistry at the College of Forest Resources of the University of Washington, Seattle, USA. She majored in soil physics on modelling soil temperature dynamics.

In 1991 she graduated and started her Ph.D.-research on rill initiation and development in relation to dynamic soil properties at the Department of Physical Geography and Soil Science of the University of Amsterdam. In this research she could integrate her knowledge of soil physics, soil chemistry and spatial patterns. She cooperated with the Experimental Farm Wijnandsrade in South-Limburg, research institute Alterra, Wageningen and the University of Valencia in Spain. Besides the research she also gave lectures on soil hydrology and geomorphology and she was active in the faculty committee on emancipation and as a member of the AIO/OIO-committee of the University of Amsterdam.

In 1998 she started working as a researcher on water quality and quantity at the Institute for Inland Water Management and Waste Water Treatment (RIZA) in Lelystad. Here, her interest for water quality was born. At the end of 2001 she left the RIZA for a project on nitrate leaching at the National Institute for Public Health and the Environment (RIVM) in Bilthoven. After this she started working on sustainable water management in the coastal dune area. She cooperated with the INHOLLAND University, Alkmaar and also worked for the project SCAPE on soil conservation in Europe. This resulted in several publications. Simultaneously she continued working on her Ph.D.-research, which resulted in this thesis.