water erosion on slopes and landsliding in a mediterranean landscape

th.w.j. van asch

WATER EROSION ON SLOPES AND LANDSLIDING IN A MEDITERRANEAN LANDSCAPE

Aan mijn Moeder
Willem
Anne-Marie

ISBN 90 6266 026 6 Utrechtse Geografische Studies
ISBN 90 6266 027 4 Thesis

Cover: A slumping area in the Collonci valley
(Photo: Th. W.J. van Asch)

DRUK: ELINKWIJK BV – UTRECHT – 030-444921

WATER EROSION ON SLOPES AND LANDSLIDING IN A MEDITERRANEAN LANDSCAPE

PROEFSCHRIFT

TER VERKRIJGING VAN DE GRAAD VAN DOCTOR IN DE WISKUNDE EN NATUURWETENSCHAPPEN AAN DE RIJKSUNIVERSITEIT TE UTRECHT, OP GEZAG VAN DE RECTOR MAGNIFICUS PROF. DR. M.A. BOUMAN, VOLGENS BESLUIT VAN HET COLLEGE VAN DECANEN IN HET OPENBAAR TE VERDEDIGEN OP WOENSDAG 3 DECEMBER 1980 DES NAMIDDAGS TE 2.45 UUR

DOOR

THEODOOR WOUTERUS JOHANNES VAN ASCH

GEBOREN OP 29 JANUARI 1944 TE BAARN

DRUKKERIJ ELINKWIJK BV – UTRECHT

PROMOTOR: PROF. DR. J.I.S. ZONNEVELD

CONTENTS

List of figures

List of tables

List of plates

FOREWORD

This thesis is the outcome of investigations in the coastal region of Amantea in Calabria (South Italy). The fieldworks were carried out in the summer of 1971, the winterperiods of 1972 and 1973 and during spring 1974. Financial supports were given by the Netherlands Organization for the Advancement of Pure Research (ZWO) and the Consiglio Nazionale delle Riserche (CNR, Italy). The region was already under study by staff and students of various disciplines of the International Institute for Aerial Survey and Earth Sciences (ITC, Enschede). Especially I want to thank Prof. Dr. H.Th. Verstappen and Drs. J.M.M. vanden Broek of ITC for their suggestion to carry out the research in the region of Calabria.
This study would not have been possible without the help of many persons and organizations.
First of all I am greatly indebted to my promotor Prof. Dr. J.I.S. Zonneveld who encouraged and supported me to start a research which, in the time, opened a new field in physical geographical research at the University of Utrecht. I am grateful for his patience and continuous support during this study.
I am most grateful to Prof.Dr. J.H.J. Terwindt for his many constructive critical remarks which have greatly improved the contents and presentation of this study.
I gratefully acknowledge the help and support of Dr. J.P. Herweyer and Dr. H.Th. Riezebos. The many uncharitable jüdgments and fatiguing discussions greatly stimulated me in finishing this study.
Special thanks are due to Drs. J.C.A. Lemkes who accompanied me in 1973 in the field and carried out many measurements even under the worst climatological conditions. Also I am very grateful to the moral and scientific support in the field of Drs. F.J.M. van Leeuwarden, Dr. Ir. J.J. Reijnders, Drs. R.A. Steenbergen and Dr. V. Spagna.
I express my cordial gratitude to my colleagues of the Department of Physical Geography, who displayed a stimulating attitude towards my work, especially Dr. P.G.E.F. Augustinus, Drs. R.J. de Boer, Drs. H. Pot, Drs. J.M. Roels and Dr. H. van Steijn.
Furthermore I would like to express my appreciation to the technical staff of the Laboratory for Physical Geography, Utrecht University, for the construction of the measuring devices and the analytical determinations. In particular Mr. C.J.M. Klawer, Mr. H.A. Maarschalkerweerd and Mr. A. Romein must be mentioned.

My thanks are also extended to the Department of Soil Science of the Utrecht University who gave the facilities to carry out the chemical soil analyses.
I thank Mr. T. Woudstra, Mr. J. Russchen and Miss N. de Vink for the many drawings; Mr. G.H. Huygen and Mr. T. Lekkerkerker for the photographic work. Special thanks are due to Miss E. Geldermans and Miss L.M. Butteling for the tiring typework. Also I am indebted to Drs. J.G. Borchert who assisted me in the preparation of this treatise for the press. Several students assisted me during the research. I am particularly grateful to Drs. M.J.N. Brouwer, Drs. G.F. Epema, Drs. G.T.A. Hof, Drs. E. Velders and Drs. W.A.M. van den Dries.

I wish to thank Mrs. H. Berendsen-Hilferink and Mrs. E.Y. Kos-Jacobs for preparing parts of the english text.
Finally I acknowledge my gratitude to my wife Anne-Marie, who assisted with many works in the field, in the laboratory and at home. I thank her for her patience of living with and supporting a husband who stayed too many times in another world.

1

INTRODUCTION

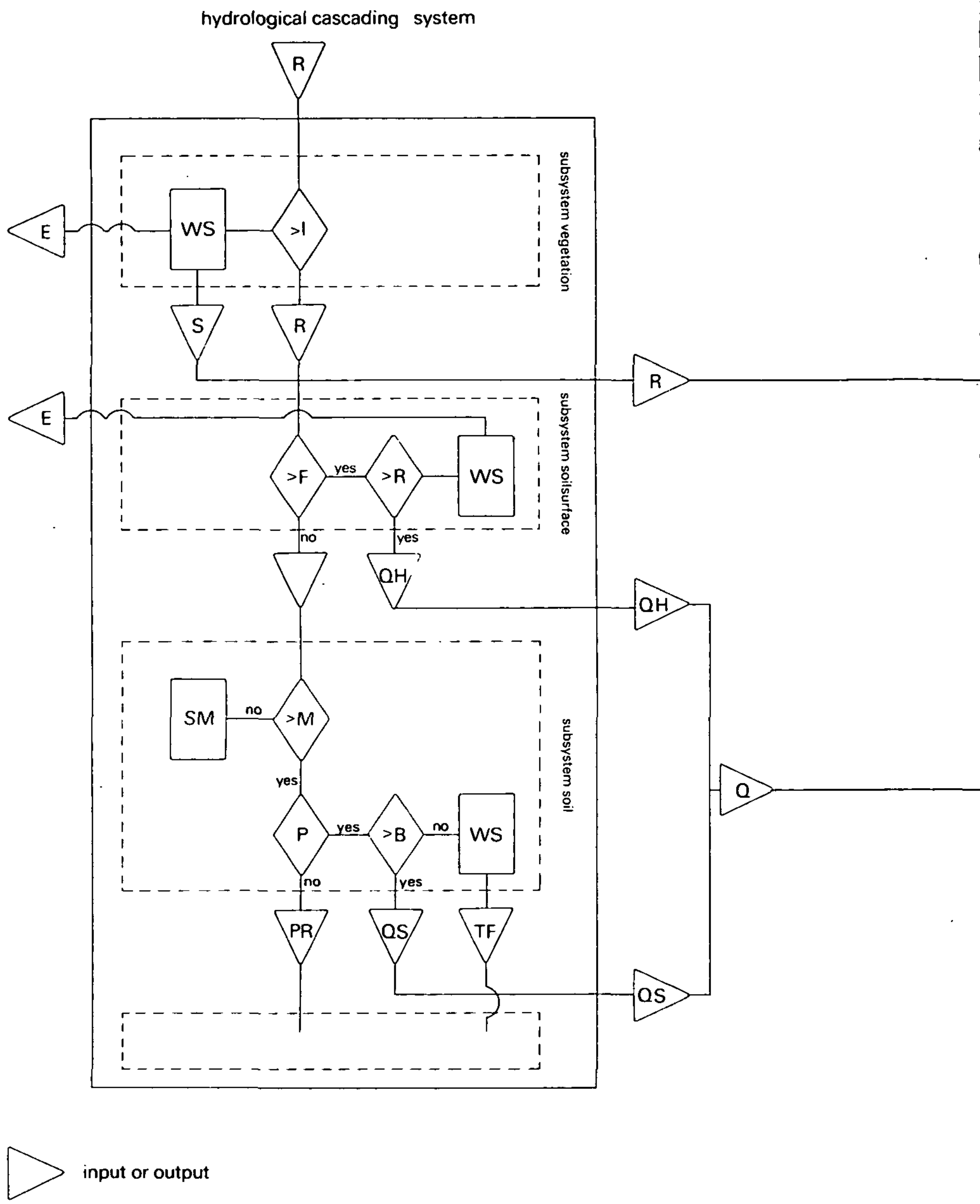
This thesis deals with processes of sediment transport on slopes in relation to the properties of different landscape units in a mediterranean area.
In our study, the landscape is considered as a system consisting of a structured set of objects or attributes (soil, vegetation, parentrock, relief etc.).
These objects are characterized by variables, e.g. vegetation density, soil-texture, slope-angle, that exhibit discernible relationships with one another and operate together as a complex whole according to some observed pattern (Chorley & Kennedy 1971, Zonneveld 1972, Vink 1975). We will call these variables landscape parameters if their value remains constant within a certain time, and landscape variables if the value changes in that time. Within the system, processes, defined here as a flow of mass or energy through the system, are operating. The energy or mass flow is transformed by so called transformation operators (Bennet & Chorley 1978) also called regulators (Chorley & Kennedy 1971). These regulators determine the manner in which the system input is transformed to become the system output. The regulators have a specific structure, made up of a number of landscape parameters or variables which determine the magnitude and shape of modulation of the flow and hence the final output (Bennet & Chorley 1978). The processes themselves are also characterized by certain magnitudes. These magnitudes can also function as variables in other process systems. Pore pressure changes and rate of slope steepening for instance are variables which influences the rate of massmovement processes. These variables are in this case called process variables. A landunit is defined as a landscape sub-system, with a certain spatial distribution in which one or more landscape parameters or variables related to certain landscape attributes, have the same value within certain preset limits. These landunits can be mapped in the field and classified on the base of certain visible criteria which are related to the landscape variables. Since these variables may influence the energy or mass flow via regulators, the possibility exists that different landunits will yield differences in the output of mass.
The main purpose of this thesis: the investigation of the differentiation of landscape units in relation to their sediment output can be expressed in two questions:

- What is influence of landscape parameters (variables) on the output of sediment transport in the study area.
- Can we distinguish landunits on the base of visible mapping criteria related to these landscape parameters, showing significant differences in output of sediment transport.

We have chosen 2 types of process-response systems:

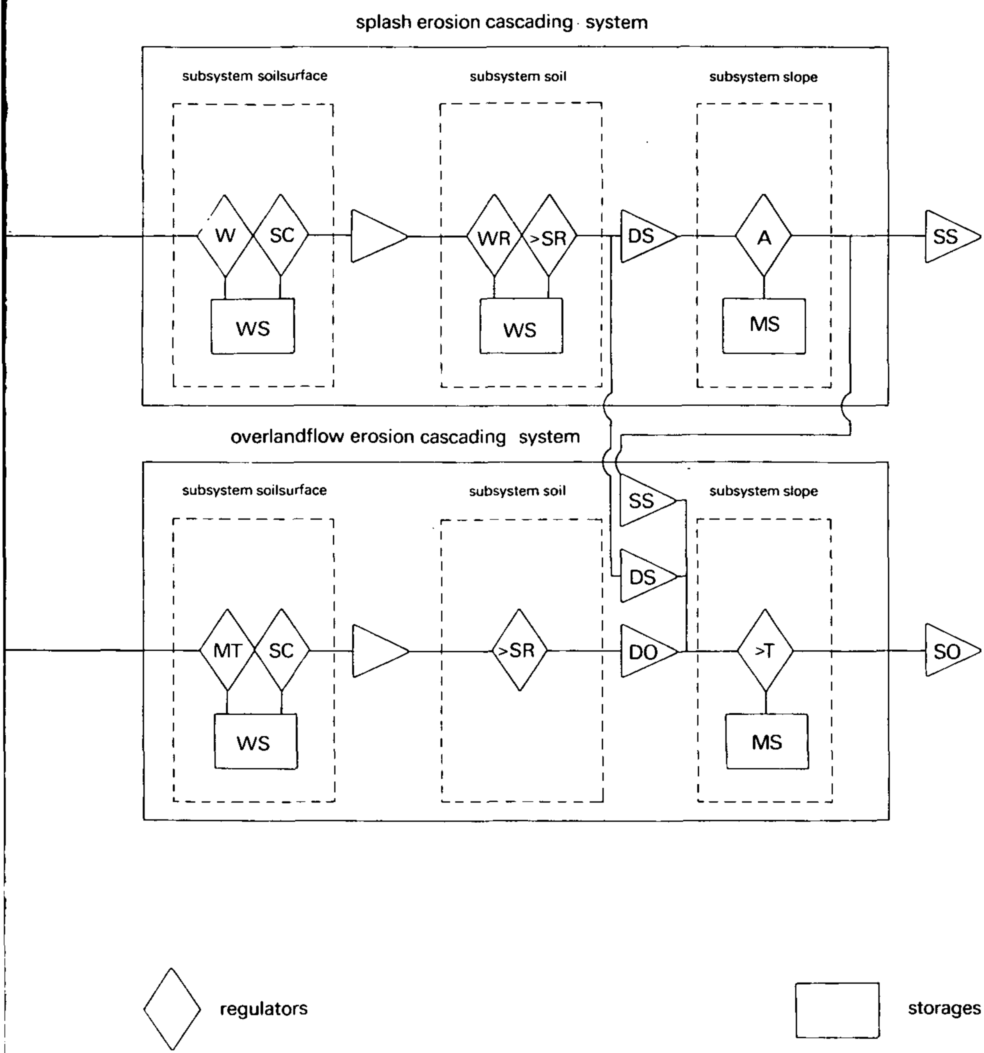
- the system of sediment transport by falling and running water on slopes and
- the system of sediment transport which takes place mainly under the influence of gravitational force.

The first type of process may be headed by the concept of surface wash (Young 1972) or water erosion by which, through the action of moving water, soil material is detached



R	rainmass	QS	saturated overlandflow	SS	final output of splashed sediment and water
E	evapotranspiration	PR	perculation to lower zones	DO	detached material by overlandflow shear
S	stemflow	TF	through flow	SO	final output of sediment by overlandflow
QH	Horton's overlandflow	PS	splash detached material		

Figure 1.1 The water erosion cascading system.



>I	exceeds interception storage?	W	water at the soilsurface	WS	waterstorage
>F	exceeds infiltration capacity?	SC	soilsurface cover	MS	sediment storage
>R	exceeds soilsurface storage capacity?	WR	waterreflection		
>M	exceeds soilmoisture storage capacity?	>SR	exceeds soil resistence?		
P	more impermeable layer present?	A	slope angle		
>B	exceeds groundwater storage capacity?	MT	soil microtopography		
>T	exceeds transport capacity?				

and transported. The grain or soil particles in the fluid medium are separated, resulting in a reduction of the importance of grain to grain contact and interaction to small proportions. The second type of process is called massmovement which comprises of sediment transport processes by which large quantities of weathering products move together is close grain to grain contact (Statham 1977).

The above mentioned processes can be considered as debris cascading systems (Chorley & Kennedy 1971). These cascading systems are one of the most important types of dynamic systems. They are defined as structures in which the output of energy or mass of one landscape attribute (also called spatial sub-system: vegetation, soil surface, soil, slope etc.) forms the input of another attribute. Within these attributes there are regulators which either divert a part of the input of mass or energy into a store or create a throughput. One of the purposes of our study is to investigate the influence of landscape variables on the regulators within the system and hence the throughflow and output of sediment material.

The cascading system of water erosion is schematically depicted in Figure 1.1. The output of rainmass (R) and overland flow (Q) from the hydrological cascade are considered as inputs for the water erosion cascade. There is a storage of water mass (WS) within the system. If the forces of the water mass exceed certain threshold values (SR) of the soil material, sediment can be set into motion and the output of the system consists in that case of sediment and water mass (SS and SO). The water erosion cascading system can be subdivided into two important process sub-systems: a) the splash erosion cascading sub-system, b) the overlandflow erosion cascading sub-system (Figure 1.1).

The amount of material which is set into motion within the splash erosion system is related a.o. to the amount of kinetic energy in the falling raindrops. The first regulator, reducing the mass of rain with a certain kinetic energy, is the vegetation structure which intercepts a part of the falling drops (I). The impact forces of the falling raindrops on the ground may be reduced by the presence of a water film (W) and the protective effect of not transportable surface stones and litter cover (SC). Most of the energy is absorbed in the soil and only a small part of the energy is used to set soil particles into motion. The amount of material set into motion depends a.o. on soil properties regulating the degree of reflection of the waterdrop momentum (WR) (e.g. soil elasticity, bulk density, soil moisture content) and soil properties regulating the resistance against the shearing forces of the waterdrop impact (SR) (e.g. soil texture, soil strength and aggregate stability).

The detached particles can be divided into portions ejected in an upslope direction and a downslope direction. The ratio between the splashed upward and downward material is determined by the slope angle (A). The travelling distance of the particles having a certain kinetic energy is also determined by the slope angle. The final output of splashed sediment (SS) is defined as the amount of sediment mass passing a unit width of slope per unit of time in a downslope direction.

The amount of overlandflow from the hydrological cascade is considered as an input for the overland flow erosion cascading system (Gregory & Walling 1973). A part of the hydrological cascade is depicted in Figure 1.1. The occurrence and amount of overland flow depends on four inportant threshold regulators: the infiltration capacity (F),

the soil surface storage capacity (R) and in the soil body the moisture storage capacity (M) and groundwater storage capacity (B). These regulators are related to different soil variables: soil porosity, soil micro topography, soil depth, etc.
We consider the input of the overlandflow erosion cascading system to be the amount of flowing water mass along the slope surface which passes a unit width of slope at a given unit of time (Q). The amount of input depends, apart from the variables given in the hydrological cascade, on the length of the slope system. The amount of material which is set into motion (detachment by overlandflow) depends on the shear stresses excerted by the fluid on the soil surface. The shear stress is related to the flow velocity. The flow velocity is determined by the amount of overland flow discharge, the roughness of the soil surface and the depth of the flow. The micro topography of the soil regulates (distributes) the discharge of flow and hence the flow velocity along the soil surface (MT). The amount of material which is set into motion by a given shear stress depends on the soil resistance regulator (SR), related to a.o. the grainsize and the soil strength. The transport of the moving material is regulated finally by the transport capacity (T) of the flow. The overlandflow erosion system is partly loaded by particles which are set into motion by the splash erosion system (DS and SS). This process is called splash pick-up (Gregory & Walling 1973).
A second and equally important debris cascading system is formed by the various types of

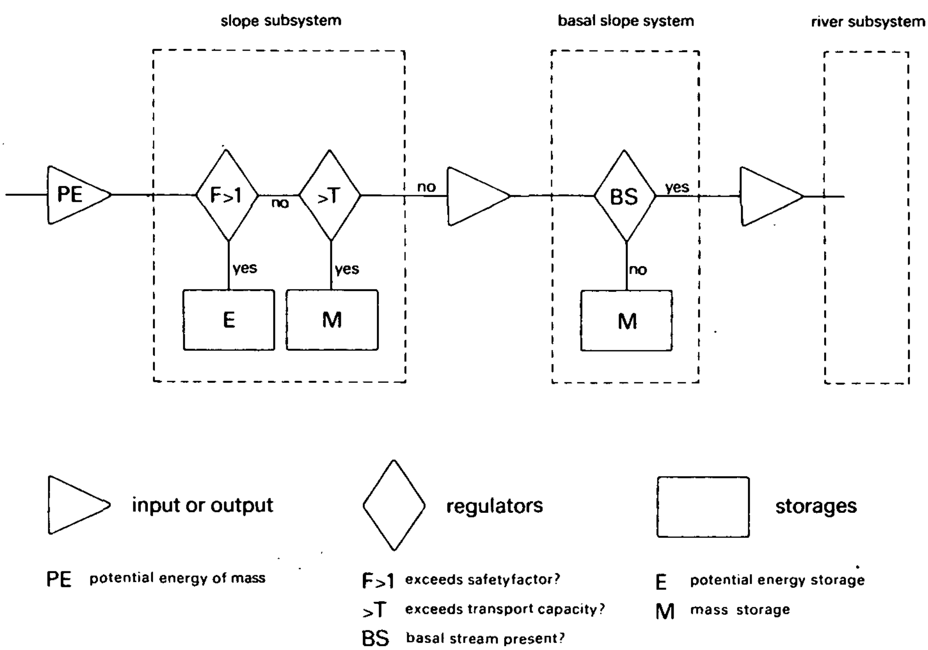


Figure 1.2 The massmovement cascading system.

massmovements. In this system we consider the input to the potential energy of the soil or rock mass. This input can be converted into the energy of moving debris. This is illustrated generally in Figure 1.2. The most important threshold regulator in the mass movement cascade is the equilibrium factor called safety factor (F) (Terzaghi & Peck 1967) which determines whether the debris is set into motion at a given time. The safety factor is determined by the shear stress (T) along a potential slip surface which tends to set the debris mass into motion and the shear strength (S – which is the resistance of the material against the shear stress. Generally we can write:

$$F = \frac{S}{T} \tag{1}$$

The system is stable if F> 1, while failure occurs if F = 1. The shear stress is related to the downslope component of the weight of mass along a potential slip plane. This weight depends on the amount of material available, the bulk density of mass, the slope-angle and the slope height. The shear strength depends on the cohesion and internal friction between particles in the soil or rock mass. The shear strength is negatively influenced by the amount of positive pore pressure of especially the soil water body.
The value of the safety factor F is related to a number of landscape attributes (topography, soil, rock and vegetation) and to the hydrological cascading system. The safety factor changes with time and this is due to the following landscape processes:

- Weathering processes resulting eventually in the decrease of bulk density and thus leading to a decrease of the shear stress and the shear strength of the material.
- The processes of linear incision of the rivers and the sediment transport processes at the slope surface change the slope-angle and slope height and hence the shear stress.
- The vegetation system, especially the binding effect of the roots, influences the cohesion of the material.

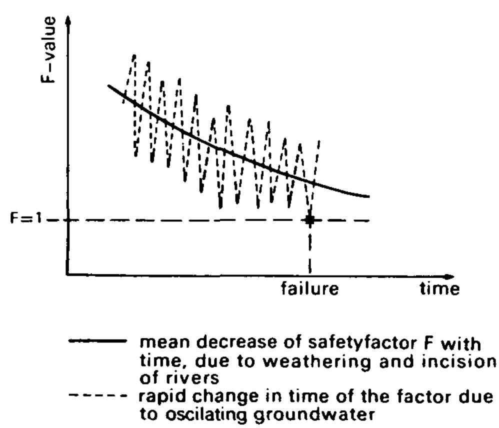


Figure 1.3 Decrease of the stability factor F with time.

- The hydrological system controls the variation of the amount of ground water and thus the pore water pressure.

Generally speaking in the course of time the F-factor decreases due to the weathering of the soil and rock material and the erosion processes (Statham 1977). The oscillating influence of the hydrological system is superimposed on this general trend. Figure 1.3 gives an illustration.

The figure shows that the fluctuating groundwater may act as a "trigger" in the starting of massmovements.

When the material is set into motion the transport capacity regulator (T) determines the distance of transport which depends on a.o. a) nature of initial rupture b) the slope-angle c) the mechanical characteristics of the debris after failure and d) the soil mechanical characteristics of the receiving material over which the debris is moving. Debris storage is possible mainly due to a loss of ground water. In this case a new state of equilibrium is created. The value of topographical, soil- and vegetation-variables influencing the F-factor has completely changed. The state of equilibrium can be of a short duration: a new rising of the ground water level to a certain critical height may cause new movements. When the sliding material reaches the base of the slope the amount of debris transport is then regulated by the presence of a basal stream, which is able to remove the mass from the slope. Up slope of the sliding area, topographical and hydrological conditions in the regolith are changed, which on its turn may provoke a disequilibrium.

In the foregoing, we have shortly described two systems of sediment transport processes, which are considered as flows of mass through a number of landscape attributes. The final output of the sediment in which we are interested is determined by the value of certain regulators in the system, which are related to a number of landscape variables. Landunits which are distinguished according to certain criteria, based on these variables may give differences in sediment output. The general problem of our study is whether such landunits can be distinguished in the study area. In relation to this problem the following subjects will be discussed:

- The environmental conditions of the study area.
- The specification of the sediment transport processes on slopes and the influence of different landscape variables on these processes.
- An analysis of the influence of landscape variables on the output of these processes in the study area.
- The selection of mapping criteria related to these landscape variables and the definition of landscape units on the base of these criteria.
- An analysis of the differences in output of sediment transport processes between the defined land units.

2

THE ENVIRONMENTAL CONDITIONS OF THE STUDY AREA

2.1 Climate

The climate in the study area has a mediterranean character with warm dry summers and relatively mild and humid winters. The climate can be classified according the criteria proposed by the UNESCO/FAO (1963). In this classification climatological

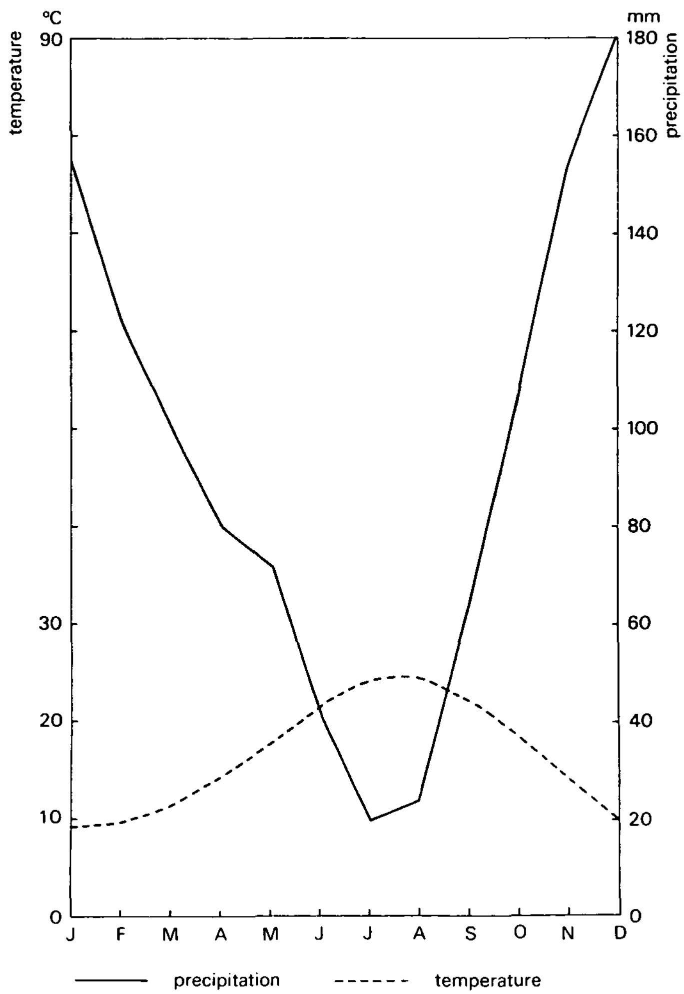


Figure 2.1 Mean monthly precipitation and temperature for the Station Fiume Freddo (1921-1950).

Table 2.1 The mean monthly precipitation of three stations in the study area (observation period 1922-1970) and the monthly precipitation during the measuring periods

Station	period	J	F	M	A	M	J	J	A	S	O	N	D	year
Nocera-Tirinese	*1922 - 1970*	*169.7*	*135.3*	*100.9*	*82.6*	*70.6*	*35.2*	*16.4*	*21.4*	*64.6*	*112.8*	*163.6*	*188.1*	*1161.2*
	1971	151.8	118.5	246.4	74.5	17.8	21.3	41.4	0.0	124.6	88.5	103.9	75.3	1064.0
	1972	235.6	177.2	69.4	76.2	84.4	4.3	25.3	86.6	61.4				
	1973		125.6	96.9	93.6									
Ayello-Colabro	*1922 - 1970*	*165.5*	*127.0*	*104.6*	*79.5*	*73.4*	*43.4*	*20.3*	*22.3*	*63.5*	*110.6*	*165.1*	*191.3*	*1166.5*
	1971	138.9	141.4	252.4	77.7	9.0	21.4	40.1	11.2	118.4	74.7	144.3	60.4	1089.9
	1972	222.4	165.2	89.8	114.6	96.4	8.0	35.2	127.2	80.2				
	1973		121.2	142.3	81.1									
Amantea	*1922 - 1970*	*127.3*	*97.5*	*78.8*	*60.0*	*63.1*	*31.4*	*17.4*	*22.9*	*57.7*	*96.7*	*132.0*	*153.5*	*938.3*
	1971	144.2	120.6	208.2	60.8	23.9	17.3	19.0	29.6	96.6	52.6	126.9	68.8	968.2
	1972	153.4	150.4	61.5	96.4	95.1	2.0	30.0	102.8	63.7				
	1973		105.6	133.0	72.1									

characteristics are related to the natural vegetation. This UNESCO/FAO classification defines the mediterranean climate as having a mean monthly temperature which is always higer than 6° C and a dry period from one to eight months, during which the longest day must occur. According to Bagnouls and Gaussen (1957) the dry period is defined as "the period in which the precipitation in mm is less than twice the temperature in °C". A further subdivision of the climate is based on the so-called "xerothermic index". This index is defined as the number of days in the above defined dry period which can be deemed dry from the biological point of view. This means that days with fog and dew are considered to be humid (UNESCO/FAO 1963).
The mean monthly precipitation and temperature at one station, 10 km north of the study area is shown in Figure 2.1. The dry period in the study area averages approximately 2½ month according to UNESCO/FAO (1963), the number of "biologically" dry days amounts to 40-50. The climate can be classified as a "meso-mediterranean" climate.
Table 2.1 shows the distribution of precipitation for 3 stations in the study area during the year, based on the mean monthly precipitation measured over the period 1921-1950. Obviously the precipitation falls primarily in the period from autumn to spring. This concentration of precipitation in the winter is of great importance to soil erosion. There is little evaporation. As a result the soil remains damp for a longer period thus giving rise to a greater overlandflow. Furthermore the erodibility of the soil increases as a result of the higher soil humidity. The precipitation often falls in showers of great intensity especially during the winter months (Nochese 1959). During our measuring periods, occasional showers with an intensity up to 40 mm per hour were measured. Considerable variations in precipitation occur from year to year. Table 2.1 shows also the monthly precipitation in the years 1971-1972-1973 in relation to the mean monthly precipitation measured over 30 years. It can be infered from the Table that during the measuring period lasting from February to April in 1972, February and April were re-

Table 2.2 Estimated annual erosion yield in tons km^{-2} in the study area calculated according to Fournier's World Erosion Index.

Location	H	P	p	p^2/P	S^a
Amantea	54	938	153	25.1	804.8
Nicastro	200	1145	181	28.5	984.3
Fiume Freddo	220	1121	178	28.2	970.7
Nocera Tirinese	240	1055	188	33.5	1247.3
Martirano	430	1565	250	39.9	1583.7
Ayello Calabro	590	1167	191	31.4	1133.4
Parenti	830	1416	232	37.8	1475.6

H: Height above sealevel in m, P: mean total yearly precipitation in mm calculated over 30 years, p: mean precipitation in mm of the months with a maximum amount of rainfall per year calculated over 30 years, p^2/P: Fournier's e4osion index, S: annual erosion yield in tons km^{-2}.

a Sediment yield estimated using Fournier's regression equation for accidentated terrain:
$S = 52.49p^2/P - 513.21$

latively wet months while March was relatively dry. In 1973 the monthly precipitation didn't differ much from the mean.
Table 2.2 shows how the mean annual precipitation measured on 7 stations within the study area and in the neighbourhood varies with the height above sealevel. In this table we have also tried to give an indication towards the effect of the rain in this climatic zone on the water erosion processes compared to the effect of other climatic zones of the world. We have used an index developed by Fournier (1960) which fits a correlation between erosion and precipation from data all over the world. This precipitation index is

$$p^2/P \qquad (1)$$

in which p = the mean amount of precipitation in the month with the maximum precipitation.
P = the mean yearly precipitation
p and P are based on long term measurements.
Fournier's correlation diagram, which relates p^2/P to the amount of erosion, was used to translate the computed p^2/P values for the different stations (based on precipitation data over the period 1921-1950) into erosion values (see table 2.2). Accordingly the mean erosion in the hilly study area is put to approximately 1000 tons per square kilometer annually. On Fournier's world erosion map (Fournier 1960 pp. 186-187) it can be seen that this value is exceeded only in the tropical areas of Africa and South

Table 2.3 The mean monthly and mean annual temperature of two stations near the study area (observation period 1926 - 1955)

Month	Station: Nicastro			Station: Fiume Freddo		
	A	B	C	A	B	C
J	13.0	5.8	9.3	12.4	7.0	9.4
F	13.7	6.1	9.9	13.2	7.0	9.8
M	15.9	7.3	11.5	15.6	8.3	11.6
A	19.2	9.6	14.3	18.8	10.5	14.3
M	22.7	12.9	17.7	22.5	13.8	17.8
J	27.9	16.9	22.1	26.9	17.1	21.7
J	30.4	19.3	24.6	29.8	20.1	24.3
A	30.7	19.8	25.1	29.9	20.2	24.6
S	28.3	17.9	22.8	27.1	18.1	22.1
O	23.4	14.0	18.5	22.2	14.4	18.1
N	18.6	10.5	14.6	18.0	11.3	14.1
D	14.5	7.3	10.9	14.5	8.4	11.1
Year	21.5	12.3	16.8	20.9	13.0	16.6

A: mean daily maximum temperature; B: mean daily minimum temperature; C: mean daily mean temperature.

East Asia (over 3000 tons per square kilometer annually). There are no snow falls in the study area.
Table 2.3 shows mean monthly temperatures at two stations located just outside the study area. January is the coldest month with a mean temperature of 9°C and August the warmest, with a mean temperature of 24°C. Calculated in the period 1922-1955, the month with the lowest mean temperature , occurred in January: 23°C; the highest calculated mean temperature occurred in August: 34.4°C. The number of days during which it freezes is few. During the winter from 1922 to 1955 November, December, January, February and March were respectively 28, 24, 22, 23 and 26 times out of 30 years free of frost. The temperature was never much below 0°C; on the average one degree.

2.2 Geology

The region of Calabria has a complex geologic structure. The main outlines of the tectonic structure was formed during the Tertiary and Quaternary periods in connection

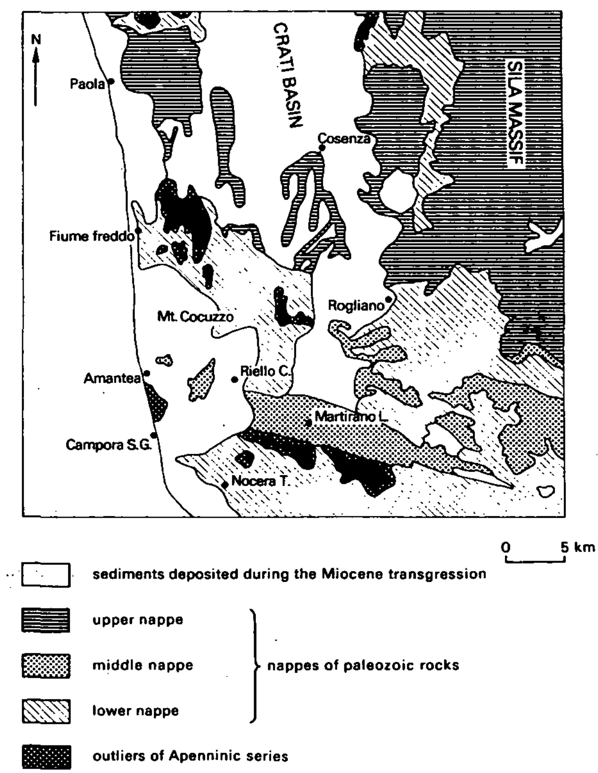


Figure 2.2 Tectonic units of Central Calabria (after Dubois, 1950).

with the Alpine orogenesis. The backbone of Calabria is formed by the massifs of Aspromonte and Serre in the South and the Sila massif (see Fig. 2.3) in the central area. These are the remnants of a Paleozoic basement consisting of crystalline and metamorphic rocks. In Central Calabria in which the study area lies, these formations are thrust a great distance over the southern extremity of the apenninic domain which is characterized by thick series of Mesozoic carbonatic rocks containing "Alpine" Triassic rocks at their base (Dubois 1970). The calcareous dolomitic massif of the Monte Pollino and just north of our study area the Monte Cocuzzo belongs to these apenninic series (see Figure 2.2). Aided by recent "horst-graben" structures these series appear under the napps in a succession of inliers (Burton 1970, Dubois 1970). These large overthrusts took place during the Lower Miocene in a WNW - ESE direction. (The "paroxysmal phase" of Burton (1970)). Dubois (1970) distinguished three napps (see Figure 2.2), the upper one containing the Paleozoic gneisses of the the Sila massif and the Triassic limestone of Longobucco, the middle one found in the south of the area (containing orthogneisses, granites, contact metamorphosed phyllites and sections of Jurassic series) and the lower napp being composed of phyllites.

The apenninic series, underlying these napps range from Trias to Titonic-Neocomien. As in the case of the deeper parts of the Calabrian napps these underlying series bear traces of a dynamic metamorphism.
Burton (1970) distinguished a second important ("postparoxysmal phase") in which the napps formed during the paroxysmal phase are folded. These movements dated mainly of middle Miocene age. After these two important phases of tectonic movements there was a major transgression during the middle Miocene, when flyshlike sediments consisting of basal conglomerates, sandstones, clays and calcareous sediments were deposited (see Figure 2.3). It is evident from the configuration of these rocks that since the deposition of these middle Miocene sediments there has been considerable renewed tectonic activity. This is the third tectonic phase which started in the Pliocene according to Burton (1970) and it is characterized by intensive faulting, involving an uplift of the Calabrian area up to 1000 mtr. (Bousquet & Gueremy 1968, 1969). Faulting occurred particularly during the Pleistocene period with throws of from 100 up to 300 mtr. Minor faulting took place during the late Pleistocene period. These observations are in agreement with the conclusions which can be drawn from the genesis of marine terraces; furthermore the difference in height among the different terrace levels also indicates a stronger tectonic movement during the early Pleistocene (Burton 1960).
Figure 2.3 shows that the southern and eastern part of the study area consists of Paleozoic rocks belonging to the lower and middle napp. Inside this arc of older rocks sandstone, clay and conglomerates dating from the period of the middle Miocene transgression can be found. On the coast a.o. Triassic limestone from the Apenninic series appears via normal faults as tectonic inliers. The Miocene rocks are characterized by strong faulting, which is a cause of many massmovements.
We will now give a description of the main lithological units in the study area. The largest part of the Paleozoic rocks in the study area consists of gray phyllites and schists (sf) (from the lower napp) with numerous intercallations of quartzite and locally lamina

of cristalline limestone. The phyllites consist mainly of chlorite, sericites and quartz. Epidote is sometimes present at the transition zone bordering on the green schists (sfe). At some places the green schists in the southern part of the area (sfe) comprise mainly epidote, chlorite and quartz. In the eastern and central part of the study area outcrops of medium to coarse grained biotite or muscovite granite (γ) belonging to the middle napp are found.
At some places in the area Mesozoic rocks from the Apenninic series appear as outliers. We can distinguish a) the Triassic compact dolomites and limestones (Tdl) light gray and brown in colour, which are well-stratified and b) Jurassic compact cristalline gray-brown limestone (Gc) locally in combination with light-brown dolomite.
The Tertiairy sediments deposited during the Miocene trangression period consist of sandy conglomeratic rocks (Mcl 2-3) at the base containing well arounded boulders of metamorphic rocks including the granites. A weakly cemented sandstone (Mars 2-3) with a light-gray or brown colour lies on these conglomeratic series. Sometimes there are intercallations of siltstone. The sediments are generally speaking well layered. This sandstone formation is followed by a limy sandstone which is more cemented (Mar 2-3) and has a light-gray or brown colour. Locally these series are followed by fine cristalline limestone (Mc 2-3) with a light-gray or brown colour. The upper Miocene formations consist of siltic claystones, silts and sandy silts (Ma 2-3). They have a dark-gray to blackish-gray colour.
The gravel deposits from marine and fluvial origin which are found in the higher fluvial and marine terraces belong to the Pleistocene formations. The fluvial deposits of the lower terraces, the alluvial fan deposits and the coastal plain formations were formed during the Holocene period.

2.3 Geomorphology

The study area is characterized by very steep slopes which originated as a result of upheavals related to the strong tectonic activities (see 2.2) and the down cutting of the rivers in the Pleistocene. The slopes are often unstable and this results in massmovements (see chapter 7).

Table 2.4 The mean slope angle in relation to the lithological units in the study area

Lithology	mean slope angle	s	n
Mar - sandstone	29.2	28.4	444
Mars - sandstone	30.0	23.4	525
Ma - claystone	14.1	5.6	474
γ - granites	34.6	29.9	510
sf- and sfe- phylites and schists	26.7	24.4	1258

s: standard deviation; n: number of slope measurements.

Table 2.4 gives an impression of the mean slope angle in relation to different rock types. The data were assembled from the topographical map 1:10.000. Sampling of the slope profiles was done according to the method proposed by Young (1971 p. 145). Along the slope profile measurements were taken at a equidistance of 20 mtr. The table shows significant differences ($\alpha = 0.1$) in most cases between the different lithological units. It appears that the silty claystone areas show distinctively the lowest mean slope angle values. The presence of marine terraces in these areas forms an indication towards the strong upheavel during Pleistocene times. In the study area 6 marine terrace levels lying above each other were found south of the Fiume Grande at respectively 1000-1020 mtr, 940-950 mtr, 640-670 mtr, 400-440 mtr, 140-170 mtr, 20-40 mtr. Burton (1964) assumes that the marine terraces in Calabria between 300 and 100 mtr. date from the Calabrian age (early Pleistocene) which lasted about 350.000 years. From this it may be concluded that the greatest tectonic movements took place during the early Pleistocene and this corresponds to the results of Bousquet & Gueremy (1968) (see 2.2).
The rivers in the study area have a typically mediterranean character. They have a broad alluvial plain in combination with a relative steep gradient. The riverbed contains coarse debris and the discharge fluctuates strongly. In the summer the river plain may fall completely dry. The greatest fluctations in discharge occur in the winter as a result of heavy showers. During the periods of heavy precipitation large amounts of debris can be transported in the river. This could be shown by the study of sediment transport in the rivers and the study of fans, which can be found in the study area on places where small rivers with a steep gradient discharge into a broad alluvial or coastal plain. Ergenziger et al. (1975) measured the sediment transport of a river in another part of Calabria from January 1972 to January 1973. He measured a net decrease in the riverbed of 27 cm to 3 cm in the upper course of the river and a net accumulation of the riverbed in the middle course varying from 2 cm - 150 cm. The largest variation in erosion and sedimentation took place in January; days with heavy precipitation occurred with an extreme of 300 mm per day. This extremity occurs only four times every century.
Another indication for the fact that the largest sediment transport is concentrated in periods of catastrophic rainfall is found in the study of the sediment deposits of the different fans. In several cuts made along the Autostrada we found in the fans an alternation of well stratified river deposits and layers several meters in thickness, which have the character of mudflow deposits. These mudflow layers can be related to catastrophic rainy periods.
Another example of a great change in the morphological conditions could be found in the alluvial fan of the Fiume Ste Maria, south of America. The water and debris is guided over the fan by means of two walls. The walls date from 1905 and are 8 m high. The canal is 40 m wide and 650 m long. It was completely filled in 1925. When calculated over the surface of the fan the original surface of the fan would have risen 70 cm in 20 years. Due to an enormous rainstorm in 1925 a large part of the debris in the canal was swept away.
We can infer from the above given examples that we must be very careful in dating the different geomorphological phenomena. E.g. the accumulation terraces along the main rivers which rise 1 - 2 meter above the alluvial plane may be recently formed under

catastrophic conditions with strong accumulation of material in the lower course of the river. Therefore it is to be doubted whether these terraces should be dated from the early Holocene as suggested by Rao & Ghanem (1972). It is also doubtful whether a distinction could be made between late Holocene fans and recent fans on the base of vegetation and landuse: certain fans with a vegetation cover or under recent agriculture need not to be fossile because depositions on these fans may take place only a few times per 100 years during catastrophic conditions.
Dams have been constructed in several rivers with steep gradient in order to slow down the irregular and often catastrophic large amounts of debris transport. Due to the stepped profile of the river resulting from the sedimentation which develops behind these dams, the stream velocity of the water is slowed down and hence the transport capacity is decreased. Observations in the field revealed that in the lower course many rivers cut down sharply into their own riverbed. This may be the result of, on the average, less debris supply from upstreams caused by the construction of the dams. This effect is also favoured by the removal of debris from the mouth of the river by men, keeping the local base level of erosion artificially low. Concrete blocks placed approximately ten years ago to protect the riverbanks and the alluvial terraces with cultivated grounds are being undercut by the running water at an increasing rate (see Plate 1).

2.4 Soils

The soils were classified in the field according to the French system of soil classification, which is also used in many African countries. The higher classification categories are resp. the "Classe", "Sous-classe", "Groupe" and "Sous-Groupe". In the study area a variety of soil types were found:

- "Classe des sols mineraux bruts" ((A)C or (A)R). A typical feature for this type of soil is the very poorly developed A-horizon in which there are only traces of organic matter in the upper 20 cm and/or not more than 1.5% organic matter in the upper 2 - 3 cm. It is possible that due to strong colluviation in this erosive area, these traces of organic matter can be present at all places in the soil profile. This soil type is related to the steepest slope in the study area and on several dune deposits along the coast.
- "Classe des sols peu évolués" (AC or AR). In this class the A-horizon is more distinct with traces of organic matter in the upper 20 cm and/or in the upper 2 - 3 cm a C-content of more than 1.5%. Most of the soils in this highly erosive area belong to the above mentioned classes. On the level of the "Sous-classe" the above mentioned soil types belong to resp. "Sous-classe des sols mineraux bruts non climatique" and the "Sous-classe des sols peu évolués non climatiques". On the level of the groupes we will find in the area the "sols mineraux bruts ou peu évolués non climatiques d'érosion ou d'apport alluvial and colluvial".

More important for the study of the erodibility of these poorly developed soils is the sub-division according to the parent material. In the French classification this is done on the level of "La Famille" which is a subdivision of the "Sous-groupes". The following soil types are very important on this level:

- "Sols mineraux bruts and sols peu évolués non climatiques d'érosion sur roche dur" on phyllites and schists. Due to strong erosion and colluviation a very vague A-horizon may be distinguished with only traces of organic matter up to 30 - 60 cm. (C-content 0.5 - 1.5%).
  Sometimes under denser shrub vegetation and (or) forest a more distinct A11 or A1 (Modeux) was found (3 - 6 cm) (C-content 1 - 2%). Laboratory analyses showed a high amount of Calcium-ions at the complex in the upper horizon.
  The C.E.C. varies from 12 to 15 ppm.; pH varies from 5 - 7.5. The soil texture is mainly sandy loam (USDA-classification). The content of gravel is relatively high in these soils in relation to other soils (20 to 50%) which is important with regard to the erodibility.
- "Sols mineraux bruts and peu évolués non climatiques d'érosion sur roche meuble", on sand stones (Mars - Mar).
  These soils also have a very vague A-horizon with traces of organic matter up to 20 cm (0.5 - 1.5%). A distinct A11 up to 3 cm with a C-content from 1.5 to 4% can develop under denser vegetation. The pH varies from 6.5 - 8. The complex is completely saturated (C.E.C.-values 5 - 15 ppm with a dominance of Ca-ions. Furthermore free Ca-ions are present. According to the USDA-classification the texture is loamy sand. Aggregate stability is weak and the soils have a moderate gravel content (5 - 15%).
- A third important groupe of soil types is the "sols mineraux bruts ou sols peu évolués non climatiques d'érosion sur roche dur" on Miocene clay stone (Ma). The A-horizon (mostly an Ap-horizon) varies from 20 - 40 cm in depth and has a C-content from 2 - 4%; pH varies from 7.5 - 8. In these soils the complex is also completely saturated (C.E.C.-values 15 - 20 ppm) with a dominance of Ca-ions.

The texture varies from clay to silty clay. The soils show strong dissecation fissures and in the lower horizons often hydromorphic characteristics. According to Palmer's tests the aggregate stability is moderate to strong.
These soils may locally be classified as vertisoils showing clear prismatic structures and slickenside phenomena.
On sandy limestone (Mar and Mc) and hard Triassic limestone (Tdl) soiltypes were locally found belonging to the "classe de sols calcimagnésiques", "sous-classe des soils carbonatés" (AC). Rendzinas were sometimes developed on hard calcarous rocks ("groupe des rendzines"). On the cemented limestone rocks (Mar) soils belonging to the groupe des sols brun calcaires" could also be distinguished.
On places where soil erosion has been less intensive due to a denser vegetation or less steeper slopes soils were found belonging to the "Classe des sols brunifiés" ("Sous - classe des soils brunifiés des climats tempérés humides - Groupe des sols bruns"). These soils have generally speaking a more distinct A-horizon up to 20 cm (C-content 2 - 4% and a structural B-horizon). On metamorphic rocks the A-horizons were "modeux" and

under forest may reach a humus content of 10% . On sandstone (Mars) a Bt.-horizon was found locally ("Groupe des sols lessivés").
In the coastal plains hydromorphic soils belonging to the "Classe des sols hydromorphes" ("Sous-classe peu humifère; Groupe à gley") were found.
On the marine terraces remnants of paleosols belonging to the "Classe des sols à sesquioxides de fer" ("Sous-classe des sols fersiallitiques") were found. They were covered by a younger colluvial layer with "sols mineraux bruts ou peu évolués".

2.5 Landuse and vegetation

The fragile equilibrium existing in the Mediterranean areas between soil and vegetation has been disturbed by man in many places; such is also the case in Calabria.
In entire Calabria there is still, despite the explosive growth of the agrarian population, relatively much natural forest especially in the higher parts of the Sila, Aspromonte and Senne (44%) (Tichy 1962). In addition many shrub and grass areas are found. In Calabria it is possible to distinguish four natural vegetation zones related to altitude:

- Zone up to 500 m:
  This is the Mediterranean vegetation zone with evergreens, such as quercus illex, pistacca lantiscum, lentiscu macchie, cistus macchie;
- Zone from 500 - 1200 m:
  Lower mountain zone with deciduous mixed forest, such as quercus cerris and castanea sativa and spartium junceum and deciduous shrubs;
- Zone from 1200 - 2000 m:
  Upper mountain zone with mixed forest vegetation, e.g. fagus enabies. This type of vegetations with undergrowth is comparable to the natural forests in the European mountains;
- Zone above 2000 m:
  This zone is largely composed of conifers, e.g. pinus heldreichii and pinus leucodermis.

The natural vegetation has disappeared especially in the coastal area due to pressure from the agrarian population.
Agricultural grounds were extended in the second half of the 19th Century as a result of the population explosion. This led to deforestation and hence increased erosion (Tichy 1962).
A large percentage of the working population in Calabria works in the agrarian sector (Huson 1970). In 1960 this was 60% (Meyriat 1970). Most farms have mixed cultivation. They are small and not mechanized. The yield is largely for personal use.
Calabria, which is one of the most densely populated areas in Italy, has the lowest production per acre. As a result the standard of living is very low.
One of the most important products is grain which is sown twice a year (Milone 1956). The heavy precipitation does a lot of damage to the winter grain and the summer grain suffers from the drought. The productivity on the steep, rocky slopes subject to erosion

is low. The cultivation of olives is, next to the growing of grain, very important. Due to drought, poor soils and diseases the production is not up to standard. Only the production of fruit in the irrigated coastel areas is of such quality and quantity that it can be exported (Meyriat 1960).

Cattle breeding is, like agriculture, not highly developed. The live-stock consists mainly of sheep and goats. Their numbers decreased sharply, especially after the war, as a result of the discontinuation of transhumance and agrarian reforms. Overgrazing is common. Areas covered with grass and shrubs serve as pastures which are then subject to strong erosion. These natural pastures are not very nutritious; additional food is provided by agricultural products and often garbage from around the house.

In the study area the percentage of land used for agriculture is fairly high. The narrow coastal plain and the terraces in the river valleys are generally used for horticulture. On the steep, terraced slopes mainly grains and fodder crops are grown in combination with horticulture (e.g. olives). As far as we could determine the yield is for personal use. On the steep slopes of metamorphic rocks, e.g. in the Savuto valley and on the siltstones of the Fiume Grande valley olives are cultivated. The less steep slopes, usually occurring in siltstone areas, are used exclusively for agriculture. The parcels of land are usually larger in these areas.

Weakly cemented sandstone, disintegrates easily and after tilling forms new soil although it is not nutritious.

When comparing the present amount of land used for agriculture with that of 1955 on aerial photographs a decrease in agrarian activity can be ascertained. Abandoned farms can be recognized in the field by the rocky ground with pavements resulting from the erosion which took place during farming, the presence of terraces, and neglected olive trees and fruit trees. Grasses, herbs and sometimes shrubs grow abundantly on these farmlands. Ruins of farmhouses are numerous in the study area.

The more or less natural vegetation of grasses, herbs and shrubs grows on the steepest slopes of the hard Triassic dolomitic rock, the even harder Mar-sandstone and on the steeper slopes of the granite and metamorphic rocks. The areas less densely overgrown with shrubs and grasses served as natural pastures. Gullies are still visible in these pastures. A spectacular example of this can be seen in the Mar-sandstone area east of Cleto where 40% of the soil has disappeared and the remaining weathering layer is held together only by sparse vegetation.

There are not many forests in the study area. They consist mostly of oaks and have deteriorated. At higher altitudes just outside the study area oak- and chestnutforest are found.

The steepest slopes in the study area, such as sandstone slopes, are partly being reforested. These are the areas where the original vegetation of grasses and shrubs has been destroyed by overgrazing to such an extent that restoration is impossible. This is due to the fact that water erosion led to the partial disappearance of the soil. Terrace ridges are hewn into the slopes of the less-cemented rock (Mars-sandstone) yielding a new soil in which shrubs are planted. These shrubs take root easily and help prevent water erosion. In the badlands the new plants are often destroyed by surfacial sliding.

3

THE SPECIFICATION OF THE WATER EROSION CASCADE

3.1 The splash erosion cascade

In chapter 1 we have already illustrated (Figure 1.1) that the splash erosion cascade is an important process sub-system of the water erosion cascade. While the overland flow erosion cascade depends on the production of overland flow by the hydrological cascade, the splash cascade only depends on the direct input of rain. We will now discuss this process cascade in relation to various landscape variables in more detail.
The input of the splash cascade (Figure 1.1) is formed by the mass of raindrops. The kinetic energy of the falling raindrops is used to set the sediment material into motion within the system. The kinetic energy per unit of time is determined by the total mass of rain per unit of time (= the rainfall intensity) multiplied by the terminal velocity of the falling drops. This velocity depends on their size (drop diameter). Laws (1941) and Gunn & Kinzer (1949) measured the terminal velocity by each raindrop diameter. The total kinetic energy of the rain which is called the erosivity of the rain (Hudson 1973) can be calculated from the drop size distribution of a rainshower. The measurement of dropsize distribution is a rather laborious and difficult technique (Hudson 1973), but through these measurements empirical relationships were found between dropsize distribution and the intensity of the rain in different parts of the world (Laws & Parson 1943, Best 1950, Hudson 1963).

A relationship was set up between rainfall intensity (which is easy to measure during the rainstorms) and the kinetic energy of the rain in different parts of the world (see Hudson 1973).
For the United States, e.g. Wischmeier (1962) found that the kinetic energy per unit of rain mass and per unit area is correlated with the 0.14 power of rainfall intensity. More precise methods of measurements of the kinetic energy or the momentum of the falling raindrops have been developed by Rose (1958), Hudson (1965), Kinell (1968), Forest (1970), Imeson (oral com.).
A number of experiments were carried out in which the input of the rain energy is compared with the output of splash discharge. The rest of the system was considered as a black box. Ellison (1944) found under laboratory conditions that splash detachment is correlated with the velocity of raindrops to the 4.33 power, the drop diameter to the 1.07 power and the rainfall intensity to the 0.65 power. Bisal (1960) found a relation between splash detachment with the drop diameter (linear) and with the drop velocity to the 1.4 power. Mihara (1951), Free (1960), Rose (1960), van Asch & Roels (1979) correlated splash detachment and transport with the total mass and velocity of the rain. It was found that depending on soil type, soil detachment can be correlated with the kinetic energy of the raindrops with an exponent varying from 0.9 (soil material with aggregates) to 2.5 (glass pearls). Van Asch & Roels (1979) calculated that only

5% of the kinetic energy from falling raindrops is transmitted into the the kinetic energy of moving grain material.
Based on a large number of data from experimental plots, Wischmeier et al. (1958) proposed a good erosivity parameter for natural rainshowers, the so-called EI-30 index. The EI-30 index (see also Ekern, 1950) is calculated by the multiplication of the kinetic energy from a rainstorm with the I-30 index which is the greatest average intensity, experienced in any 30 minute period during the storm. Given this relationship and the fact that for moderate up to intense rainstorms the kinetic energy per unit of rainmass per unit of area is correlated with $I^{0.14}$ (where I is rainfall intensity). Meyer & Wischmeier (1969) proposed that during steady state conditions the splash erosion S is correlated to the rainfall intensity to approximately the 2.14 power. Similar values are obtained when the laboratory data of Ellison (1944) (Meyer & Wischmeier 1969) are used. David & Beer (1975) concluded that $S \approx I^2$. Hudson (1973) showed that there is a certain threshold rain intensity value which is in Africa 25 mm/hr (one inch). Below this intensity the rain has little or no erosive power. He therefore introduced the KE> 1 index which is defined as the total kinetic energy of rain falling at intensities of more than 25 mm/hr (1 inch/hr). He found good correlation figures between this index and the amount of splashed sandy soils.
In Figure 1.1 the first regulator in the splash cascade is called vegetation structure. Important factors of the vegetation structure are the density of the vegetation and the height of the vegetation canopy. The vegetation canopy intercepts a part of the falling raindrops (I). A part of the water remains on the leaves until it is evaporated. A part of the water flows down the plants or trees to emerge as stemflow around the base and the third part drops to the ground from the leaves.
Depending on the height of the leaves above the soil surface the third part of the intercepted water can regain a certain kinetic energy which together with a part falling directly on the ground (through fall) form the input of kinetic energy to the soil surface sub-system. Therefore a dense vegetation canopy near the ground considerably reduces the transference of kinetic energy to the soil surface.
However, under forest (with a high canopy) the total kinetic energy delivered to the ground can be the same as in an open landscape (Chapman 1948, Trimble & Weitzmann 1954, Rougerie 1960, Ruxton 1967, Geiger 1975, Van Zon 1978). The studies show more or less directly that the mean dropsize of water falling from the leaves is larger than of rainwater in the open field. When the tree canopy is high enough (> 9 mtr, see Laws 1941) these drops can reach their terminal velocity again. Due to this increase in mean dropsize the kinetic energy of drops that fall from the canopy is increased.
This increase in kinetic energy of a part of the total rainmass may counterbalance the loss of kinetic energy due to evaporation and stemflow.
The second regulator in the splash cascade is the presence of a water film (W) due to overlandflow. According to Palmer (1964) and Mutchler & Young (1975) the way of energy transmission to the grains depends on the depth of the waterfilm. Up to a critical waterfilm thickness (which is according to Mutchler and Young 0.14 - 0.20 x the drop diameter and Palmer 3 x the drop diameter) the impact force on the grains will be

greater than when the soil surface is bare. Above this critical value the waterfilm works as a protective cover, absorbing all the kinetic energy while the impact force exerted on the grains is strongly reduced.

The soil grains may also be protected by the presence of a stone pavement and/or a litter-layer (SC), which can absorb a part or all the kinetic energy of the drops.
A third important category of regulators is formed by the transmission of a part of the kinetic energy of the rainmass into the kinetic energy of moving particles. The "water reflection regulator" (WR), see Figure 1.1 determines which part of the momentum of the falling raindrops is reflected. The reflected water droplets carry some soil particles into the air. According to Carson & Kirkby (1972) the amount of momentum reflection depends on the presence of water in the soil surface pores or at the soil surface. Van Asch & Roels (1979) suggested that the elasticity and the bulk density of the soil body are also important factors. If no soil water is present in or at the surface no reflection of raindrop momentum takes place and therefore no ejection of soil particles (Carson & Kirkby 1972). For this condition the exerted force of the raindrops on the soil body can be resolved in a normal force and a shear force along the surface. The normal force causes a consolidation of the surface particles down into the soil pore space, or the formation of small craters. In this manner a great part of the kinetic energy is lost. The shear force along the soil surface causes the soil particles to be transported a certain distance along the surface (Carson & Kirkby 1972). This type of process is called splash-creep.
The most important regulator is the soil resistance (threshold) regulator (SR, see Figure 1.1), which determines if the exerted forces of the water energy are large enough to set the material into motion. The resistance against these forces is determined by the cohesion and internal friction of the soil particles which build up the soil strength. The soil strength is influenced by the amount of water pressure or air pressure in the pores. The air pressure and (or) pore pressure increases particularly during the impact of rain and this (according to Coulomb's Law) means a reduction of the soil strength. The particle size is also of importance since it determines whether a given exerted forse of a raindrop mass is large enough to carry the particle into the air. Up till now little experimental work has been done to determine the effect of the above mentioned regulators and their related variables on the energy and mass flow.
We have already mentioned the effect of the waterfilm on the surface. Sloneker et al. (1976) investigated the effect of the pore water pressure of water saturated soils. They measured an increase in splash amount at first as the pore pressure decreases to around - 20 mb, followed by a decrease of splash, which is especially rapid in coarser sand. It is clear that techniques have to be evaluated in order to measure the soil strength and cohesion of the material and the change in pore pressure during the impact of raindrops such as done by Sloneker et al. (1976).
In the above the soil body is considered as an accumulation of loose grains. In most soils the grains are bound together in aggregates, which have a certain cohesion. It is the strength of these aggregates, expressed as an aggregate stability parameter, which proved to be an important parameter in the determination of soil resistance (or erodibility)

against splash detachment (Bryan 1968, 1976). The cohesive strength of the soil particles or aggregate stability is determined by the binding effects of organic compounds, the clay content, types of absorbed cations, the Ph and Al- and Fe-hydroxides (Chester et al. 1957, Allison 1968, Baver et al. 1972). The decrease of the cohesive strength of these aggregates is possible due to the differential swelling of mainly clay minerals (Henin 1938) and compression of entrapped air.
Yoder (1936) proposed a method of measuring the stability of the aggregates by agitating them in water. Other methods essentially based on mechanical analysis have been proposed by e.g. Nishikata & Takeudi (1955), Henin (1963). Another method used for the measurement of the stability of the aggregates is to subject the aggregates directly to the process of rain fall impact (McCalla 1944, Pereira 1956). Bryan (1968) suggested that the aggregate stability, determined by the water drop technique of McCalla (1944), modified by Smith & Cernuda (1951), proved to be a more efficient index of soil erodibility than the indices derived from other methods, because soil aggregates which showed to be waterstable by the gently shaking activity of wet sieving may not in fact be stable when subjected to the impact of raindrops with high fall velocity.
Another soil resistance factor which can be measured is the grain size distribution. The grain size is of importance to the soil resistance regulator in two ways:

- It has already been stated that smaller particles are much easier to detach and transport than coarser particles. Ellison (1944) showed that, compared to coarse particles, finer soil particles are preferentially lifted from the surface (see also Rose 1960, De Ploey & Savat 1968, Yariv 1976).
- However, very fine particles like clay are much more difficult to detach since they have strong cohesive bindings.

Various textural indices have been evaluated but the work of Bryan (1968), who tested these indices, shows that no strong correlation exists with the amount splash detachment on natural soils with aggregate building. The erodibility of the soil may be reduced strongly due to the formation of a crust at the soil surface, McIntire (1958), Epstein & Grant (1973).
These crusts have a greater bulk density, shearing resistance, a lower degree of aggregation and a higher content of finer material in comparison to the subsurface (Lemos & Lutz 1957). Soil crusts are formed by the impact of raindrops, which results in a physical compaction of the soil surface material (Epstein & Grant 1973) and by long periods of heating and drying (Lemos & Lutz 1957). Soils which are susceptible to crust formation have a large content of silt or total material < 0.10 mm and 2:1 type clay minerals (Lemos & Lutz 1975).
The vegetation system influences the resistance regulator: the production of organic material and the stimulation of biological activity leads to a better structure and greater stability of the aggregates. Yamato & Anderson (1973) stressed the importance of binding effects of especially the grass roots on the soil resistance against splash detachment.

The effect of the slope regulator (A), see Figure 1.1, on the final output of sediment discharge is explained in 3 ways:

– Slope steepness determines the ratio between the amount of soil which is splashed upwards and downwards through the air. At higher slope angles more soil particles are transported downwards due to the increasing downslope component of the impact of the raindrops. Ratios are given by Ellison (1944), Mosely (1974), De Ploey & Moeyerson (1976), Morgan (1978), Savat (in prep.).
– By an increasing slope angle, the splashed particle will reach the soil surface at a greater distance downslope and a shorter distance upslope from the point of impact De Ploey & Savat (1968), Mosley (1974), Savat (in prep.).
– By an increasing slope angle the downslope impact shear force is able to carry more soil particles along the slope over a greater distance (Carson & Kirkby, 1972).

A summary of the effect of different regulators on the output of the splash erosion cascade is given by the equation developed by David & Beer (1975) and Savat (in prep.) which is an approximation for the calculation of the splash discharge.

$$S = I^{\alpha} \,.\, V \,.\, e^{-\beta d} \,.\, C \,.\, R \,.\, (\sin a)^{\gamma} \qquad (1)$$

in which S = the amount of splash discharge in weight per unit width, I = the rainfall intensity in length per hour, V = vegetation density factor, d = depth of waterfilm in length, C = soil cover factor, R = soil Resistance factor, a = slope angle and α, β and γ are constants.

The following remarks can be made with regard to this equation:

– The rainfall intensity factor I is only a rough index for steady state conditions based on the relationships which exist between rainfall energy of natural rainstorms and rainfall intensity (see Meyer & Wischmeier (1969). The EI-30 and KE > I indexes were developed for natural showers which vary in intensity with time.
  The calculation of the amount of kinetic energy based on drop size and velocity of drops are rather inaccurate, and for this reason methods are being developed for a direct measurement of the rainfall energy.
– There is only limited empirical information available concerning the influence of the vegetation density and height on the amount of kinetic energy of rainwater, which is supplied to the soil surface and the related amount of splash-output.
– The relationship between the depth of the waterfilm and the amount of splash detachment is rather complex. The factor given in the formula demonstrates the protective effect of the waterfilm. In the above we stated, however, that at a very shallow depth the amount of splash detachment increased compared to conditions where no waterfilm is present. There is, however, little experimental work which supports this theory (e.g. Mutchler & Young 1975).
– Few experimental data relating vegetation cover and soil cover parameters with the amount of splash discharge (Screenivas et al. 1947) are available.
– In order to determined the soil resistance factors more experiments must be carried out to develop techniques for the direct measurement of the resistance of the soil against erosion, e.g. the measurement of the shearing resistance at the soil surface as proposed by Bryan (1976). The evoluation of soil parameters which determine the

amount of waterdrop reflection (soil moisture conditions, bulk density, etc.) is also very important.
- Many experiments have been carried out under laboratory conditions so that the influence of slope angle on the netto sediment discharge could be measured. Due to differences in measuring techniques it is difficult to compare the results.

Equation (1) is a first step in the evaluation of an empirical equation for the amount of splash discharge on the slope.
We will show in Chapter 5 that this type of transport is very important especially on slopes with more or less natural vegetation. In the evaluation of such an empirical equation we must develop an uniform definition of splash discharge and use the same measuring techniques. In this way uniform parameters can be evaluated for e.g. vegetation structure, soil resistance, soil moisture, conditions and water conditions.
In Chapter 4 some of the appropriate parameters used for the splash transport model will be treated.

3.2 The hydrological cascade as a generator of overlandflow

In Chapter 1 we considered the output of overlandflow from the hydrological cascade as an input in the overlandflow erosion cascade (Figure 1.1). It was stated that four important threshold regulators are involved in the production of overlandflow (given a certain input of rain). Therefore, for the purpose of our study this part of the hydrological cycle and particularly the influence of the landscape variables on these threshold regulators must be discussed in more detail.
The most important regulator is the infiltration capacity regulator (F) (Figure 1.1). It can be defined as the maximum rate at which water can infiltrate the soil body during a given time t. If the rainfall rate (intensity) at that time is in excess of the infiltration rate water is stored on the soil surface.
Two components are involved in the infiltration process of water into the soil:
- the transmission- or conductivity component, which can be described as an unimpeded laminar flow through a continuous network of large pores, due to the effect of gravity,
- a diffusion component, which can be described as a flow in very small discrete steps going from one pore space to the next in a random fashion due to capillary suction (Kirkby 1969, Knapp 1978).

Several authors have given theoretical and empirical formulas to describe the infiltration of water into the soil (see for a summary Seyhan (1977). A wellknown empirical equation was set up by Horton (1945):

$$f = f_c + (f_o - f_c)\, e^{-kt} \qquad (2)$$

in which f = the instantaneous infiltration rate at time t, in volume per unit of time, fc = the minimum infiltration rate in volume per unit of time at time $t = \alpha$ and f_o is the maximum infiltration rate in volume per unit of time at t = o; k = a constant which depends on the characteristics of the soil. The formula shows a decreasing infiltration rate to a constant f_c-value from the beginning of the rainfall and this decrease is due to a declining average of the potential gradient for the diffusivity flow and to the swelling capacity of the clay minerals which decreases the total pore spaces. The pores can also be filled with suspended clay particles (Knapp 1978). The infiltration formula of Childs based on the formula of Green & Ampt (1911) gives a number of measurable physical parameters related to the infiltration process:

$$f_a = K_s \frac{(H + H_f + Z_f)}{Z_f} \qquad (3)$$

in which f_a = the instantaneous infiltration rate in volume per unit of time, K_s = the hydrological conductivity factor (based on Darcy's Law), H = the thickness of the waterfilm on the soil surface, H_f = the pore water pressure (weight per unit area) measured directly above the wetting front and Z_f = the depth of the wetting front.
Apart from the influence of the time factor we must now draw our attention to the question in what way the maximum infiltration rate (= the infiltration capacity regulator) is influenced by landscape variables of different landscape attributes (soils, vegetation and topography).
The most important soil variables which are related to the infiltration rate of the soil are the total amount of pore space (soil porosity) and the size distribution and structure of the pores. The ratio between the amount of capillary- and non-capillary pores is important because the first determines the diffusivity component of the infiltrating water and the latter the conductivity component of the flow. The total amount of pores, the size distribution and the structure of the pores is determined by the texture (grain-size distribution) and structure (size distribution and structure of aggregates) of the soil (Wischmeier et al. 1971).
The stability of the aggregates is an important soil variable because soils with stable aggregates maintain their pore spaces better, while soils with unstable aggregates, e.g. due to the swelling of clay minerals, tend to have lower infiltration capacities. The horizon with the lowest infiltration capacity is critical where soil properties vary with profile depth. In the case of sandy soils, the critical horizon is often the surface where a crust may be sufficient to decrease infiltration in such a way that overland flow occurs while the underlying soil may be dry (Morgan 1979).

The infiltration capacity is also influenced by the presence of organic layers (Aoo, Ao and A1. The presence of these layers, which is related to the amount and type of vegetation has a positive effect on the infiltration capacity of the soil (e.g. Yamato & Anderson 1973).
A litter cover (Aoo) can also influence the infiltration rate indirectly: in increases the surface roughness of the soil which, by a given constant overlandflow discharge, increases the waterfilm thickness (according to the Manning's equation (see below). An increase in the waterfilm depth increases the infiltration rate (Best 1950, Green & Ampt 1911).

Another important soil variable influencing the infiltration capacity is the initial soil moisture content of the soil. This variable (see Figure 1.1 SM) changes relatively rapidly. The infiltration capacity generally diminishes with the increasing initial soil moisture content (Ward 1967). Data from a.o. Free, Browing & Musgrave (1940) and Carson & Kirkby (1972) show that the initial infiltration rate (Horton's fo-value) is drastically reduced by a wet soil and that a lesser reduction of the minimum infiltration rate (fc) takes place to about one half or one third of the dry value (see also Nassif & Wilson 1975).

The following explanations are given:

- The diffusivity component is influenced by the amount of soil moisture storage in the capillary pores.
  In initially dry soils the suction force of the capillary pores works at a maximum and therefore the diffusivity flow has a maximum rate. However, when the soil is saturated there is no diffusivity flow component, because the water-filled capillary pores from a blockage (Carson & Kirkby 1972).
  Therefore during saturated conditions of the soil the minimum infiltration rate is correlated closely with the non-capillary porosity (Free, Browning & Musgrave 1940).
  During moderate initial moisture conditions of the soil the conductivity component is numerically more important than the diffusivity component (Carson & Kirkby 1972).
- Increasing soil moisture causes swelling of the clay colloides and this reduces pore space. Furthermore the pores can be filled up by suspended clay from the infiltrating water.

Vegetation variables can also influence the infiltration capacity regulator. Micro-vegetation at the soil surface and the production of litter have an effect in the soil surface roughness and hence on the hydraulic conditions of overlandflow and infiltration (see above). The root-system of the plants may have an effect on the amount of pore space. The vegetation cover also protects the soil surface against the impact of rain which in turn prevents the sealing of the soil.

Topographical variables also influence the infiltration capacity of the soil indirectly. At steady state conditions an increase in slope length means an increase in waterfilm depth of overlandflow and thus an increase in infiltration rate (Green & Ampt 1911). However, by an increasing slope angle and a given constant discharge, the mean stream velocity will increase while the mean flow depth decreases (Manning's equation). In that case the infiltration rate will decrease. Furthermore we must keep in mind that an increase in slope angle at a constant rain intensity, means a decrease in water supply per unit length of slope. This means a decrease in discharge (Horton 1945). Nassif & Wilson (1973) tested the infiltration capacity of different soils under different slope angles. They found (under laboratory conditions) that Horton's fc-value decreases especially for permeable soils with increasing slope angle up to some limiting value varying between 8 and 24%.

When the rainfall intensity exceeds the maximum infiltration rate of the soil, water is stored at the soil surface. The soil surface storage capacity (see Figure 1.1) is determined by the micro-topographical characteristics of the soil, micro-vegetation and waste

of plants and trees. The amount of surface storage has a positive effect on the infiltration rate due to the increase of the mean water depth at the surface. Overlandflow (Horton's overlandflow) starts when the surface storage capacity is exceeded.
A part of the water which infiltrates the soil, is stored as soil moisture (SM) and when a more impermeable layer is present it is stored as soil groundwater (BS). On a slope the groundwater starts to flow as saturated throughflow parallel to the surface. A section of the soil body along the slope can become completely saturated when the amount of water, flowing into the section by throughflow plus the amount of percolating water per unit of time is greater than the amount of water flowing out of this section. So-called saturated overlandflow (Kirkby 1969) can take place when after a certain time the ground water storage capacity of the soil (B, Figure 1.1) in that section is exceeded. This may be the case at places on the slope with certain flow concentration (due to profile concavity or contour concavity), or at places where the soil is thinner or less permeable in a downslope direction. When rain is falling on the slope and a steady state condition is reached, throughflow discharge increases in a downslope direction. Saturated overlandflow at the foot of the slope may occur when the groundwater storage capacity (depending on the depth of the soil) is not large enough to let through all the water of the sub-surface flow.

It is obvious that the production of saturated overlandflow depends on the character of the soil profile (presence of impermeable layers, IMP (Figure 1.1) the soildepth and the total amount of pore space which influences the soil moisture and groundwater storage capacity. The hydrological conductivity in the soil (depending on the amount of pore space and poresize distribution) is also of importance.
In the above we have shown how different landscape variables determine the amount of rainfall excess at each part of the slope. The amount of rainfall excess is determined by the intensity of the rain minus the infiltration rate at each part of the slope. An integration of this rainfall excess along the slope, determines the total flow discharge of the slope which will be considered as the input of the overlandflow erosion cascade (see 3.3). An integration of the rainfall excess along the slope is very difficult to obtain for natural circumstances, because the change in the values of landscape variables determining the infiltration rate (e.g. vegetation cover, moisture content, slope angle) is in most cases discontinue along the slope.
The hydrology of the sub-surface must also be taken into consideration because further downslope an important threshold may be surpassed, causing saturated overland flow conditions for a certain part of the slope. Computer-simulation is the only way of obtaining a realistic insight of the effect of the variation in landscape variables along the slope on the amount of overlandflow.

3.3 The overlandflow erosion cascade

We define the input for the overlandflow erosion cascade as the total amount of mass per unit of time of overlandflow (QI Figure 1.1) produced by the hydrological cascade.

The overlandflow Q for steady state conditions can be expressed (according to Carson & Kirkby (1972)) as:

$$Q = \int_0^X i_\star \, dx \qquad (4)$$

in which Q = the volume of water per unit of time per unit slope width; X = distance from the divide measured over the slope and $i_\star$ = the amount of rainfall excess in volume per unit of time. The amount of rainfall excess is determined by the rainfall intensity I minus the infiltration capacity F of the soil and the storage capacity. Generally speaking, the amount of mass of water which serves as input into the system depends (apart from the variables of the hydrological cascade) on the length of the subsystem slope.
The overlandflow excerts a boundary shear stress on the soil surface and can produce a flow of sediment mass in the system. Generally speaking the shear stress is related to the velocity of the fluid[1]. The velocity of the flow depends on the roughness of the soil surface, the slope angle and the depth of the flow. The velocity of flow for turbulent flow is given by the Manning's equation:

$$V = \frac{1}{n} S^{0.5} . D^{0.07} \qquad (5)$$

in which V = the velocity of the flow, n = Mannings's n (roughness factor), S = the tangent of slope and D = the depth of the waterfilm. Emmett (1970, 1978), Savat (1977) showed that the exponents of S and D vary by different Reynold numbers and hence flow type conditions.
Meyer (1965) showed, with the aid of the continuity and of the Manning's velocity equation (5), that:

$$V \propto S^{1/3} . Q^{1/3} \qquad (6)$$

An equation for the mean shear stress of flowing water in infinite wide channels can be evaluated from static equilibrium conditions, and this yields measurable parameters (see Carson 1971):

$$\bar{\tau}_0 = \sigma_W \, D.S \qquad (7)$$

in which $\bar{\tau}_0$ = "the mean unit tractive force" (Du Boy), or mean shear stress, and σ_W is the density of the fluid. The mean shear stress based on equation (7) and the Manning's equation for turbulent flow is approximately propotional to the flow velocity squared Meyer & Wischmeier 1969).
Therefore, using equation (5) for turbulent flow, we arrive at the following:

$$\bar{\tau}_0 = V^2 = K.S^{2/3} . Q^{2/3} \qquad (8)$$

in which K = a constant depending on the surface roughness.
The question arises, whether the shear stress of the overlandflow water is large enough to set the sediment into motion. According to David & Beer (1975) a waterfilm under ideal conditions on a uniform surface has shear stresses which are too low in relation to the shear strength of the soil and therefore detachment by overlandflow is very low. Bryan (1974) also suggested that the flow velocities are well below the critical minimum velocity, observed for sediment transport. There are, however, some factors which favour the detachment by overlandflow:

- Firstly, we must consider the fact that there is an extra input of kinetic energy by falling raindrops (see Figure 1.1) which gives the waterfilm a more turbulent character increasing the velocity gradient and hence the scouring capacity of the water flow (Emmett 1970, Savat 1977)
- Secondly, we must consider the fact that on natural slopes there is no uniform continuous waterfilm.
  Due to the micro relief of the soil surface (depressions, rills and litter cover) or due to the relatively great particles of soil aggregates in relation to the mean thickness of the waterfilm, the flowing water can have a complex pattern of small streams with varying depths velocities. This means that the water is concentrated in streams with much greater velocities and flow depths and hence locally greater shear forces than the mean shear force, excerted on the surface (see equation (7) or (8)) (Emmett 1970, Bryan 1974, David & Beer 1975, Mutchler & Young 1975).

In other words we might say that the micro relief of the soil surface, which is also influenced by vegetation and stone cover is an important regulator (OD Figure 1.1). It determines the amount of concentration of the flow at the soil surface and therefore influences the amount of detachment of the soil particles. It is clear from the discussion above about the scouring capacity of overlandflow that it is difficult to determine a critical mean velocity value for overlandflow detachment, because, due to a complex stream pattern, real flow depths, flow velocities and the shear stresses at one place are difficult to measure. To evaluate certain threshold values for stream velocities we must now consider the next important regulator of the cascade: the shear strength of the soil (SR see Figure 1.1). Generally speaking, the critical shear stress of uniform grains is related to the number of soil particles, the submerged mass of the grains and friction angle and cohesion. Little empirical work has been done to evaluate shearing resistance parameters of natural soils against the shear stresses excerted by overlandflow (Ovens 1969).

We can asssume, that the overlandflow waterfilm is loaded with material detached by overlandflow shear forces. Figure 1.1 shows that the flow can also be loaded with material, delivered by the splash erosion cascade. The total amount of soil material – supplied

from these two sources – which can finally be transported by the flow, is regulated by the transport capacity of the flow (T Figure 1.1).
According to the results of Laurens (1958) the transport capacity of flowing water is approximately proportional to the fifth power of the flow velocity (when the Mannings' equation (5) for turbulent flow is used). According to Meyer & Wischmeier (1969) we arrive at the following:

$$T = K.S^{5/3} . Q^{5/3} \tag{9}$$

in which T = the transport capacity of overlandflow and K = a constant, depending on the soil surface roughness factor.
Two conditions of overlandflow erosion are possible:
– The total amount of material delivered by splash detachment (Ds) and by overlandflow detachment (Do) is greater than the transport capacity of the flow (T).
– The transport capacity (T) is greater than the total amount of detached material (Ds + Do).
If Ds + Do > T than storage of material (sedimentation) takes place. The amount of sediment discharge out of the system is determined by the transport capacity of the flow and using equation (9) we can write:

$$SO_t = T = K_1 .S^{5/3} . Q^{5/3} \tag{10}$$

in which SO_t = the amount of sediment which is discharged over a unit width of slope.
If Ds + Do < T, the amount of sediment discharge is determined by the amount of material delivered by overlandflow detachment (Do) and splash detachment (Ds). If we assume that the amount of overlandflow detachment is proportional to the mean unit tractive force of the flow, the amount of material (Do) which is detached in a certain area (A) can be expressed (using equation (8)) by the following equation:

$$Do = K_2 .S^{2/3}.Q^{2/3}.A \tag{11}$$

in which K_2 expresses soil factors.
The amount of material, which is detached by splash in a certain area (A) and delivered to the flow, can be expressed by the following equation:

$$Ds = K_3.A .I^a \tag{12}$$

in which K_3 expresses soil and soil cover factors (see equation (1)), and I is the rainfall intensity.
According to (11) and (12) the total sediment discharge under detachment limited conditions for a unit width of slope (SO_d) is given by the following equation:

$$SO_d = K_2 \cdot S^{2/3} \cdot Q^{2/3} \cdot L + K_3 \cdot I^a \cdot L \qquad (13)$$

in which L = the length of the slope.

In the next chapter we will use the above given equations in order to obtain insight into the mechanism and the output of sediment transport on the slopes in different landscape units. We must remark here that for future research the evaluation of hydraulic formulas for thin overlandflow waterfilms on natural slopes is necessary and in this context, the effect of raindrop energy must also be considered (Emmett 1970, Savat 1977). Furthermore techniques for measuring the real discharges (velocity and stream depth) in the concentrated streamlets on the slope must be evaluated in order to achieve the determination of the real shear stresses and transport capacity of the flowing water.
Shear strength parameters for natural soils must be evaluated, which makes it possible to determine whether detachment by overlandflow is possible.
In this manner we can determine which part of the material is delivered by splash detachment (see 3.1) and which part by overlandflow. Furthermore it is possible to determine whether the discharge by overlandflow is controled by the transport capacity of the flow (equation (10)) or by the total amount of detached sediments (equation (13)).
In this manner we may achieve more insight into the system of sediment transport on the slopes. Equations can be evaluated giving a more accurate output of sediment yield on the slope in relation to topographical and soil variables.

3.4 Empirical measurements as regarded to the total output of the water erosion cascade

Up till now, many studies have only given empirical relationships between some important landscape variables and the total output of sediment discharge from the water erosion cascade. No separation has been made in a given period between the output of sediment discharge of the splash erosion cascade (3.1) and the sediment discharge delivered by the combination of the splash erosion cascade and the overlandflow cascading system. Many empirical relationships were set up between the input of rain energy (e.g. EI-30-index) and the total output of sediment from the wash erosion cascade (see a.o. Wischmeier & Smith (1958) for agricultural areas, Hadley and Lusby (1967) for natural bare areas, Musgrave (1947)). In areas with a denser vegetation and a variable infiltration capacity the output of sediment discharge was correlated with the input of overlandflow water. Carson & Kirkby (1972) correlated the results of erosion data with overlandflow data for different landunits in different parts of the world with comparable rainfall conditions. They found that the average soil loss in $cm^3/cm/year$ is proportional to the annual overlandflow to the 1.85 power. It would be interesting to compare this result with equation (10).
For the purpose of our study we are particularly interested in the empirical relationships between topographical variables (slope angle and slope length), soil variables, vegetation variables and the total sediment output of the water erosion cascade. Zing (1940) ana-

lysed the results of laboratorium and field experiments and found that total sediment discharge correlates with the tangent slope angle to the 1.49 power. Musgrave (1947) and Carson & Kirkby (1972) found a 1.35 power function and Hudson & Jackson (1959) found an exponent 2 under tropical conditions (all data concern agricultural slopes). (Compare these results with the theoretical formulas given in (10) and 13).)
Wischmeier & Smith (1958) found that the combined data for the USDA-field experiments best fitted a slightly different equation $E = 0.43 + 0.30\ S + 0.04\ S^2$.
Few data are available concerning slopes under natural conditions. Carson & Kirkby (1972) analysed data from Schumm (1956, 1964) for unvegetated and sparsely vegetated hill slopes and found a relationship between total sediment discharge and the sinus of slope angle. If we look at equation (1), this may be an indication towards the fact that splash transport is the main agent in the delivery of sediment towards overlandflow or that most of the time only the splash cascading system is working.
According to several authors, the slope angle exponent is influenced by other landscape variables. Gabriels, Pauwels & De Boodt (1975) show that on agricultural plots the exponent increases with grainsize of the material from 0.6 for particles of 0.05 mm to 1.7 for particles of 1 mm.
The exponent value may also be sensitive to the slope angle itself, decreasing with increasing slope steepness. Laboratory studies show that the exponent = 1.6 for slopes between 0 and 2.5° and 0.7 for slopes between 3 and 6.5° and 0.4 for slopes over 6.5° (Horvath and Eröde, 1962). Furthermore the exponents vary with slope shape: on 3 mtr. long plots and average steepness between 2° and 8° under simulated rainfall, D'Souza and Morgan (1976) obtained values of 0.5 for convex slopes 0.4 for straight slopes and 0.14 for concave slopes. Morgan (1979) mentioned the influence of vegetation cover on the slope exponent and reported an increase of the exponent with decreasing grass cover. Lal (1976) reported the influence of organic mulch on the exponent changing from 1.13 to 0.14.
In many cases no explanation can be given of these changes of the slope angle exponent. Therefore transport by splash (see equation (1)) and transport by overlandflow erosion have to be separated. Further it is necessary to determine under what conditions overlandflow takes place. (see equation (10) and (13))
As regard to the influence of slope length Zing (1940) found that the total sediment discharge is correlated with the 1.6 power of slope length. Musgrave (1947), Hudson & Jackson (1959) and Kirkby (1969) found respect. 1.35, 1.73 and 2 power functions. When these data for agricultural areas are compared to data of Schumm (1956, 1964) for unvegetated and sparsely vegetated areas on natural slopes in the USA, the slope length exponent seems to be much lower (0.77 and 1). Apart from the explanation given by Carson & Kirkby (1972) this might be an indication towards the fact that on these natural slopes sediment transport is controled by detachment of material and perhaps mainly splash detachment. It can be inferred from equation (13) that SO_d is correlated with a lower power function of Q and hence the slope length, than SO_t in equation (10).
Furthermore soil variables were related to the total output of sediment discharge from the water erosion cascade. We have seen that the soil is generally important to the cas-

Table 3.1 A survey of the regulators[a] of the water erosion cascade and the hydrological cascade and the related landscape parameters (variables)

Cascading system	Regulator	Related landscape parameters (variables)
Hydrological cascade	Interception regulator > **I**	Density and height of vegetation structures
	Infiltration regulator > **F**	Rootdensity and structure Thickness and porosity of Aoo and Ao layers Soil porosity and poresize distribution Aggregate stability Grainsize distribution of the soil Slope angle
	Soil surface storage regulator > **R**	Microtopography of the soilsurface
	Soil moisture storage regulator > **M**	Soil porosity and poresize distribution
	Soil profile regulators **P** and > **B**	Soil profile development Depth of regolith
Splash- and Overlandflow cascade	Soil cover regulator **SC**	Herb vegetation: density and structure Aoo layer Stone pavement: density and structure
	Soil resistance regulator > **SR**	Rootdensity and structure Bulkdensity of the soil Aggregate stability and size distributions Grainsize distribution
Splash cascade	Water reflector regulator **WR**	Soil porosity and bulkdensity Slope angle
Overlandflow cascade	Overlandflow distributor **MT**	Herb vegetation: density and structure Aoo layer Stone pavement: density and structure Microtopography soilsurface
	Transport regulator > **T**	Slope angle Slope length

a see also figure 1.1

cading system because it functions as an important regulator in the production of overlandflow and it determines the resistance of the soil (soil erodibility) against the erosion forces of the water. Many soil variables have been evaluated especially for the determination of the soil erodibility. The aggregate stability a.o. Yoder (1936), Henin (1963), Bryan (1968) are worth mentioning. Further soil texture indices have been developed (Bouyoucos 1935, Middleton 1930, André & Anderson 1961, Wischmeier 1971). Generally speaking, the amount of silt increases the erodibility, while a rising amount of clay and sand decreases the erodibility of the soil. Bryan (1976) suggested that the shear strength of the soil might be a good parameter of the resistance of the soil against erosion forces. According to him this is especially valid for natural hill slopes where the soils involved are usually coherent and therefore the resistance of the soil is determined by intergranual friction, by cohesion and pore water pressure. It is interesting to note that these soil erodibility parameters correlate well to both the sediment output from the splash erosion cascade and the sediment output of the overlandflow cascade (Bryan 1968). These experimental results point to the fact that splash detachment is the most important factor in the supply of sediment to overlandflow in the overlandflow cascading system (see Figure 1.1) and/or that the parameters determining the resistance of the soil against splash detachment are also valid for the detachment by overlandflow.
The vegetation variables also have a great effect, directly and indirectly on the output of the water erosion cascade. It has already been shown in 3.1 en 3.2 how vegetation influences important regulators of the splash erosion cascade and the hydrological cascade which both serve as input for the overlandflow cascade.
In the overlandflow erosion cascade chiefly the micro vegetation determines the surface roughness regulator (SR Figure 1) and when the waterfilm is thin it determines the distribution of the flow along the surface (OD Figure 1.1).
The litter cover and organic mulch which is related to the vegetation and the soil development also influences these regulators (Lal 1976, Singer & Blackbard 1978). There are no systematic studies concerning natural areas which evaluate certain vegetation variables in relation to water erosion. Wischmeier (1958) evaluated empirical parameters for different types of crops in agricultural areas. Many studies proved, however, that vegetation is an important and a dominant factor: Kirkby & Carson (1972) stated that differences between rates of water erosion on vegetated and unvegetated slopes are of the order of 100 - 10.000 (see a.o. studies of Fournier 1972, Ewell & Stocking 1976, Lal 1976, Epema et al. 1978).
Table 3.1 gives a summary of the various landscape variables and their effect on the regulators of the 3 cascading systems.

NOTES

1. Theoretically, the shear stress on the soil surface is related to the velocity gradient of the fluid at the soil surface (see Carson 1971). The velocity gradient and hence the scouring power of the flow depends on the flow type of the water: in the case of laminar flow the scouring capacity of the water is lower than in the case of turbulent flow. In the latter case the velocity gradient of the water is much greater in the neighbourhood of the soil surface (Carson 1971).

4

THE EFFECT OF LANDSCAPE VARIABLES ON THE OUTPUT OF DIFFERENT PROCESS (SUB-)SYSTEMS OF THE HYDROLOGICAL AND WATER EROSION CASCADE IN THE STUDY AREA

In Chapter 3 we have given a general survey of landscape variables which might be of importance to the water erosion system. In this Chapter we will test by a given rain input the effect of some of these landscape parameters (variables) on different output variables in the field. We were able to measure the following output variables using different measuring techniques: (see Figure 4.1 and also Figure 1.1)

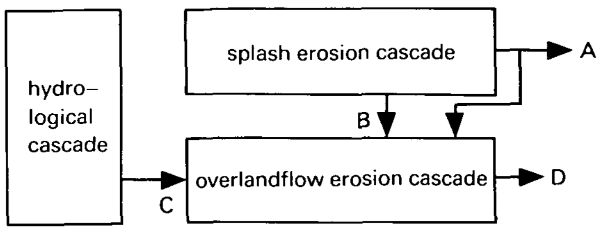


Figure 4.1 The measuring of output in the water erosion cascade.

- The final output of the splash erosion cascade (A).
- The output of the amount of splash detached material (B).
- The output of overlandflow (C) from the hydrological cascade which serves as input in the overlandflow erosion cascade.
- The final output of the overlandflow erosion cascade (D).

If overlandflow is present, A (partially) and B serve as input in the overlandflow erosion cascade.

The measuring of these output variables was done with the following equipments:

- The portable rainfall simulator of a type used by Adams et al. (1957). It was possible with this apparatus to measure the effect of landscape variables on the output of splash detached material (B) and Horton's overlandflow (C) (see Appendix A1).
- Splashshields which were installed at different erosion plots in the study area in order to measure the effect of landscape variables on the final output of the splash erosion cascading system (A) (see Appendix A2).
- "Gerlach troughs" were installed on the same erosion plots (Gerlach 1966) in order to measure the effect of landscape variables on the final output of the overlandflow erosion cascade (D) and the amount of overlandflow (C).

Table 4.1 The relation of the output of the measuring plots to the results of the rainfall simulator on these plots.

Plots	n	Regression equation	r	F
T	11	SS = 1.50RS − 1.89	0.98	12.3
T	11	Sr = 0.11RS − 0.31	0.50	9.4
N	8	Sr = 0.01RS − 0.08	0.80	5.7
T	11	Sc = 1.04RS − 2.50	0.73	7.3
N	8	Sc = 0.60RS − 0.33	0.89	8.6
T	10	Qr = −0.75RI + 109.27	0.51	3.1
N	7	Qr = −0.24RI + 40.87	0.79	3.0

T: all plots, N: natural plots, SS: mean splash erosion rate in g mm^{-1} rain, Sr: mean overlandflow erosion rate in g mm^{-1} rain, Sc: mean sediment concentrationt in g l^{-1}, Qr: mean overlandflow in ml mm^{-1} rain, RS: material detached by splash in g 100 mm^{-1} rain measured with rainfall simulator, RI: amount of water infiltrating into the soil as a percentage of the totally supplied rain by the rainfall simulator.

Note: Mean output of erosion plots calculated over a period of three months. The unit width of slope for the output from the plots is 50 cm.

Details of the measuring techniques are given in Appendix A2. The measuring plots were installed in a number of different landunits which show distinct differences with regard to certain landscape variables influencing the output of the erosion process. A detailed description of the erosion plots is given in Appendix A3 while a description of the landunits is given in the next Chapter (see Table 5.1).

Table 4.1 shows the relation between rainfall simulator results and plot results. The splash output measured with the rainfall simulator (RS) correlates quite well to the mean splash output of the plots (SS) and even with the sediment discharge delivered by overlandflow (S_r) and (S_c), especially on the natural plots. Furthermore, the infiltration characteristics measured with the rainfall simulator show that the natural plots correlate to the mean overlandflow production (Q_r). These relationships supports the idea that the rainfall simulator can be used in the field, especially on natural slopes in order to investigate the effect of certain landscape variables on the final output of the erosion system. Furthermore the rainfall simulator may be used to test the differences in erosion potentials between different landscape units quickly and reliably (see chapter 5).

4.1 The effect of landscape variables on the outputs of the splash erosion cascade

In Chapter 3 (table 3.1) a survey was given of different landscape variables which might have an effect in various ways on the output of the splash erosion cascade (A and B, Figure 4.1). We mentioned in Chapter 2, that particularly the herb and shrub vegetation

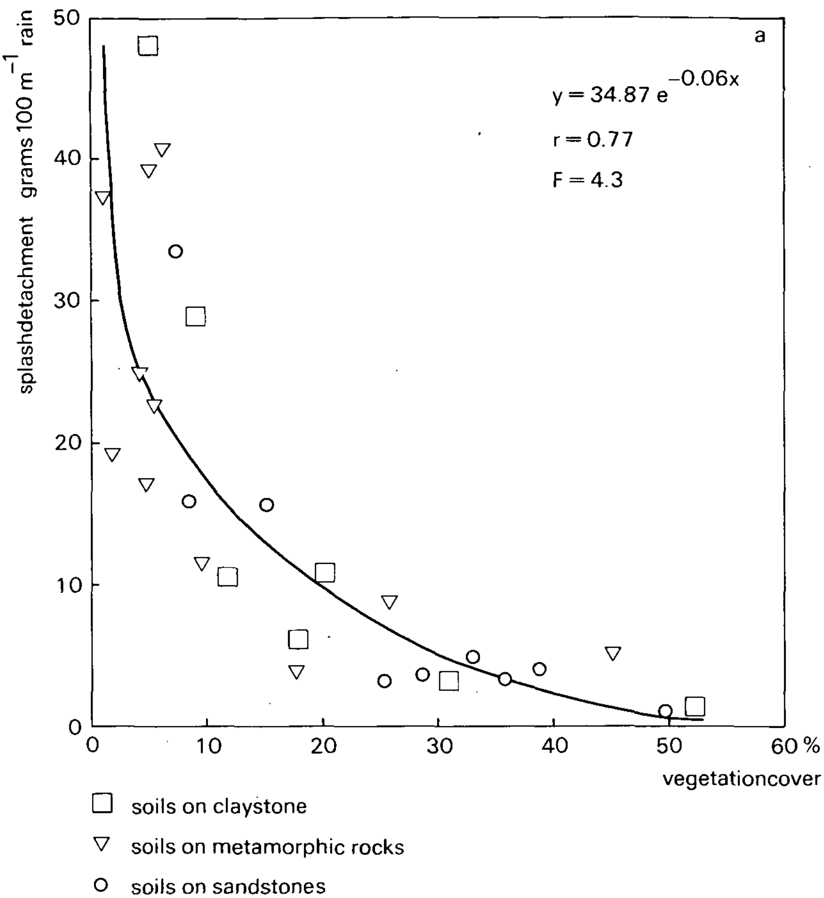


Figure 4.2 a The relation between splashdetachment measured with the rainfall simulator and vegetation cover.

zones are present in the more or less natural areas and the abandoned agricultural areas.
We chose the following variables from the landscape attribute soil: (see Table 3.1)

- Aggregate stability, which can influence the soil resistance (SR) regulator,
- the bulk density (related to soil porosity) which might be of importance for the water reflector (WR) regulator, but especially the soil resistance (SR) regulator or the mechanical soil strength,
- the grainsize distribution (soil resistance SR)
- the percentage of stone cover (soil cover SC regulator) and overlandflow distributor (OD).

From the landscape attribute topography we tested the effect of slope angle on the final output of the splash erosion cascade. Also the effect of the herb vegetation cover

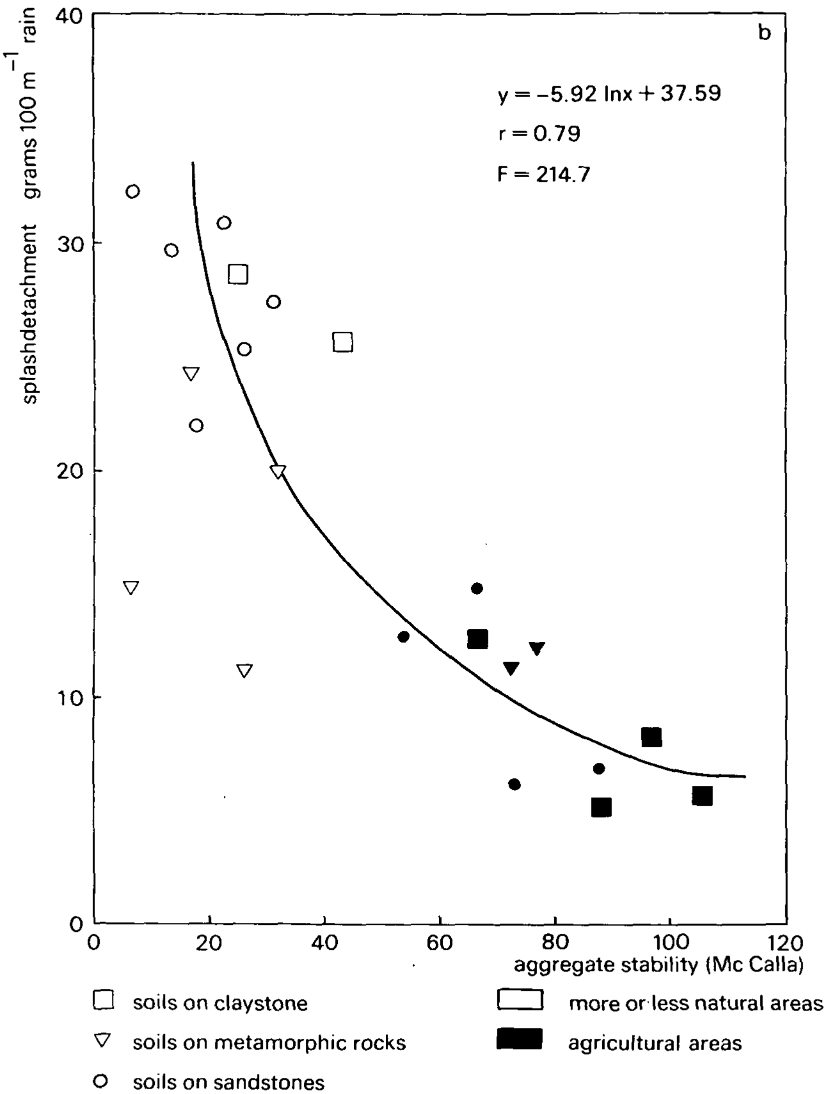


Figure 4.2 b The relation between splash detachment measured with the rainfall simulator and aggregate stability.

was tested. Figure 4.2a-g show the effect of the different variables on the amount of splash detachment (output B, Figure 4.1) measured with the rainfall simulator on different places in the study area. The influence of slope angle could not be measured with this technique, because tests could only be done on samples placed horizontally. Table

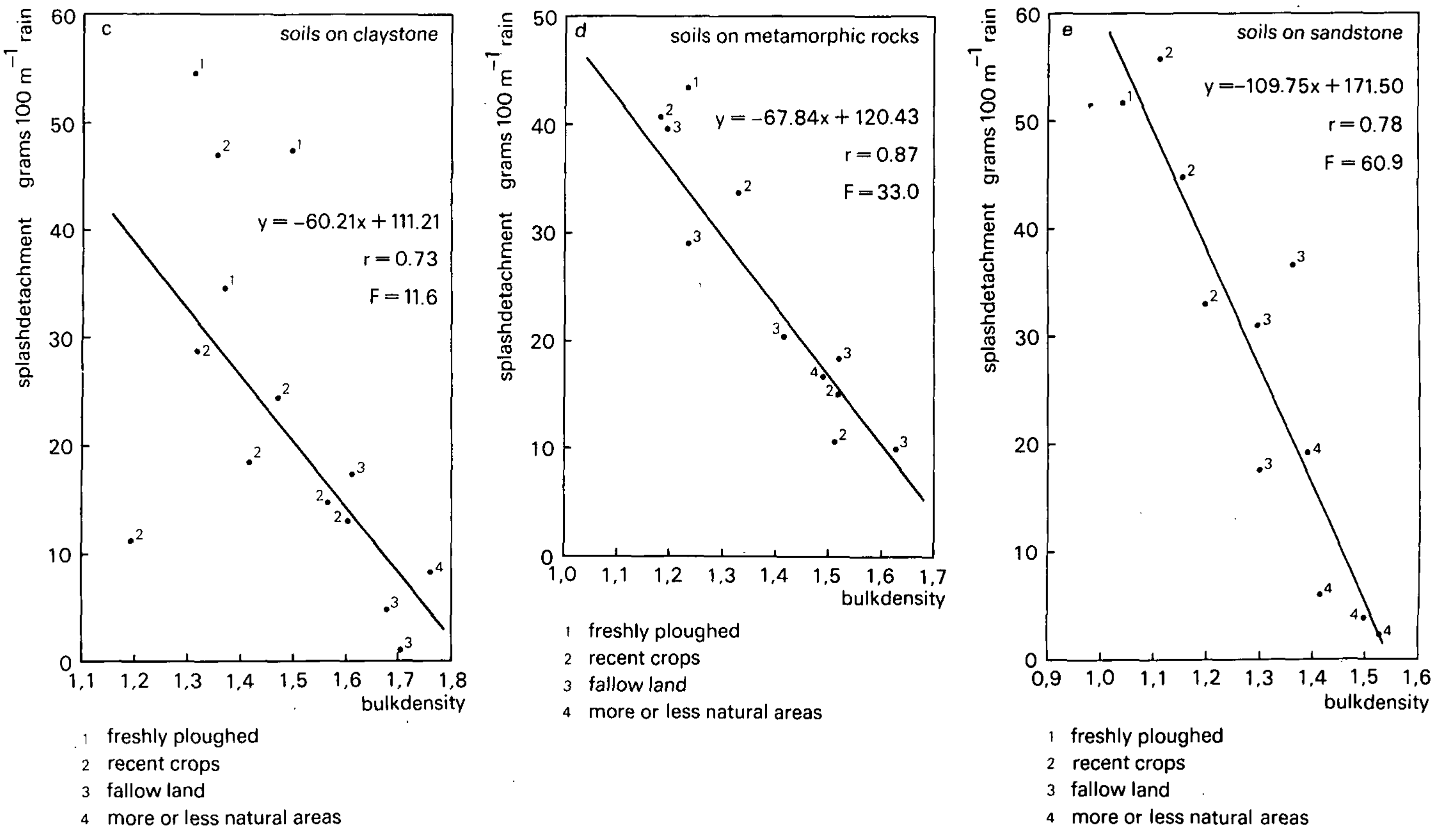


Figure 4.2 c, d, e The relation between splashdetachment measured with the rainfall simulator and bulkdensity.

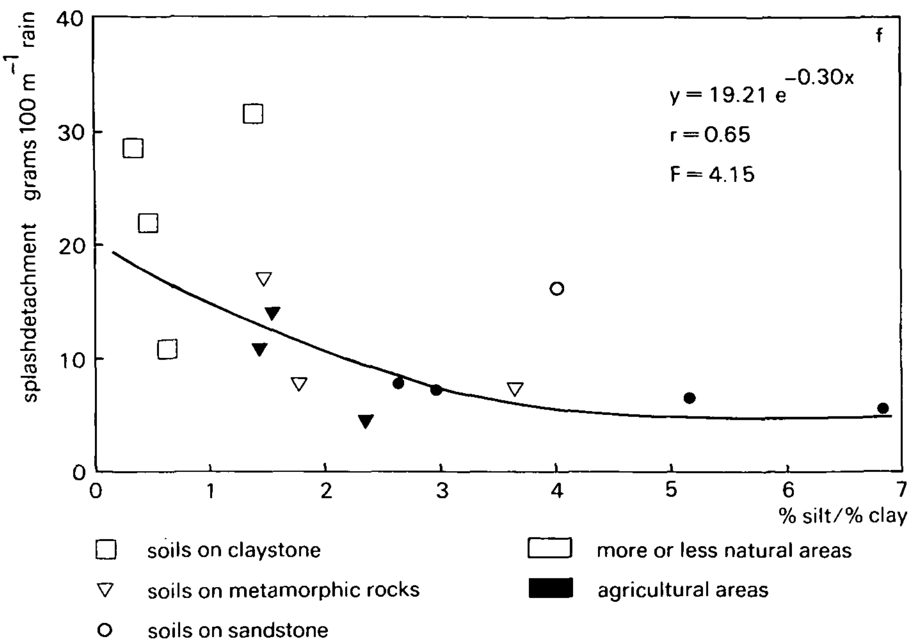


Figure 4.2f The relation between splashdetachment measured with the rainfall simulatorand and % silt-% clay ratio.

4.2 shows the results of the effect of these variables on the final output (A, see Figure 4.1) of the splash cascade, measured with the splash shields on 11 erosional plots of which 8 were lying in more or less natural areas and 3 in agricultural areas (see Appendix A3). The output is the result of measurements, taken during 3 months and is given as the mean splash discharge in grams per mm rain for that period.

The results of the rainfall simulator tests (Figure 4.2a) show that the herb vegetation zone strongly effects the amount of splash detachment, because it drastically reduces the input of the kinetic energy of the raindrops (Chapter 3). There is an exponential decrease of splash detachment with increasing micro vegetation cover.

A simular exponential reduction was etablished a.o. by Singer & Blackbard (1978) for soils with increasing soil cover mulch. The following explanations for this relationship can be given:

- Observations made on the plots showed a rapid increase in the percentage of litter cover (Aoo) when the vegetation density reached a certain level.
- An increase in vegetation density and litter cover from about 0 - 25% leads to a strong interception of particles which are ejected under small angles.
- The appearance of a small vegetation and litter cover immediately leads to a damming of surface water which may reduce the effect of splash. (see Chapter 3).

On the natural plots we could also establish an exponential reduction between splash discharge (SS) and the vegetation cover (H) (table 4.2).

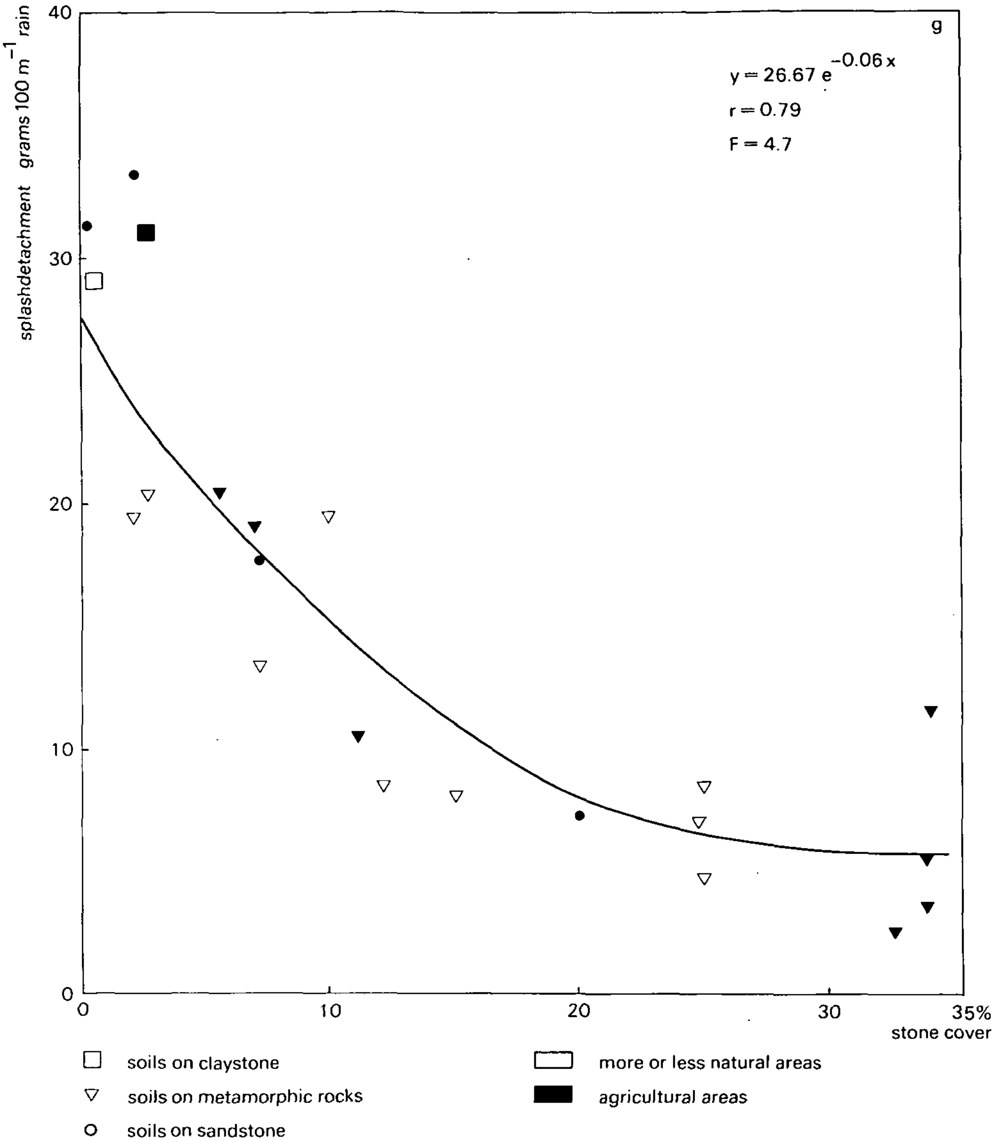


Figure 4.2 g The relation between splashdetachment measured with the rainfall simulator and % stone cover.

Figure 4.2b shows that the aggregate stability measured with McCalla's method (see Appendix A6) such as proposed by Bryan (1968) seems to be a relevant soil variable expressing the soil resistance against splash detachment. At this point we may note that

Table 4.2 The relation of different landscape parameters to the output of the splash erosion cascade

Plots	n	Landscape parameter	Regression equation	r	F
N	8	H	SS = −0.21ln H + 0.46	0.71	1.9
T	11	G	SS = −0.22ln G + 0.60	0.66	4.0
N	8	G	SS = −0.25ln G + 0.57	0.69	12.9
T	11	B	SS = −1.04B + 1.76	0.68	20.9
N	8	B	SS = −0.70B + 1.22	0.79	17.4
T	11	Tc	SS = 0.61Tc + 0.43	0.62	1.0
N	8	Tc	SS = −0.21Tc + 0.21	0.69	3.2
N	8	Ts	SS = −0.17Ts + 0.27	0.67	4.2
T	11	C	SS = 0.035C + 0.26	0.74	5.7
N	8	C	SS = 0.047C + 0.02	0.85	1.2
T	11	A	SS = −1.64sin A + 1.00	0.69	4.8
N	8	A	SS = 0.16sin A + 0.66	0.83	0.4

T: all plots, N:natural plots, SS: mean sediment discharge in g mm^{-1} rain, H: density of herb vegetation in % of total area, G: aggregate stability[a], B: bulkdensity in kg dm^{-3}, Tc: silt − clay ratio, Ts: silt − clay and sand ratio, C: % stone cover, A: slope angle in degrees, n: number of plots, r: regression coefficient, F: F-test.

a According to the method of Mc. Calla (see Appendix A6) in number of drops per mg soil.

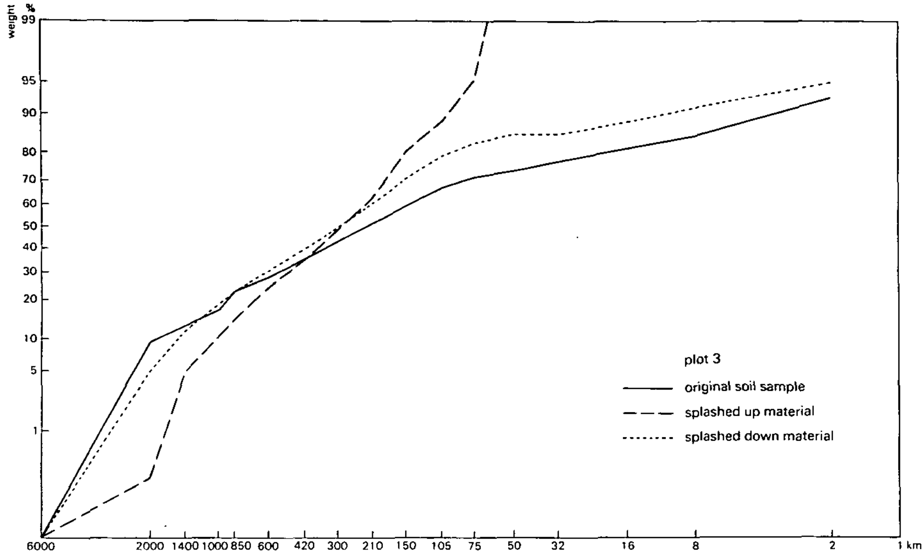
Note: Unit width of slope is 50 cm. Mean output of the erosionptots calculated over a period of three months.

the aggregate stability of soils under recent cultivation is lower than of soils lying in more or less natural areas. This may be due to the agricultural activity of man (especially ploughing). Another more important reason is a significant difference in organic content between the soils in both areas: C = 2.5% for natural soils (n= 25. SD= 0.7) and 10.5% for agricultural soils (n= 12, SD= 0.43). We have already stated in Chapter 3 that several investigations revealed a positive effect of the C-content on the aggregate stability. The same tendency was evident in our measuring plots. The soils on these plots show a positive correlation between aggregate stability and C-content (r=0.75). It is also interesting to note in Figure 4.2b that the clay-rich soils derived from clay-silt stone do not show significantly higher aggregate stability values than the less clay-rich soils derived from sandstone and metamorphic rocks. This may be due to the swelling capacity of clay-minerals in these clay-rich soils (see Appendix A3) which weakens the aggregate stability when the soil becomes wet (Henin (1938), Bryan (1968)). Table 4.2

shows that furthermore, particularly on the natural erosion plots, a correlation could be established between splash discharge and aggregate stability.
We stated in Chapter 3 that the bulk density (related to the soil porosity) may influence the mechanical shear strength of the soil (which is built up of intergranual friction and cohesion) and, therefore, the shearing resistance against the impact forces of the rain. We also stated that a denser soil might reflect a greater part of water from the falling drops and this would increase the amount of erosion. Figure 4.2c-e show, however, that an increasing bulk density has a negative effect on the amount of splash detachment and we might conclude that the bulk density increases the soil strength or resistance against the shearing forces of the rain impact.
In Figure 4.2c-e a subdivision is made of soils which have undergone a different degree in cultural activity (see Chapter 2) and we can conclude that generally freshly ploughed soils show low bulk densities whilde the soils lying in more or less natural areas generally show higher bulk densities (see next Chapter).
No correlation could be found between splash detachment and Wischmeier's index of grainsize distribution (Wischmeier et al. 1971) which is determined by the division of the percentage of silt by the percentage of sand and clay. Figure 4.2f, however, shows the effect of a modified index: the % of silt divided by the % of clay. There is a trend that an increasing clay content leads to a decrease in soil resistance against splash detachment. This may be explained by the weakening effect of the swelling clay minerals on the stability of the aggregates. Therefore the Wischmeier index is not always valid for soils with strong swelling clay minerals.
The correlation figures in table 4.2 show the same trend as the result found with the rainfall simulator (see Figure 4.2f).

In the scope of testing the effect of these grainsize indices on the splash output, it would be interesting to know whether, given a certain grainsize distribution of the soil, special grainsize fractions of the soil are more susceptible towards splash erosion than others. We therefore compared the grainsize distribution of the original soil surface sample with samples of material which was caught in the splash shields on the measuring plots. Figure 4.3 shows the differences in grainsize distribution between soil material scraped from the soil surface near several splash shields and the material which was assembled in the reservoirs for the duration of three months.
The following conclusions can be drawn from the Figure:
- There is no strong selection in grainsize compared to the original soil sample
- There is a difference in grainsize distribution between material splashed upwards and downwards. The material splashed downwards is coarser
- Material which is splashed down is generally coarser than the original soil sample; splashed upward material is finer in grainsize distribution on natural plots and coarser on the agricultural plots.

The weak selection of grainsize is explained in two ways:
  - The intensity of the rain varied during the 3-month measuring period and this led to a variation in grainsize of the splashed material.
  - An examination of the material caught in the splash shields revealed that a part



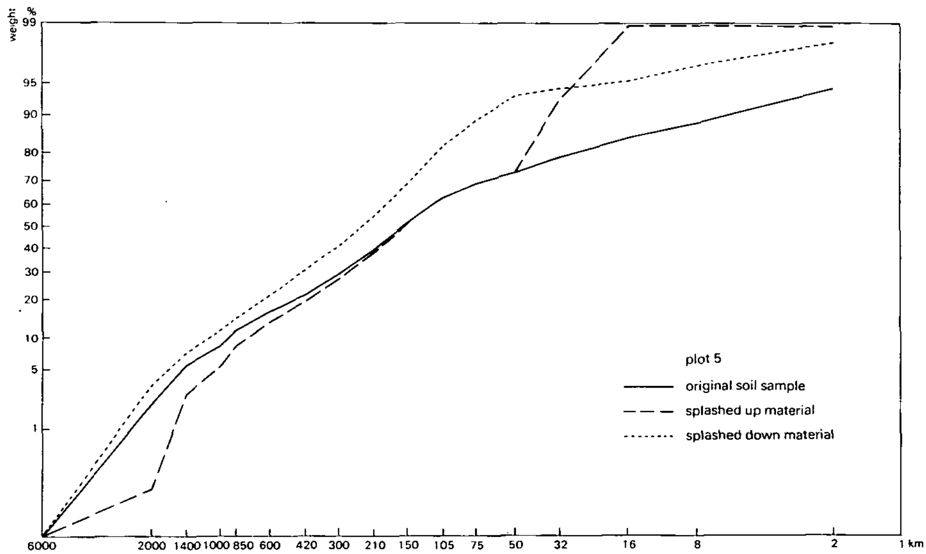
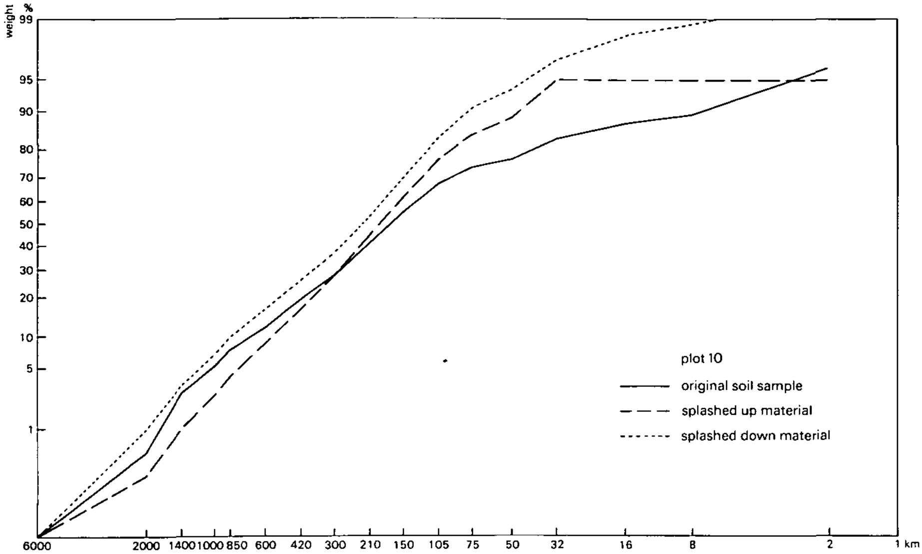
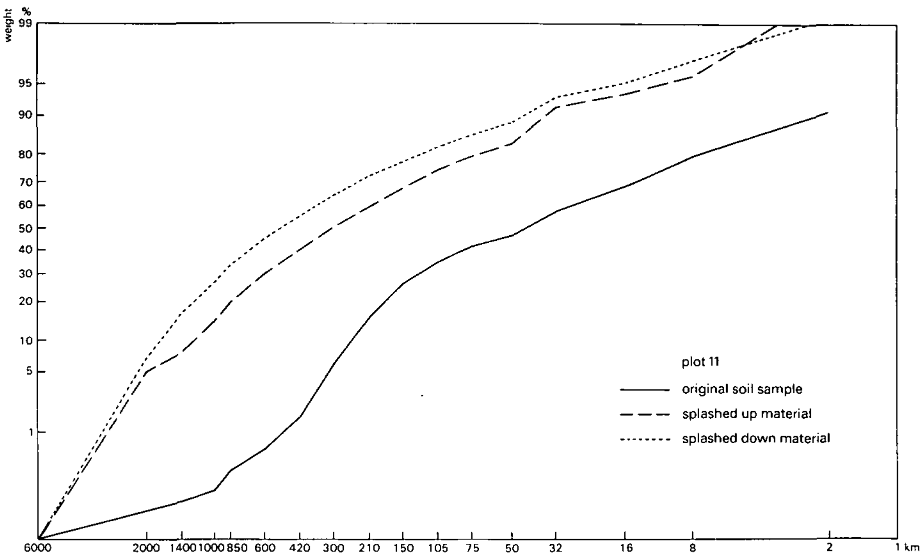


Figure 4.3 Grainsize distributions of splashed material compared with the original soil material.


weight %
99
95
90
80
70
60
50
40
30
20
10
5
1
6000
2000
1400
1000
850
600
420
300
210
150
105
75
50
32
16
8
2
1 km
plot 10
original soil sample
splashed up material
splashed down material


weight %
99
95
90
80
70
60
50
40
30
20
10
5
1
6000
2000
1400
1000
850
600
420
300
210
150
105
75
50
32
16
8
2
1 km
plot 11
original soil sample
splashed up material
splashed down material

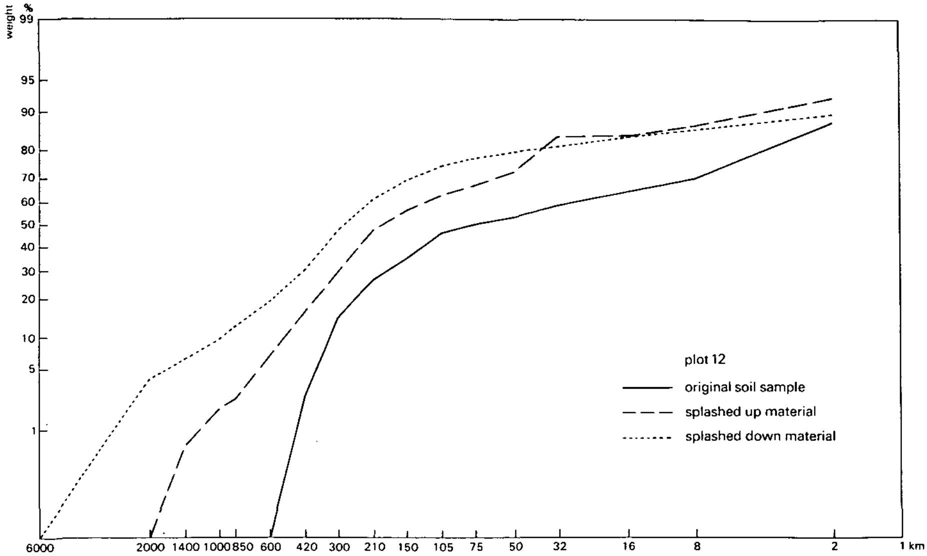


Figure 4.3 (continued) Grainsize distributions of splashed material compared with the original soil material.

of the soil particles is transported in aggregates which comprises grains of different size.

We may conclude that due to the net shear force component downslope of the raindrop inpact it is much easier to detach coarser particles in a downslope direction than in an upslope direction.

Furthermore an interesting fact is that particularly the coarsest sizes (> 2000μ) are the most easily transported; a fact which does not agree with a.o. Ellison (1944) whose results showed that the finer fraction, particularly the silt, had a stronger selection.

The following explanations can be given:

- When samples had been taken of the soil surface, relatively fine material from the layer beneath the surface, may have accidentally been included in places where a well-developed pavement occurred. In this case the soil sample has a lower mean grainsize than the material from the soil surface which is detached by splash. However, it became apparent that soil without a strong pavement and especially the freshly ploughed soils with a more or less artificially homogenized upper horizon also produces coarser material by splash.
- The following may provide a better explanation: If we consider a certain solid weight of material consisting of coarse grains (e.g. > 2000μ) and a same solid weight of material consisting of small grains (< 2000μ) we can say that the cohesive bonds between the finer particles is larger than between the coarser particles, because the finer particles are tied into aggregates. Therefore it takes more energy to detach a solid weight of finer material than a solid weight consisting of coarse grainsize.

The effect of a stone cover on splash detachment measured with the rainfall simulator is depicted in Figure 4.2g. The Figure suggests an exponential decrease of splash detachment which may have the same explanations as given above for the protective effect of the herb- and litter-cover. These tests were done on a horizontal surface (see Appendix A1). The results in Table 4.2 show, however, that on the slopes of the measuring plots splash discharge is positively correlated with the percentage of surface stone (> 2 mm). An explanation for this phenomenon might be that on a horizontal surface the coarsest fraction (varying from 6 - 2 mm) is not easily detached and transported and therefore forms an immobile protective cover. However, on steeper slopes (in our case varying from 18 - 30°) there is an increase in the downslope shear force of the raindrop impact and an increase in the downslope weight component of the stone particles which both facilitate the mobilisation of the stone particles by splash creep. The analyses of the

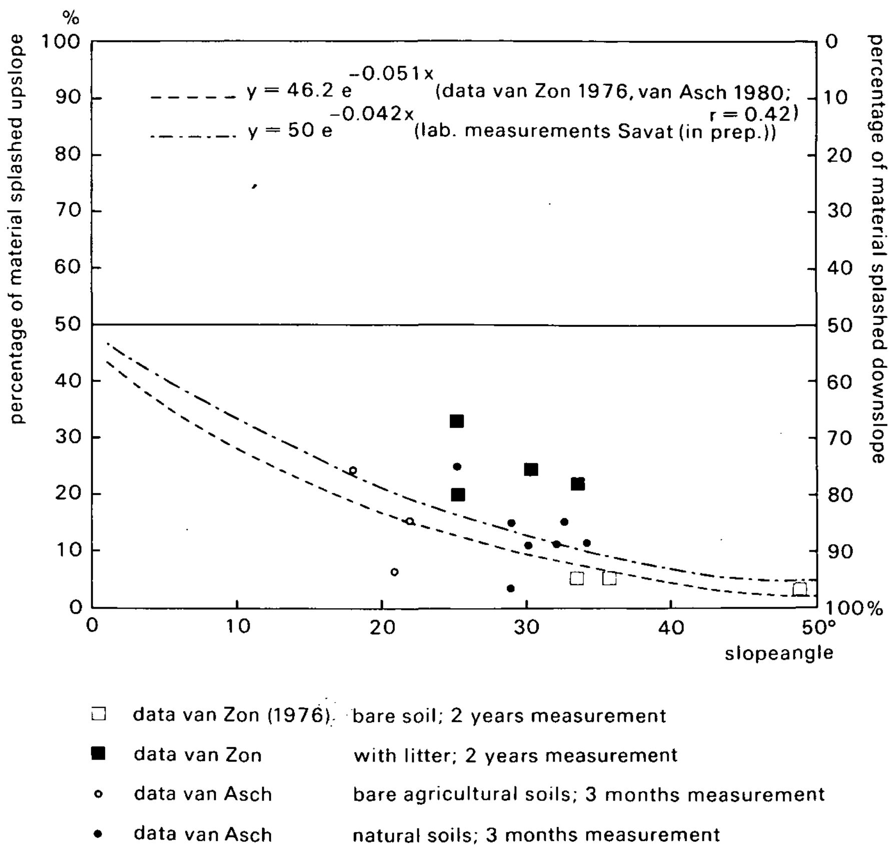


Figure 4.4 Distribution of splashed up- and downslope material in relation to slope angle.

grainsize fraction showed that on these slopes the coarser fractions are transported even more easily than the finer fractions (see above).
The effect of slope angle on the net splash discharge (amount of material splashed downward minus the amount of material splashed upward) was measured on the plots. Table 4.2 shows, especially for natural soils, a rather strong correlation with the sinus of the slope angle.
The net splash discharge is determined by the amount of material splashed upward and downward. Figure 4.4 gives the ratio between the amount of splashed up and down material in relation to the slope angle. The data of Van Zon (1978) of a forested area in Luxembourg are also given. Curve fitting techniques reveal that an e^x-function gives the best correlation which agrees with the results of Savat (in prep.) measured under laboratory conditions. Unfortunately the regression coefficient is very low.
We can summarise that, with regard to the output of splashed material, the following landscape variables are of importance:

- The density of the herb vegetation. A slight density of this vegetation in relation to bare soil already proved to be very effective in the protection against splash erosion. The effect of other vegetation zones could not be investigated, but due to the height of the vegetation canopy the protective effect must be less stronger.
- The bulk density of the soil particularly seems to be strongly correlated with the resistance of the soil against splash impact. Furthermore the aggregate stability measured according to the method of McCalla seems to be a good parameter .
- We must be careful with the textural indices as, for example, proposed by Wischmeier et al. (1971): A higher clay content does not always means a higher stability of the soil against erosion. In the case that the soil particles are tight together in aggregates, swelling clay minerals may have a weakening effect on the aggregates. The investigated soils show an increase in splash detachment with an increasing clay mineral content.
- The investigations showed that a stone cover on steep slopes with grainsizes varying from 2 mm - 6 mm does not have a protective effect on the soil surface because they are transported away more easily than finer particles by splash (creep) erosion.
- As distinct from the variables mentioned above, the relation between slope angle and splash discharge has been measured by a number of authors. Unfortunately the method of measuring splash discharge is not uniform and hence the empirical equations differ. In the study area on natural slopes splash discharge gives the best correlation with the sinus of slope angle.

4.2 The effect of landscape variables on the amount of overlandflow in the hydrological cascade

In this Paragraph we will study the effect of different landscape variables on the output of overlandflow (C in Figure 4.1). The effect of landscape variables, particularly the infiltration capacity regulator could be studied with the rainfall simulator. We chose Horton's fc-value as a parameter for the infiltration rate (see Chapter 3) because this

parameter is the least effected by process variables (rainfall intensity and moisture variation). On the erosion plots we could measure the amount of overlandflow with the aid of the closed "Gerlach troughs" (Appendix A2). No distinction could be made here between saturated overlandflow and Horton's overlandflow. We tested the following landscape variables (see Table 3.1): a) The density of herb vegetation, b) the aggregate stability, c) the bulk density of the soil (related to soil porosity), d) grainsize distribution, e) stone cover, f) the depth of the soil body, g) slope angle and h) slope length. Figure 4.5a-d show the relation of some variables which seem to have an effect on the f_c-infiltration capacity regulator, measured with the rainfall simulator, while Table 4.3 shows the results of different landscape variables on the mean overlandflow production (in ml per mm rain) measured over a period of 3 months on the erosion plots.
Figure 4.5a shows that in more or less natural areas and abandoned agricultural areas the density of herb vegetation has a positive effect on the infiltration rate especially in density classes ranging from 0 - 30%. This might be due to the effect of a greater root density in the soil which improves the soil structure, but also to an increase of the litter cover which has a positive effect on the permeability of the soil surface zone (see 3.2). On the plots, no correlation could be established between vegetation cover and overlandflow.
Figure 4.5b-d show that a fairly strong relationship exists between f_c-values and the bulk density of the soil in the upper 40 cm. We can learn from the figures that clay soils under cultivation have low bulk densities and therefore have relatively high infiltration rates.
On the other hand certain soils, derived from sandstone in more or less natural units, have a high bulk density and therefore show relatively low infiltration rates. We must realize therefore that the structure of the soil is of importance and this is not always reflected by the grainsize distribution of the soil (see also Wischmeier et al. 1971). In the study area no correlation could be found between aggregate stability, different grainsize parameters and the f_c-values (see 3.2). On the measuring plots a positive relationship could be established between bulk density and the amount of overlandflow production in more or less natural areas (Table 4.3). No correlation was found between

Table 4.3 The relation of landscape parameters to overlandflow

Plots	n	Landscape parameter	Regression equation	r	F
N	8	B	$Q = -9.9B + 8.43$	0.86	25.0
N	8	A	$Q = 110.9 \sin A - 33.19$	0.85	3.6
N	8	L	$Q = -7.6 \ln L + 43.74$	0.70	2.1

N: natural plots, Q: mean overlandflow discharge in ml mm^{-1} rain, B: bulkdensity in kg dm^{-3}, A: slope angle in degrees, L: slope length in m, n: number of plots, r: regression coefficient, F: F-test.

Note: Unit width of slope is 50 cm. Mean output of plots calculated over a period of three months.

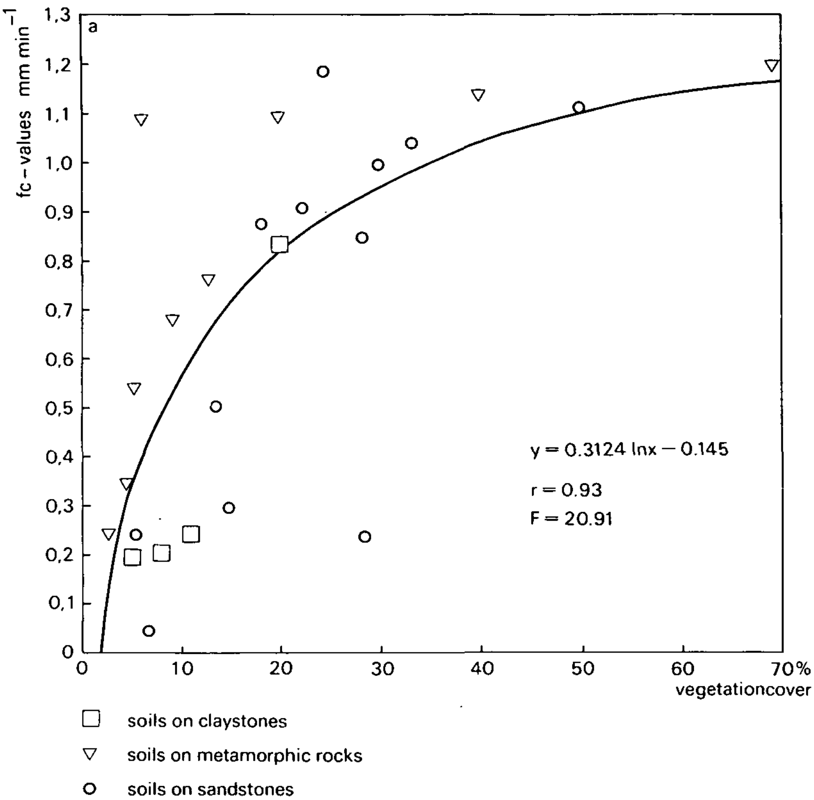
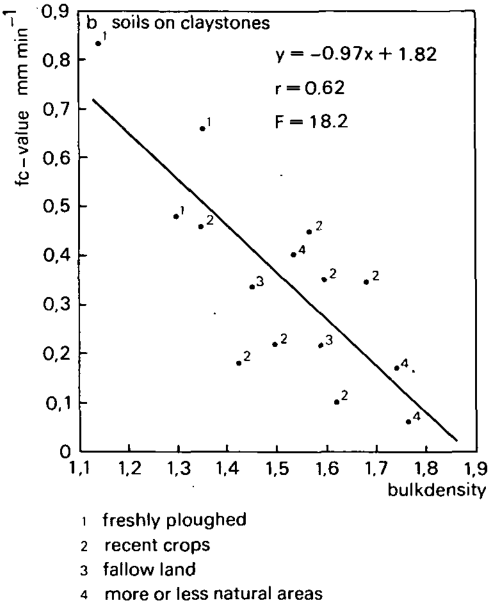
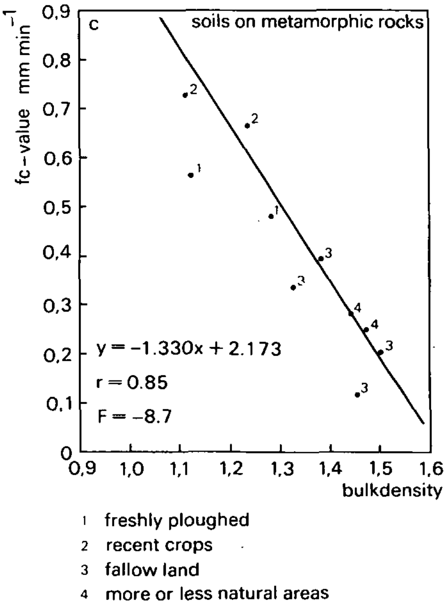


Figure 4.5 a The relation between the rate of infiltration (fc-value), measured with the rainfall simulator and % vegetation cover.

grainsize distribution, percentage stone cover, soil depth and the amount of overlandflow production (see 2.2).

Table 4.3 also shows the effect of topographical variables on the production of overlandflow. There is a positive correlation between the amount of overlandflow and slope angle which agrees with the experiments made by Nassive & Wilson (1975). An explanation lies in the theory of overlandflow in Chapter 4. It was stated that given a constant discharge, the mean overlandflow depth decreases and flow velocity increases at an increasing slope angle. According to the infiltration equation of Green & Ampt a decrease in overlandflow depth means a decrease in infiltration rate. Strangely enough there is a negative correlation between slope length and the amount of overlandflow (see Table 4.3). One partial explanation is given by the fact that the excess amount of rain water at one place on the slope fully disappears at a more downslope spot which has greater infiltration rate capacities, or in sufficiently large depressions which are not fully stored during most rainstorms. In this case only local overlandflow exists and this can explain the





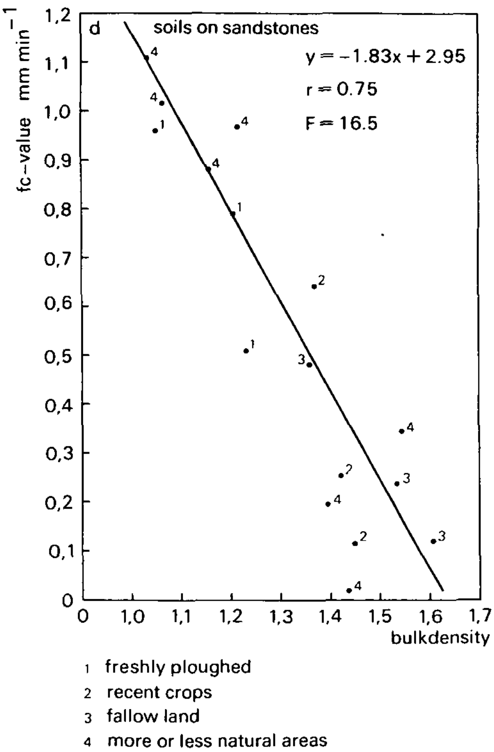


Figure 4.5 b, c, d The relation between the rate of infiltration (fc-value), measured with the rainfall simulator and bulkdensity.

fact that the amount of overlandflow discharge is independent of the slope length. The negative correlation with the slope length is rather difficult to explain. A theoretical explanation might be that the storage capacity per unit length of slope increases with the slope length. This theoretical explanation is not supported by observations made in the field.

4.3 The effect of landscape variables on the output of the overlandflow erosion cascade

The output of the overlandflow erosion cascade (D in Figure 4.1) was measured with the Gerlach troughs on different erosion plots in the study area (Appendix A3). We consider output parameters to be the mean sediment discharge in grams per mm rain and the mean sediment concentration in grams per liter overlandflow water calculated from the total output of a period of 3 months.

The effect of the following landscape parameters were tested (see Table 3.1): a) the density of the herb vegetation, b) the aggregate stability, c) the bulk density, d) grain-size distribution parameters, e) stone cover, f) slope angle, g) slope length.

Apart from the effect of these landscape variables on the overlandflow erosion cascade, we are interested in the input-output relationships of the overlandflow erosion cascade or in other words: the effect of the hydrological cascade and the splash erosion cascade on the overlandflow erosion cascade.

Table 4.4 shows input-output relationships of the overlandflow erosion cascade while in Table 4.5 a survey is given of the effect of landscape variables on the output. To achieve a greater insight into the transport conditions by overlandflow, we will

Table 4.4 Input – output relationships of the overlandflow erosion cascade

Plots	n	Input	Output	Regression equation	r	F
T	11	Qr	Sr	Sr = 0.03Qr − 3.510	0.97	18.8
N	8	Qr	Sr	Sr = 0.01Qr + 0.032	0.91	7.4
T	11	Qr	Sc	Sc = 0.39Qr + 7.150	0.72	5.9
N	8	Qr	Sc	Sc = −0.12Qr + 6.600	0.69	5.1
N	8	SS	Sr	Sr = 0.12SS + 0.110	0.76	6.1
T	10	SS	Sc	Sc = 44.89SS + 0.820	0.89	11.3
N	7	SS	Sc	Sc = 25.25SS + 2.930	0.93	8.1

T: all plots, N: natural plots, Qr = mean overlandflow in ml mm^{-1} rain, SS: mean splash erosion in g mm^{-1} rain, Sc: mean sediment concentration in g l^{-1} overlandflow, n: number of plots, r: regression coefficient, F: F-test.

Note: Unit width of slope is 50 cm. Mean output calculated over a period of three months.

compare the results of the input-output relationships of the overlandflow erosion cascade given in Table 4.4 with the equations evaluated in 3.3 (equations 10 and 13) for transport capacity limited- and detachment limited conditions.
If we assume that the mean sediment discharge Sr (Table 4.4) per mm of rain calculated from the total discharge after three months is related to SO given in equation (10) and (13) (Chapter 3) and the mean overlandflow in ml/mm rain (Qr Table 4.4) is related to Q (equation 10 and 13) (Chapter 3) we can write:

$$Sr = C_1 . S^{5/3} . Qr^{5/3} \text{ for transport limited conditions} \quad (1)$$

or:

$$Sr = C_2 . S^{2/3} . Qr^{2/3} . L + C3 . I^a . L \text{ for detachment limited conditions} \quad (2)$$

and if we consider the mean sediment concentrations Sc (Table 4.4) in gr/liter overlandflow we can write:

$$Sc = C_1 . S^{5/3} . Qr^{2/3} \text{ for transport limited conditions} \quad (3)$$

or:

$$Sc = C_2 . S^{2/3} . Qr^{-1/3} . L + C3 . I^a . Qr^{-1} . L \text{ for detachment limited conditions} \quad (4)$$

It can be inferred from the above given equations that the mean sediment discharge (Sr) is positively correlated to the overlandflow discharge for both conditions (equation 1 and 2). If, however, detachment limited conditions exist and the sediment supply towards the waterfilms is only by splash detachment (which is stated by some authors, a.o. Mutchler & Young 1975) then, according to equation (2), the sediment discharge is not correlated to the overlandflow (Qr). It even may be negatively correlated with Qr if we consider the fact that the thickness of the water streams on the surface has a negative effect on the amount of splash detachment (see Chapter 3). If we consider the amount of sediment concentration (Sc) we will find that there is a possible correlation to Qr in case of transport limited conditions (equation 3) while for detachment limited conditions (Sc) is negatively correlated to the mean overlandflow discharge (equation 4). We will now compare these theoretical considerations with the results given in Table 4.4. The Table shows that the mean sediment discharge (Sr) is positively correlated to (Qr) but the mean sediment concentration (Sc) on the natural plots is negatively correlated to the amount of overlandflow. This means that on these plots sediment transport under detachment limited conditions is dominant and equation (2) and (4) are valid. Since (Sr) is positively correlated to (Qr), there must be a certain amount of detachment by overlandflow shear, according to equation (2).
Table 4.4 also shows the correlation between the input of splashed material into the overlandflow erosion cascade (SS) (measured with the splash shields on the plots) and the total output of sediment discharge (Sr) and (Sc). The positive correlation especially on natural plots indicates that the part of sediment, which is delivered by splash de-

tachments (Ds, see Chapter 3.3) towards the overlandflow erosion cascade must be relatively important.
We will now study the effect of different landscape variables on the output of the overlandflow erosion cascade. Table 4.5 shows that the total density of all vegetation zones

Table 4.5 The relation of different landscape parameters to the output of the overlandflow erosion cascade

Plots	n	Landscape parameter	Regression equation	r	F
N	8	V	Sr = −0.01V + 0.16	0.60	11.9
N	8	V	Sc = −0.10V + 10.07	0.53	9.4
N	8	H	Sr = −0.01H + 0.21	0.71	8.4
N	8	H	Sc = −0.12H + 18.07	0.69	3.2
N	8	G	Sr = −0.03ln G + 0.23	0.54	4.5
T	10	G	Sc = −8.08ln G + 41.42	0.54	4.5
N	7	G	Sc = −2.81ln G + 16.99	0.78	4.4
N	8	B	Sr = −0.10B + 0.26	0.82	5.5
N	8	B	Sc = −12.60B + 24.28	0.84	2.1
N	8	Tc	Sr = −0.40Tsc + 0.23	0.57	1.4
T	11	Tc	Sc = 1.07Tsc + 10.29	0.50	31.9
N	8	Tc	Sc = −12.05Tsc + 9.06	0.71	1.3
N	8	Ts	Sr = −0.02Tss + 0.13	0.74	30.0
N	8	Ts	Sc = −0.21Tss + 5.72	0.80	55.9
N	8	C	Sr = 0.01P + 0.07	0.79	1.5
T	11	C	Sc = 0.01P + 11.99	0.54	1.7
N	8	C	Sc = 0.13P + 3.24	0.87	2.6
N	8	A	Sr = 0.42sin A − 0.09	0.84	2.2
T	11	A	Sc = −108.17sinA + 61.12	0.59	4.8
N	8	A	Sc = −10.17sinA + 10.86	0.85	3.6
N	8	L	Sr = −0.04lnL + 0.23	0.79	2.3
N	8	L	Sc = 3.35lnL + 3.75	0.89	2.8

T: all plots, N: natural plots, Sr: mean sediment discharge in g mm^{-1} rain, Sc: mean sediment concentration in g l^{-1} overlandflow, V: total vegetation density in % of total area, H: density of herb vegetation in % of total area, G: aggregate stability[a], B: bulkdensity in kg dm^{-3}, Tc: silt − clay ratio, Ts: silt − clay and sand ratio, C: % stone cover, A: slope angle in degrees, L slope length in m, n: number of plots, r: regression coefficient, F: F-test

a According to the method of Mc. Calla (see Appendix A6) in number of drops per mg soil.

Note: Unit width of slope = 50 cm. Mean output calculated over a period of three months.

(shrubs, trees and herbs) (V) is weakly correlated to the amount of sediment discharge, while there is a stronger correlation to the density of herb vegetation (H). We must consider the fact that the density of shrub- and tree vegetation is rather difficult to estimate. However, the stronger correlation of especially the herb vegetation density in the neighbourhood of measuring troughs might indicate that a) herb vegetation is the most effective zone as protection against overlandflow detachment and splash detachment, b) the Gerlach troughs are fed by local overlandflow and the related sediment discharge (see 4.2).

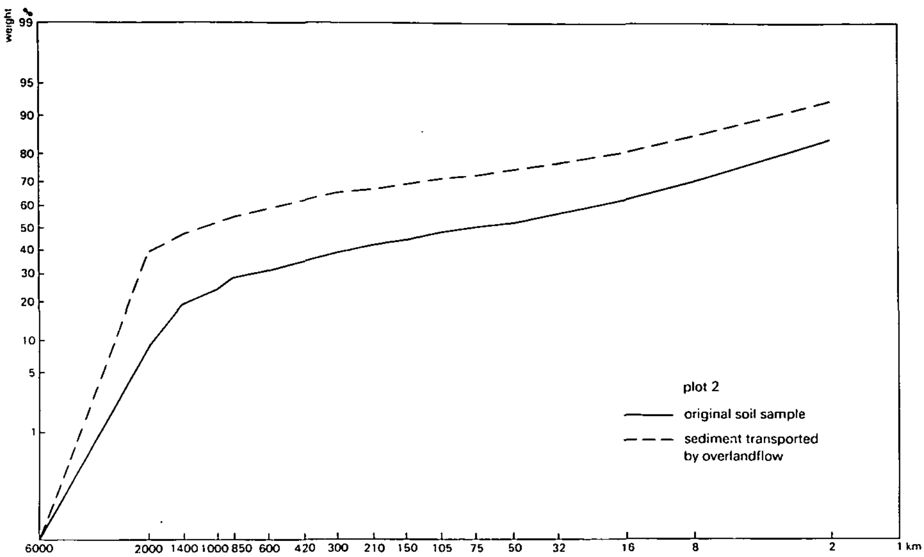
The correlation of different soil variables with the amount of sediment discharge or sediment concentration in Table 4.5 shows that aggregate stability (G) and bulk density (B) are important factors which must influence the soil resistance regulator of the overlandflow erosion system. In the foregoing paragraph, we found that an increasing bulkdensity increases the amount of overlandflow, which means an increase in shear stress of the water. This obiously did not have a positive effect on the amount of sediment discharge (Sr, Sc; see Table 4.5). The following explanations can be given:

- The resistance of the soil against detachment by splash and overlandflow shear, decreases with increasing bulkdensity.
- Detachment by overlandflow shear is of minor importance in the overlandflow erosion system, in comparison with detachment by splash.

We can conclude, if we regard the %silt/clay (Tc) and the %silt/sand + clay indices (Ts) that the clay content has a negative effect on the soil resistance. As was stated in Chapter 4.1, this may be explained by the weakening effect of swelling clay minerals on the aggregate stability. An interesting fact is that the landscape variables influencing the (SR) regulator in the splash erosion cascade, also have an effect on the output of the overlandflow erosion cascade (see 4.1). For example the aggregate stability, measured with Mc Calla's raindrop impact test (see Appendix A6), is a typical soil resistance factor in splash detachment. When we look at the textural indices we can establish that it is not the amount of silt (which normally is most easily detached by overlandflow) that has a positive effect on the sediment discharge, but, on the contrary, the amount of clay which tends to reduce the stability of the aggregates in these soils. We may therefore suggest that an important part of the sediment delivered to the overlandflow waterfilm is done by splash detachment, as was stated a.o. by Mutchler and Young (1975).

This was also proved by the fact that there is a positive correlation between the total amount of splash discharge measured in the plots and the mean sediment concentration (see Table 4.4).

In Table 4.5 the effect of surface stones (C) on the amount of sediment discharge and concentration is also given. An interesting fact is that the amount of surface stones has a positive effect on the sediment discharge and concentration. In Chapter 3 it was stated that a stone cover can increase the surface roughness and hence decrease the shearing force of the water (equation (8), Chapter 3). This will lead to a negative correlation between sediment output and %surface stones. If, however, the waterfilm is thin in comparison to the surface stones, the water is more concentrated in streams with higher flow velocities and flow depths and this increases the shearing force of the water (Chapter 3). In our view a better explanation is that especially on steep slopes the surface



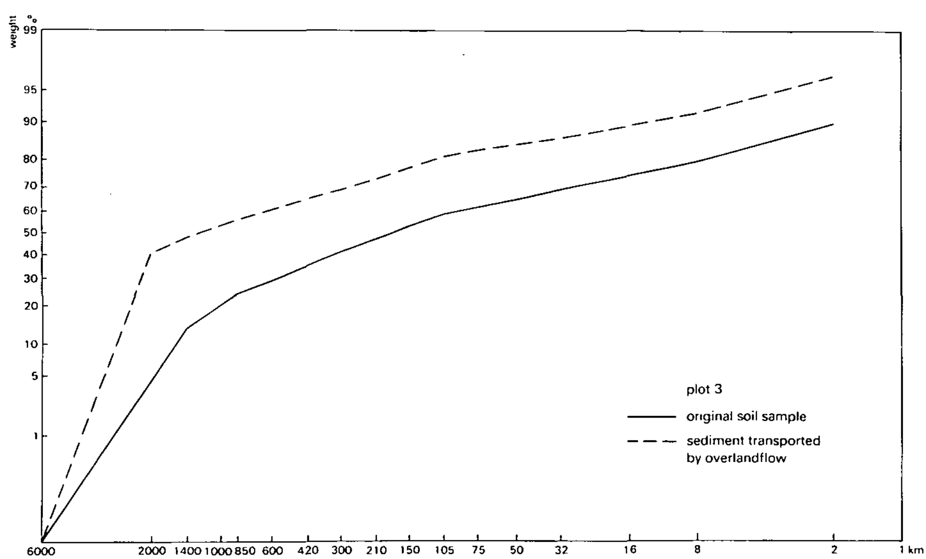
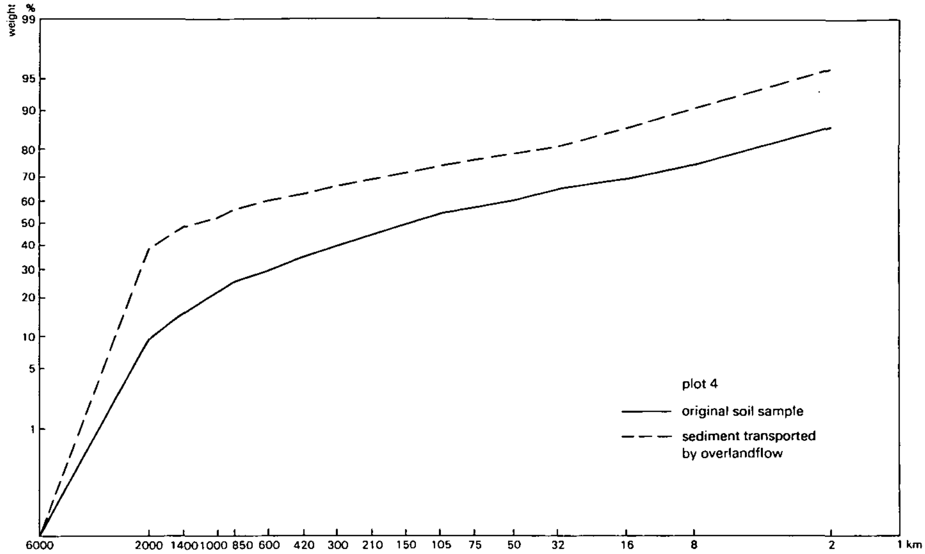
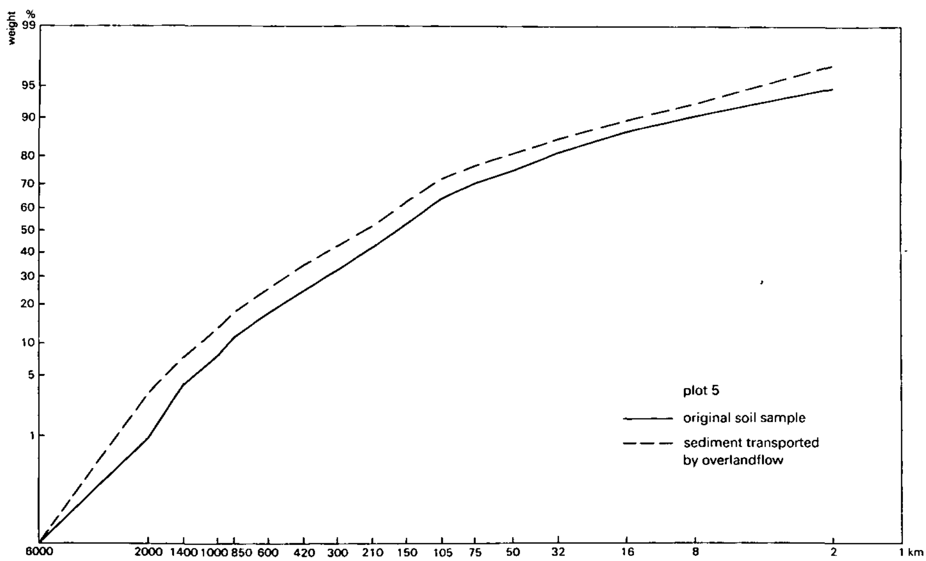
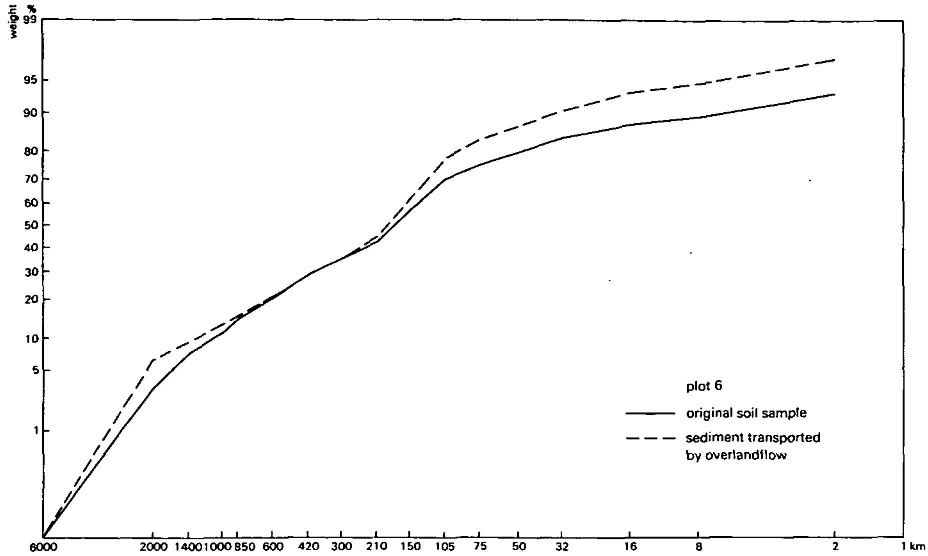


Figure 4.6 Grainsize distributions of material transported by overland flow compared with the original soil material.


weight %
99
95
90
80
70
60
50
40
30
20
10
5
1
plot 4
original soil sample
sediment transported by overlandflow
6000
2000
1400
1000
850
600
420
300
210
150
105
75
50
32
16
8
2
1 km


weight %
99
95
90
80
70
60
50
40
30
20
10
5
1
plot 5
original soil sample
sediment transported by overlandflow
8000
2000
1400
1000
850
600
420
300
210
150
105
75
50
32
16
8
2
1 km



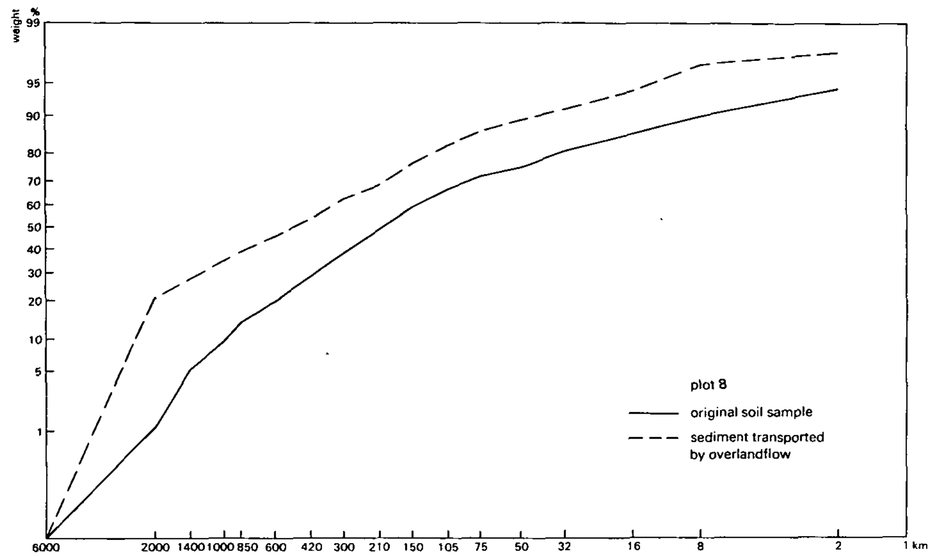
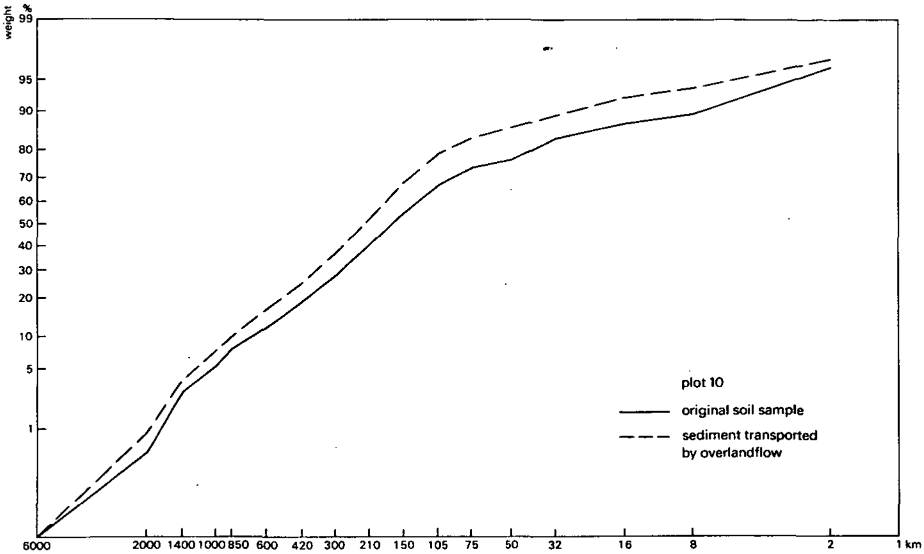
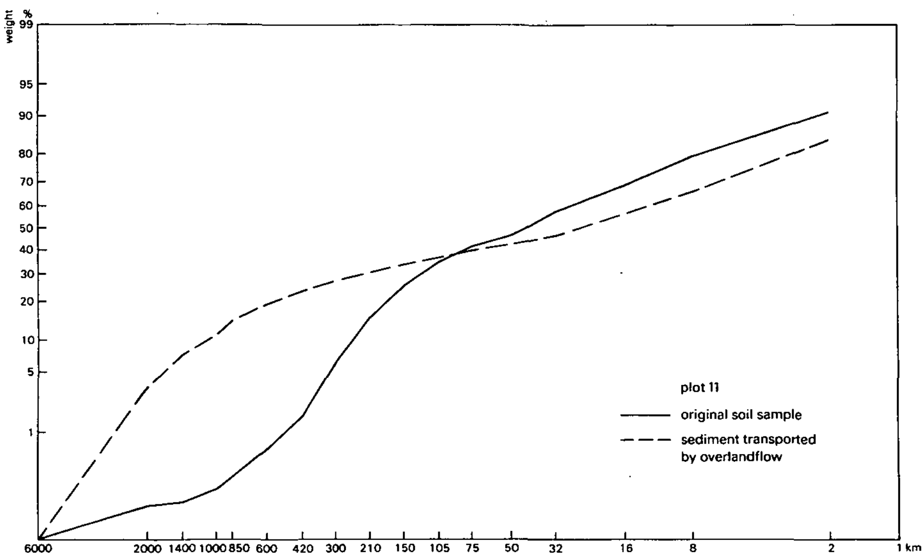


Figure 4.6 (continued) Grainsize distributions of material transported by overland flow compared with the original soil material.



weight %
99
95
90
80
70
60
50
40
30
20
10
5
1
6000
2000
1400
1000
850
600
420
300
210
150
105
75
50
32
16
8
2
1 km
plot 10
original soil sample
sediment transported by overlandflow



weight %
99
95
90
80
70
60
50
40
30
20
10
5
1
6000
2000
1400
1000
850
600
420
300
210
150
105
75
50
32
16
8
2
1 km
plot 11
original soil sample
sediment transported by overlandflow

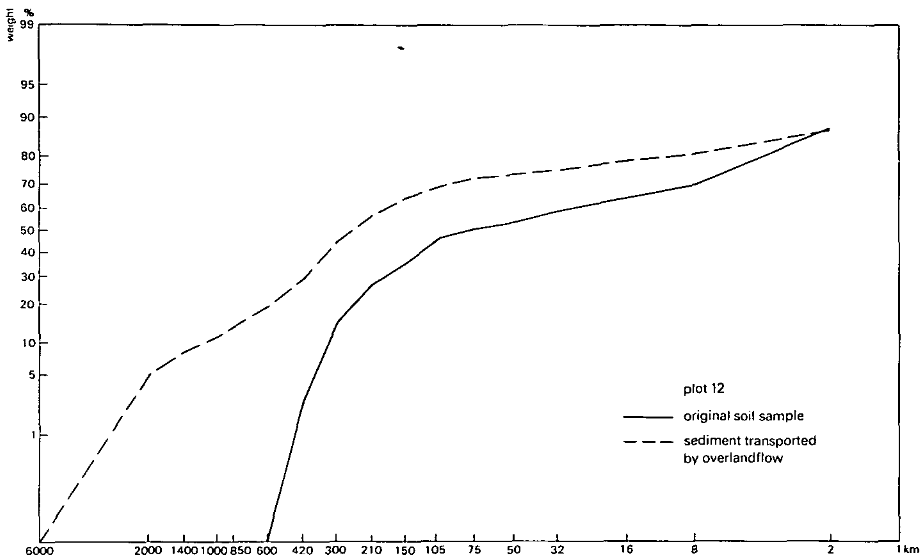


Figure 4.6 (continued) Grainsize distributions of material transported by overland flow compared with the original soil material.

stones of which the greatest part has a size varying from 6 mm - 2 mm are not stable, but easily detached and transported by splash erosion (see 4.1). In Figure 4.6 we compare the grainsize fraction of the original soil samples with the grainsize distribution of sediment which forms the output of the overlandflow erosion cascade. This figure shows that in this overlandflow cascade there is a tendency for picking up the coarser fractions (6 - 2 mm). We saw the same tendency in the comparison of the original soil samples with the material which was caught in the splash shields (see 4.1). This might explain why the sediment discharge is positively correlated to the amount of stone cover. Again, it forms an indication towards the fact that the soil material is mainly delivered by splash detachment towards the waterfilm or put in directly in the troughs by splash-creep.

We will now try to explain the effect of slope angle and slope length on sediment discharge and sediment concentration as given in Table 4.5. To this end we refer to the fact that

a) The input of overlandflow (Qr) in the system was positively correlated to slope angle (Table 4.3)
b) The input of overlandflow (Qr) was negatively correlated to slope length (Table 4.3). This may indicate that usually local overlandflow occur which means that the factor L (equation (2) and (4) is of no importance; and furthermore we assume, that
c) the equations (1-4) given in 4.3 are valid for the overlandflow cascading system.

In that case:

1. The positive correlation of the mean sediment discharge to the slope angle is explained by a) and equation (1) or (2)
2. The negative correlation of the mean sediment discharge to the slope length is explained by b) and equation (1) or (2)
3. The negative correlation of the mean sediment concentration to the slope angle is explained by a) and equation (4)
4. The positive correlation of the mean sediment concentration to the slope length may be explained by b) and equation (4).

We may conclude that the relationship of both the output of mean sediment discharge and mean sediment concentration to slope angle and slope length can be explained by the conditions in which the sediment output is controled by detachment of splash and overlandflow shear and not by the transport capacity of the flow.

4.4 Summary and conclusions

In this chapter we have analyzed the effect of different landscape variables on the output of the water erosion cascade. On the erosion plots we were able to measure the final output of the splash and overlandflow cascade under natural conditions. With the aid of the portable rainfall simulator we could test, over a larger area, the effect of certain landscape variables on the output of the amount of detached material and the infiltration regulator of the hydrological cascade. The relationships between landscape variables and the output of the rainfall simulator are important since we could prove that the amount of splash detachment and the infiltration capacity correlate strongly to respectively the mean output of the water erosion cascade and to the amount of overlandflow measured on the plots.

We found that the density of the micro-vegetation, the aggregate stability and the stone cover pavements have a relatively strong effect on the outputs of the water erosion cascade. We could establish that the stone pavement with gravel, varying in size from 6 - 2 mm, has a protective effect on a horizontal surface, but on steep slopes (20 - 30°) the gravel is easily transported by splash and overlandflow processes.

The bulk density and the soil texture have also an effect on the output of the cascade. We could establish that particularly the bulk density, which must be related to the mechanical strength of the soil, shows strong correlations with output of splash and overlandflow erosion and, therefore seems to be a good parameter for the determination of the erodibility of the soil. The textural indices seem to be of lesser importance. The amount of clay particularly seems to have a negative effect on the erodibility of the soil due to the weakening effect of the swelling clay minerals on the aggregate stability.

Slope angle had a positive effect on the water erosion outputs. It was interesting to find that the slope length has a negative effect on the output of the overlandflow erosion cascade. This was due to the fact that the amount of overlandflow production was negatively correlated with slope length. We concluded that particularly during natural conditions overlandflow occurs locally on the slopes most of the time and therefore overlandflow erosion is not effected by slope length. Transport by overlandflow on natural slopes must therefore be considered as a "point to point transfer" of sediment and not as an "instant removal" of material from the slope (Ahnert 1977). The study of the input-output relationship of overlandflow and sediment discharge in the overlandflow erosion cascade reveals, that especially on natural slopes the transport of sediment is controled by the amount of material which is detached by splash impact shear and overlandflow shear and not by the transport capacity of the flow. The positive correlation of the input of splashed material and the output of sediment from the overlandflow erosion cascade, shows that an important part of the sediment is supplied towards this cascading system by means of the splash process.

5

THE DISTINCTION OF LANDUNITS IN RELATION TO THE OUTPUT OF THE WATER EROSION CASCADE

5.1 The definition of landunits

In this Chapter we will discuss whether landunits can be distinguished on the base of one or more visible landscape characteristics which can be used as mapping criteria resulting in significant differences in erosion output between the landunits.
An alternative approach is to take measurements in the field of the important erosion parameters, mentioned in the previous Chapter systematically and according to a certain pattern. Estimation can be made on the base of these parameters of the output of the water erosion cascade. In this manner a map can be constructed with isopleths of different erosion values. Landscape units can also be constructed with different erosion value classes. The use of this so called "parametric" approach of landscape classification (Mitchell 1973) requires a good knowledge of the erosion model and the quantitative effect of different landscape parameters on the output. Empirical relationships have been evaluated for certain agricultural areas to enable the prediction of the amount of output (Wischmeier et al. 1958) but there is not much empirical information available on the water erosion processes, working on more or less natural slopes (see previous Chapters). A second difficulty in constructing such a map is the large amount of required measurements and this might be very time-consuming from a practical point of view. This method is therefore appropriate for mapping on a detailed scale (e.g. 1:1000 - 5000). A second approach is the "physiographic" or landscape ecological classification. Theoretically the visible characteristics of different landscape attributes are the results of the interaction of a complex of landscape variables and their related process-systems which are not directly visible (Vink 1975, Zonneveld 1972, Mitchell 1973). This type of classification of the landscape units forms the base for landscape ecological research. It is also used as a base for information for practical needs in agriculture, forestry, engineering etc. ("pragmatic landscape classification"; see Zonneveld 1972). Depending on the information which is requested in a "pragmatic landscape classification", specific information can be given within the units on the values of certain landscape variables. For the purpose of our study we must deliniate landscape units on the base of the characterics of landscape attributes which are related to landscape variables influencing the water erosion output. The "physiographic" method of landscape classification has practical advantanges since, with limited techniques, a differentiation of the landscape into landunits can be made, showing different kind of erosion potentials over a large area (a.o. Van Asch & Steenbergen 1972, Zonneveld 1972). A great disadvantage of the method might be that for certain problems, e.g. in our case the output of sediment from the water erosion cascade, there is no certainty whether such a classification leads to landscape units with significant differences in output, because:

- Certain landscape variables which have a strong effect on the output of water erosion might not be constant within the landunits,
- The different landscape variables have an opposite effect on the output of water erosion (see Chapter 3 and 4) within a given landunit and this does not always lead to a differentiation in output between different landunits. It is therefore important to test whether a proposed classification system is appropriate for showing significant differences in erosion output between landunits. Apart from classification systems in agricultural areas (based on numerous measurements carried out in the United States (see Wischmeier et al. 1958) classification systems are not tested for more or less natural areas.

In this study the second approach of landscape classification has been chosen in order to find an appropriate classification system. The following steps have been taken:

- The selection of mapping critteria based on the characteristics of certain landscape attributes which were visible in the field and which are related to important landscape variables influencing the water erosion system.
- Maps were made of landscape units in the field which were based on the defined criteria.
- Tests were made of differences in erosion output between the distinguished land units.
- A hierarchical system of classification criteria, based on these tests was set up. This system shows an optimal differentiation in erosion output between the distinguised units on each classification level.

We considered types of vegetation structure, soil types and topographical characteristics (slope angle, -length) based on the information given in the previous Chapters to be important criteria for the deliniation of landscape units. The agricultural activity of man, which is reflected in many ways by the characteristics of the landscape attributes are also considered to be an important classification criterium. We will discuss at this point in more detail the criteria which are used for the mapping of the landscape units.
The agricultural activities of man were taken into consideration because these activities strongly effect the vegetation and soil variables which are of importance to the water erosion cascade. In Chapter 4 we found that the agricultural areas have lower bulk density and aggregate stability values than the more or less natural areas. The ploughing of the soil might particularly have a strong effect on the bulk density, aggregate stability and on the soil surface variables (litter and stone cover). Furthermore, the type of crop management is of importance (Hudson 1973). Observations made in the field revealed that the areas under recent cultivation show distinct traces of severe erosion (formation of earth pillars due to splash erosion, rills, stone pavements, depositions of fresh, coarser material behind soil surface obstacles).
In the study area are also abandoned fields which show clear traces of agricultural activities from the past (olive- and fruit-trees, remnants of cultivation terraces). We considered these areas to be different from other areas because the soil has traces of the agricultural activities from the past (lower bulk densities, stone pavements due to accelerated erosion). On the other hand these areas are characterized by a relatively strong develop-

ment of especially the herb vegetation cover. These areas generally show less traces of recent soil erosion. We concluded from our observations (in the field) that the degree of agricultural activity of man must be considered as an important mapping criterium. We have made a division into the following classes: 1. Areas under recent cultivation. 2. Areas with fallow land which mostly forms a complex unit with areas under recent cultivation. 3. Areas with fallow land where no tillage has taken place for at least the last ten years. 4. Areas with no traces of tillage (more or less natural areas).
A second important criterium is the vegetation structure. In Chapter 3 we discussed the influence of vegetation on the erosion system and in Chapter 4 we established the relationship of especially the herb vegetation zone on different outputs of the system. In the agricultural areas the crop vegetation changes within the year, according to certain types of crop management. We could not study these types in detail and as was discussed above, we only made a distinction between areas under recent crops and fallow land on which the herb vegetation can grow rather fast to a certain density of 70-80% cover. The more or less natural areas with no activity of agricultural tillage and mostly a sparse vegetation cover show traces of severe erosion in the past. Particularly in areas with cemented sandstone (Mar) sparsely covered with tussocks of grass the soil has completely disappeared on many places. The soils are also truncated (see Chapter 2). There are some areas with a dense shrub and herb vegetation cover and on the soil surface a strong litter layer. On other places traces of decideous forest could be mapped, especially on higher altitudes in the Savuto drainage basin. These forests usually have very little underbrush such as shrubs and grasses. The forest soil surface is basely protected except for a thin litter layer which is easily transported downslope. We could also find distinct traces pointing to strong erosion processes (high splash pillars, stone pavements usually observed at the foot of the slope, accumulation of debris and litter behind obstacles). We have subdivided the vegetation zone in 4 density classes: 1. dense: 85 - 100% cover, 2. scattered: 40 - 85%, 3. sparsely covered areas 5 - 40% and 4. bare areas 0 - 5%.
A third important criterium is the soil type and the related soil variables. Soils were classified in the field according to the French system of Soil Classification which is based on the degree of horizon development of soils. We assumed that in general the degree of horizon development is connected to differences in soil variables which are of importance to the water erosion cascade (e.g. character of A-horizon, aggregate stability, soil texture).
As we have shown in Chapter 2, soils with an (A) C or (A) R profile ("classe des sols mineraux bruts") and soils with an AC or AR profile ("classe des sols peu évolués) frequently occur in the study area on different parent materials. On places where soil erosion is less intensive soils which belong to the "classe des sols brunifiés" with an A (B) C profile occur locally. The practice of mapping revealed that within a bounded area there is a strong alternation between "classe des sols mineraux bruts" and "sols peu évolués", and therefore we mapped these groupes of soils as a complex unit. We considered it more appropriate for our purpose to made a further distinction of the soils according to the parent material, because the parent material determines the soil texture, especially for these poorly developed soils. Based on the instruction given in the Guidelines for soil profile description (F.A.O. 1966) we further classified the textural

and structural characteristics of the soil (porosity, form of aggregates, stability of aggregates). Notes were also taken of the characteristics of the A-horizon, the percentage of stone cover and, when possible, the depth of the soil. It appears that within the units which were distinguished on the base of soil type and related parent material, there is a variation in the values of certain soil variables. However, these variations were not clear and therefore a further sub-division into spatial units on the base of differentiation of one or more of these variables was not possible. Furthermore we must keep in mind that without instrumentation it is very difficult to estimate differences of values of e.g. aggregate stability, porosity, soil texture within these soil types.
With regard to the topographical criteria slope angle was arbitrarely divided in 3 classes: 1) 0 - 5°, 2) 5 - 20°, 3) 20 - 35°. Furthermore the general form of the slope was taken into consideration (convex, concave, irrigular). Special attention was given to the fact whether the slopes were terraced due to agricultural activity and in that case the mean

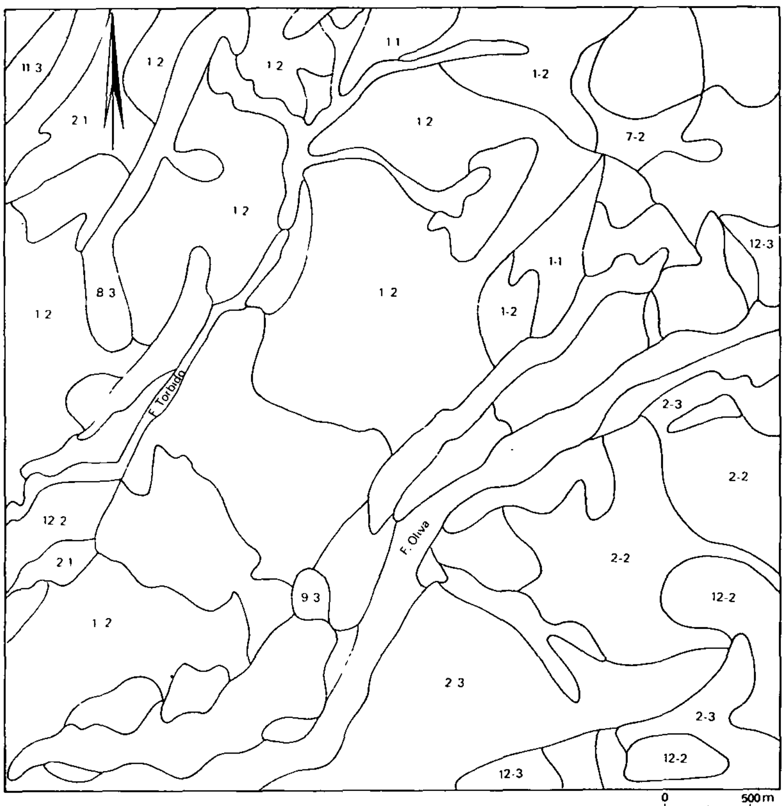


Figure 5.1 Three maps of the study area showing the type of landunits in which erosion measurements have been carried out. (The first figure refers to the type of landunit, given in Table 5.1. The second figure refers to the slope angle classes given in Table 5.1)

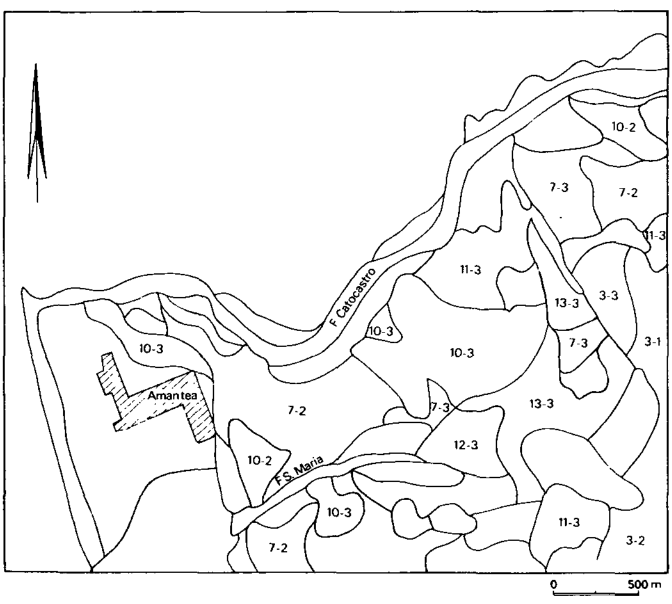


Figure 5.1. (continued)

Table 5.1 The description of landunits in which measurements have been carried out.

Degree of agricultural activity	vegetation structure	soil type[a] and parent material	slope class[b]	land unit
Recent agricultural activities	medium dense olive trees with crops	"sols peu évolués non climatiques"; sometimes "sols bruns des climats temperés humides". Soils with a poorly developed Ap; C content is low (0.5-2%; silty clay to clay texture; fine to medium subangular blocky structure; moderate aggregates; surface stones 3-10%; soil depth until 1 mtr.	1-2	1 (r,p)
		"sols peu évolués non climatiques" on metamorphic rochs some times "sols bruns des climats temperés humides" Soils with a poorly developed Ap; C-content 1.5-2%; sandy loam texture; fine subangular blocky structure; weak aggregates; surface stones 30-50%; soil depth until 60 cm.	2-3	2 (r,p)
		"sols peu évolués non climatiques" on sandstones; sometimes "sols bruns des climats temperés humides" soils with poorly developes Ap; C-content 0.5-2%; loamy sand texture; very weak aggregates; surface stones 5-15%; soil depth until 80 cm	2 and 3	3 (r,p)
	medium dense crops	"sols carbonatés" on limestone. Soils with a distinct Ap (C-content 3-4%); sandy loam texture, fine granular structure; moderate to strong aggregates; surface stones 5-15%; soil depth until 80 cm	2	4 (r)
Follow land forming a complex with landunit n° 1 and 2	medium dense herbs	"sols peu évolués non climatiques" on claystones sometimes "sols bruns des climats temperés humides"; local surface sealing; surface stone 10-15%	1 and 2	5 (r)
		"sols peu évolués non climatiques" on metamorphic rocks; sometimes "sols bruns des climats temperés humides"; surface stone 40-50%	1,2 and 3	6 (r)
Abandoned fields	dense herbs and shrubs	"sols peu évolués non climatiques" on sandstone; sometimes sols bruns des climats temperés humides"; Soils with Ap and locally a thin Aoo-horizon (C-content 1-2%); loamy sand texture; fine blocky angular structure;	2 and 3	7 (r)

		weak to medium strong aggregates; surface stones 5-10%; soil depth until 1 mtr.		
More or less natural areas	scattered herbs	"sols peu évolués non climatiques" on claystone; sometimes "sols bruns des climats temperés humides"; C-content 3-4% in A_1 horizon; silty clay structure; moderate fine to coarse subangular blocky structure; stable aggregates; surface stones 5-10%; soil depth until 1 mtr.	2 and 3	8 (r,p)
		"sols peu évolués non climatiques" on metamorphic rocks; sometimes "sols bruns des climats temperés humides"; soils with locally a thin Aoo cover; C-content of A1: ± 2%; sandy loam texture; fine subangular blocky structure; weak aggregates; surface stones until 25%; soil depth until 60 cm	2 and 3	9 (r,p)
		"sols peu évolués non climatiques" on sandstones; sometimes "sols bruns des climats temperés humides"; soil with locally a thin Aoo cover; C-content of A1: ± 1.5%; loamy sand texture; fine subangular blocky structure; weak aggregates; surface stones 5%; soil depth until 1 mtr.	2 and 3	10 (r,p)
	dense shrubs and herbs	"sols bruns des climats temperés humides" soils with with Aoo, Ao and A1 horizons; C-content A1, 5-6%) sandy loam texture; fine granular loose structure; weak to moderate strong aggregates; surface stones 5-10%; soil depth until 1 mtr.	2	11 (p)
	dense forest	"sols bruns des climats temperés humides" on metamorphic rocks; C-conten A1 horizon 5-6%; sandy loam texture; fine subangular blocky structure; medium strong aggregates; surface stones 20-30%; soil depth until 1 mtr.	2	12 (r,p)
		"sols bruns des climats tempere's humides; on sandstone; C-content A1-horizon 4-6%; locally a Aoo horizon; sandy loamy texture; fine granular loose structure; weak aggregates; surface stones 20-40%; soil depth until 1 mtr	2	13 (p)

r: landunits in which rainfall simulator measurements were carried out; p: landunits in which measuring plots were constructed.

Note: a) soils classified in the field according to French C.P.C.S.-system

b) slope classes: a) 0-5° b) 5-20° c) 20-35°

length of the terraces were noted. The slope length can be expressed in the map as the size of the distinguished unit, measured in a direction perpendicular to the contours. Figure 5.1 shows main parts of the study area in which the type of landunits, which have been selected for erosion measurements are indicated. The landunit types were selected on the base of frequency of occurrence. Also landunits were selected which show typical characteristics of certain landscape attributes. The units on the map are based on a landscape map which is constructed according to the above described criteria by Van Leeuwarden (1973), supplied with observations by the author. Table 5.1 gives a description of the landunit types which were selected for erosion measurements. The hierarchical sequence of criteria given in this table is only based on qualitative observations in the field with regard to the intensity of erosion. In the next Paragraph we will test by means of erosion measurements the validity of the criteria and the hierarchical sequence.

5.2 The differences in outputs of the water erosion cascade and hydrological cascade in relation to landunits

In this Paragraph we will test whether the above mentioned mapping criteria lead to a distinction of landunits with significant differences in erosion output. Furthermore we will test various sequences of criteria in order to obtain a hierarchy of criteria showing a maximum differentiation in output between the distinguished landunits on each classification level.

Firstly we will use the data from the rainfall simulator, assembled at random in the study area. As we stated in the previous Chapter, the rainfall simulator does not give the final output of the splash erosion cascade and the overlandflow erosion cascade. We have shown, however, that there is a relationship between the amount of splash detachment and the final output of the splash erosion cascade and the output of sediment concentration of the overlandflow erosion cascade measured on the plots. This is explained by the fact that the erosion process on the slopes mostly takes place under detachment controled conditions in which the supply of sediment by splash detachment towards the overlandflow cascade is a very important factor. The infiltration data measured with the rainfall simulator also correlate well with the output of the hydrological cascade, particularly on the plots lying in more or less natural areas. Therefore we assume that differences in output measured with the rainfall simulator between landunits indicate, that there are also significant differences in the final output of the water erosion cascade between these landunits. A portable rainfall simulator in the field might be a good instrument for the testing of the erosion output variations of distinguished landunits in a certain area. However, this instrument neglects the factors slope angle and slope length. The importance of these landscape variables as differentiating criteria between landunits will be discussed below with the aid of erosion data from the measuring plots.

In the previous paragraph we have set up a classification scheme in which we have chosen the following sequence of criteria: 1. degree of cultural activity of man 2. vegetation structure (cover), 3. soil type related to parent material. 4. slope angle and slope length. For the time being we will use the first 3 criteria to test whether this sequence leads to an optimal differentiation in water erosion output between landscape units on the three hierarchical classification levels. We have used a F-test and two T-tests to analyse the differences[1] in output between the landunits. The F-test is used to test the equality of variances of the samples taken from different landunits and T-tests[1] were used to find out whether there are significant differences in mean output between the landunits. The first question to be answered is which criterium would be the most important on the highest classification level. We have therefore grouped the data of the rainfall simulator (splash and infiltration capacity expressed as a fc-value, (see Appendix A1) in three ways: a. according to the criterium of the degree of agricultural activity of man (Table 5.2a, b), b. the criterium of vegetation structure (Table 5.2c, d) and c. according to the criterium of soil type (Tabel 5.2e, f) which in the case of selected units is mainly based on differences in parent material (see Table 5.1). In the case of the degree if agricultural activity of man we have made a further distinction concerning areas with recent cultivation, between data from soils which were freshly ploughed and from fields under crop cultivation. The cross Tables show the mean splash discharge (x). (Table 5.2a, c, e) and fc-values (z) (Table 5.2b, d, f). These data were grouped according to the above mentioned criterium classes. In the cross Table the significant differences of the means between the groups of data were tested with the use of various statistical tests[1]. The Tables also show the percentage of cases in which the differences between two groups of data proved to be statistically significant. We can learn from the Tables that the grouping of the data according to the degree of agricultural activity of man leads to a maximum score in significant difference between the mean of the splash values and the fc-values of the landunits. In 70% of the cases a comparison between two groups of data show significant differences between the means of splash output and in 90% of the cases significant differences between the means of the fc-values could be established. When the data are grouped according to the vegetation structure criterium (Table 5.2c, d) it is evident that in 60% of the cases the differences between two means of the splash values are significant and in 40% the differences between two means of the fc-values. Grouping of the data according to the criterium soil type (Table 5.2e, f) (parent material) leads to little differenyiation between the mean (0% of the cases for the splash means and 40% for the fc-means). We may conclude, on the base of these tests, that a first sub-division of the landscape according to the degree of activity of man may give a number of landscape units showing an optimal differentiation in splash and fc-values and hence in erosion output.

We must now decide which criterium is to be taken for a further sub-division of the landscape to the second level. To this end the data are grouped at the second level according to two criteria. The criterium at the first level is the degree of agricultural activity of man. In Table 5.3a, b the splash- and fc-values are grouped, according to the degree of agricultural activity of man and the vegetation structure.

In Table 5.3c, d the data are grouped according to the degree of activity of man and parent material of the soils. The cross Tables show that a grouping of data according to the degree of activity of man and the vegetation structure gives the best differentiation between the means of splash values and fc-values (respect. 81% and 67%). A grouping

Table 5.2 Splash erosion values and infiltration rates in landunits distinguished according to respectively degree of agricultural activity, vegetation structure and the parent rock of soils, measured with the rainfall simulator. The significance of differences between the mean values of landunits

SPLASH (a)

Degree of agricultural activity	n	x	s		1	2	3	4	5
Freshly ploughed	15	50.53	15.49	1		T F	T –	T –	T –
Crops	30	30.16	9.23	2			T –	T –	T –
Fallow land	12	9.82	5.78	3				– –	– –
Abandoned	9	10.77	8.40	4		D = 70%			– –
No tillage	33	9.82	7.44	5					

SPLASH (c)

Vegetation structure	n	x	s		1	2	3	4	5
Medium dense crop and olivetree-cover	47	24.67	15.08	1		T F	T F	T F	– F
Dense herbcover on fallow land abandoned field	21	10.25	7.20	2			– –	– F	T F
Scattered herbcover	21	7.64	5.64	3				– F	T –
Dense herb and shrubcover	4	2.89	1.62	4		D = 60%			T F
Dense forestcover	6	22.07	3.33	5					

SPLASH (e)

Soils on:	n	x	s		1	2	3	4
Claystone	30	19.04	16.82	1		– –	– F	– –
Sandstone	30	14.35	13.80	2			– F	– –
Metamorphic rocks	33	16.59	9.53	3		D = 0%		– –
Limestone	5	21.27	10.60	4				

n: number of measurements with rainfall simulator; x mean splash detachment of landunit is gr 100 mm^{-1} rain; z mean infiltration rate (fc - value) of landunit in ml mm^{-1}; s: standard deviation; T: differences between two compared means is significant ($\mu_1 \neq \mu_2, \alpha = 2.5\%$) according to Student's t-test or

Fc-VALUE (b)									
Degree of agricultural activity	n	z	s		1	2	3	4	5
Freshly ploughed	15	0.32	0.16	1		T F	T –	T F	– –
Crops	30	0.21	0.10	2			T F	T F	T F
Fallow land	12	0.50	0.27	3				T –	T –
Abadoned	9	0.54	0.32	4		D = 90%			T F
No tillage	33	0.30	0.18	5					

Fc-VALUE (d)									
Vegetation structure	n	z	s		1	2	3	4	5
Medium dense crop and olivetree-cover	47	0.29	0.19	1		T F	– –	– –	T F
Dense herbcover on fallow land abadoned field	21	0.52	0.30	2			T F	– –	T F
Scattered herbcover	21	0.31	0.20	3				– F	– –
Dense herb and shrubcover	4	0.40	0.24	4		D = 40%			– F
Dense forestcover	6	0.20	0.07	5					

Fc-VALUE (f)								
Soils on:	n	z	s		1	2	3	4
Claystone	30	0.24	0.21	1		T –	– –	T –
Sandstone	30	0.42	0.25	2			T F	– –
Metamorphic rocks	33	0.31	0.17	3		D = 67%		T –
Limestone	5	0.62	0.27	4				

t-test of Welch: F: Samples are drawn from two populations with no equality of variances ($\sigma^1_2 = \sigma_2^2$; $\alpha = 2.5\%$; –: $\mu_1 = \mu_2$; –: $\sigma_1^2 = \sigma_2^2$ ($\alpha = 2.5\%$); D: percentage of cases showing significant differences between the mean values ($\mu_1 \neq \mu_2$) of two landunits.

Table 5.3 Splash erosion values and infiltration rates in landunits distinguished according to 1: degree of agricultural activity, and 2: respectively vegetation structure and the parent rock of soil, measured with the rainfall simulator. The significance of differences between the mean values of landunits

SPLASH (a)

Degree of agricultural activity	vegetation structure	n	x	s		1	2	3	4	5	6	7
Freshly ploughed	bare	15	50.53	5.49	1		T –	T –	T –	T –	T –	T F
Crops	crops	30	30.16	9.23	2			T –	T –	T –	T F	T –
Fallow land	medium dense herbs	12	9.82	5.78	3				– –	– –	T –	T –
Abandoned	medium dense herbs	9	10.77	8.40	4					– –	T F	T –
No tillage	scattered herbs	21	7.64	5.64	5		D = 81%				– –	T –
	dense herbs and shrubs	4	2.89	1.62	6							T –
	dense forest	6	22.07	3.33	7							

Fe - VALUE (b)

Degree of agricultural activity	vegetation structure	n	z	s		1	2	3	4	5	6	7
Freshly ploughed	bare	15	0.32	0.16	1		T –	T –	T –	– –	– –	T –
Crops	crops	30	0.21	0.10	2			T F	T F	T F	T F	– –
Fallow land	medium dense herbs	12	0.50	0.27	3				T –	T –	– –	T F
Abandoned	medium dense herbs	9	0.54	0.31	4					T –	– –	T F

No tillage	scattered herbs	21	0.31	0.20	5						D = 67%					--	-F
	dense herbs and shrubs	4	0.40	0.24	6												T F
	dense forest	6	0.20	0.07	7												

SPLASH (c)

Degree of agricult-ural activity	soils on	n	x	s		1	2	3	4	5	6	7	8	9	10	11	12
Freshly ploughed	claystone	9	45.31	7.24	1		--	T -	T -	T -	T -	T -	T -	T -	T F	T F	T -
	sandstone	6	52.34	8.41	2			T -	T -	T F	T -	T -	T -	T -	T F	T F	T -
Crops	claystone	8	11.14	4.23	3				-F	-F	T F	--	--	-F	T -	T -	T -
	metamorfic rocks	16	18.31	10.40	4					T F	-F	T F	--	--	T F	T F	--
	sandstone	8	10.02	4.20	5						T F	--	--	-F	T -	T -	T -
	limestone	5	21.86	11.86	6							T F	-F	--	T F	T F	--
Fallow land	claystone	6	7.73	4.35	7								--	--	--	--	T -
	metamorphic rocks	6	11,99	5.70	8									--	T -	T -	--
Abandoned	sandstone	9	10.82	8.87	9					D = 61%					-F	-F	--
No tillage	claystone	7	5.41	3.09	10											--	T F
	sandstone	12	5.60	3.45	11												T F
	metamorphic rocks	12	17.40	7.15	12												

(to be continued on page 92)

Table 5.3 (continued)

Fc-VALUE (d)																	
Degree of agricultural activity	soils on	n	z	s		1	2	3	4	5	6	7	8	9	10	11	12
Freshly ploughed	claystone	9	0.29	0.15	1		--	--	--	--	T –	T –	--	–F	T F	--	--
	sandstone	6	0.35	0.18	2			–F	--	–F	--	--	--	--	T F	--	--
Crops	claystone	8	0.11	0.7	3				--	--	--	--	--	T F	--	--	--
	metamorphic rocks	16	0.37	0.16	4					–F	T –	T –	--	T F	T F	T –	T –
	sandstone	8	0.15	0.8	5						--	--	--	T F	--	--	--
	limestone	5	0.62	0.28	6							--	--	--	T F	--	T F
Fallow land	claystone	6	0.55	0.30	7								--	--	T F	--	T F
	metamorphic rocks	6	0.41	0.21	8									--	T F	--	T F
Abandoned	sandstone	9	0.54	0.33	9				D = 35%						T F	–F	T F
No tillage	claystone	7	0.13	0.05	10											T F	T F
	sandstone	12	0.48	0.16	11												T –
	metamorphic rocks	12	0.22	0.11	12												

n: number of measurements with rainfall simulator; x : mean splash detachment of landunit in gr 100 mm^{-1} rain; z.: mean infiltration rate (fc-value) of landunit in ml mm^{-1}; s: standard deviation; T: differences between two compared means is significant ($\mu_1 \neq \mu_2, \alpha = 2.5\%$) according to Student's t-test or t-test of Welch; F: Samples are drawn from two populations with no equality of variances ($\sigma_1^2 \neq \sigma_2^2; \alpha = 2.5\%$); –: $\mu_1 = \mu_2$; –: $\sigma_1^2 = \sigma_2^2$ ($\alpha = 2.5\%$); D: *percentage of cases showing significant differences between the mean values ($\mu_2 \neq \mu_2$) of two landunits.*

of data according to the degree of activity of man and parent material shows a degree of differentiation between splash means and fc-means of respect. 60% and 35%. Therefore the vegetation may be chosen as the criterium at the second level for a further subdivision of the landscape.
In Table 5.4a, b the data are grouped according to the three criteria. In this Table we combined the data from freshly ploughed fields and the data from fields with crops. because the character of these fields changes rapidly and has to be mapped as complex units. The criterium classes given in Table 5.4a, b have been used for the deliniation of landscape units in the field. They are depicted in Figure 5.1 and described in Table 5.1. The cross Tables 5.4a, b show that a sub-division of the landscape up to the third level lowers the degree of differentiation between the means of the splash- and fc-data grouped according to the three mentioned criteria. This can mean that different parent materials of the soil have relatively little influence on the erosion output in the study area.
The Table also reveals that the standard deviation of the means of data grouped according to three mapping criteria remains high. This is explained by the fact that landscape variables, important to the erosion process in landunits, which are distinguished on the base of these criteria, are still far from being homogeneous. We can assume that particularly the soil variables (bulk density, aggregate stability, stone cover and litter cover, the presence of a sealing crust) varies strongly within an area containing the same soil type and parent material. It has already been stated that in the practice of mapping it is very difficult to classify exact values of particularly the soil parameters.
We have not yet discussed the differences in variation of output between the distinguished groups of data which are given in the cross Tables. These differences can be analysed by a F-test[1].

- Significant differences in variation between the distinguished groups can mean that there is a difference in the range of values of certain landscape variables between landscape units, which are defined according to the above mentioned criteria. These landscape variables which influence the erosion process also cause differences in the range of output values of the erosion process. In other words there is a difference in homogenity between landunits with regard to certain landscape variables.
- A variation in input of rain with the rainfall simulator (but also by natural showers) gives a greater variation in erosion output for e.g. soils with a higher sensibility for splash erosion.

The statistical analysis of the means of rainfall simulator data, grouped according to various sequences of mapping criteria, reveals that the best hierarchical sequence of classification criteria which can be chosen in the study area, is 1. degree of agricultural activity of man, 2. vegetation structures and 3. the soil parent material. These criteria can easily be mapped in the field. Differentiation in soil type, e.g. as regard to the degree of profile development, is not large and therefore has little effect as a differentiating factor for the erosion output. Besides, the variation in soil variables influencing the erosion process (aggregate stability, bulk density etc.) within one soil type may be very large and these parameters are very difficult to estimate and to map. Before testing whether the proposed sequence of criteria is also supported by the measuring results of the ero-

Table 5.4 Slash erosion values and infiltration rates in landunits distinguished according to 1. degree of agricultural activity 2. vegetation structure 3. the parent rock of soils, measered with the rainfall simulator. The significance of differences between the mean values of landunits.

SLASH (a)

Degree of agricultural activity	Vegetation structure	Soils on	n	x	s		1	2	3	4	5	6	7	8	9	10	11	12
Freshly ploughed	scattered trees, crops	claystone	17	28.58	17.17	1		--	--	--	TF	TF	TF	TF	TF	TF	TF	-F
		metamorphic rocks	16	18.84	12.29	2			--	--	TF	--	--	TF	--	TF	TF	-F
		sandstone	9	29.56	15.31	3				--	TF	TF	T-	TF	T-	TF	TF	-F
	crops	limestone	5	21.86	11.86	4					T-	--	--	T-	--	TF	TF	--
Fallow land	medium dense herbs	claystone	6	7.73	4.35	5						--	--	--	--	--	--	T-
		metamorphic rocks	6	11.99	5.70	6							--	T-	--	--	--	T-
Abandoned	scattered herbs	sandstone	9	12.33	8.51	7								T-	--	T-	TF	T-
No tillage	scattered herbs	claystone	7	5.41	3.09	8		D = 52%							T-	--	--	T-
		metamorphic rocks	6	12.25	6.42	9										T-	T-	T-
		sandstone	9	6.77	3.29	10											--	T-
	dense shrubs and herbs	sandstone	4	2.96	1.40	11												T-
	dense forest	metamorphic rocks	6	21.16	3.18	12												

Fc-VALUE (b)

Degree of agricultural activity	Vegetation structure	Soils on:	n	z	s		1	2	3	4	5	6	7	8	9	10	11	12
Freshly ploughed	scattered trees, crops	claystone	17	0.18	0.07	1		TF	-F	TF	TF	TF	-F	--	--	T-	TF	--
		metamorphic rocks	16	0.34	0.17	2			--	T-	T-	--	--	TF	--	T-	--	--
		sandstone	9	0.23	016	3				T-	T-	--	T-	TF	T-	T-	--	--
	crops	limestone	5	0.62	0.28	4					--	--	--	TF	T-	-F	--	TF
Fallow land	medium dense herbs	claystone	6	0.55	0.30	5						--	--	TF	T-	-F	--	TF
		metamorphic rocks	6	0.41	0.21	6							--	TF	--	--	--	--
Abandoned	medium dense herbs	sandstone	9	0.50	0.33	7								TF	-F	--	--	-F
No tillage	scattered herbs	claystone	7	0.13	0.05	8		D = 45%							TF	TF	TF	TF
		metamorphic rocks	6	0.25	0.13	9										T-	--	--
		sandstone	9	0.51	0.11	10											--	T-
	dense shrubs and herbs	sandstone	4	0.40	0.21	11												--
	dense forest	metamorphic rocks	6	0.20	0.11	12												

n: number of measurements with rainfall simulator; x : mean splash detachment of landunit in gr 100 mm^{-1} rain; z.: mean infiltration rate (fc-value) of landunit in ml mm^{-1}; s: standard deviation; T: differences between two compared means is significant ($\mu_1 = \mu_2, \alpha = 2.5\%$) according to Student's t-test or t-test of Welch; F: Samples are drawn from two populations with no equality of variances ($\sigma_1^2 = \sigma_2^2; \alpha = 2.5\%$); $-$: $\mu_1 = \mu_2$; $-$: $\sigma_1^2 = \sigma_2^2$ ($\alpha = 2.5\%$); D: percentage of cases showing significant differences between the mean values ($\mu_1 = \mu_2$) of two landunits.

sion plots, we will give some comments on the established differences between the means of groups of data related to different landunits.
Table 5.2a shows that the amount of splash detachment is large in comparison to landunits of fallow land or abandoned fields and to areas with no traces of crop cultivation. The freshly ploughed fields particularly show a very high sensibility towards splash. In Chapter 4 (Figure 4.2) we have established a clear differentiation in bulk density and aggregate stability and hence splash sensibility between areas under recent cultivation and more or less natural areas, which must be due to the ploughing activity of man. The lower splash sensibility of the abandoned areas in relation to areas with fallow land is explained by a denser herb vegetation in the abandoned areas and the absence of ploughing activity which leads to compaction of the soil surface due to the impact of rain.
Table 5.2b shows that apart from a decrease in splash sensibility there is also a decrease in infiltration capacity between areas, which are freshly ploughed, and areas under crop vegetation. The impact of raindrops on the bare freshly ploughed soils leads to a rapid compaction and even a sealing of the soil surface. The Table also shows that the development of a denser herb cover, which we could observe on fallow land and abandoned fields, has a positive effect on the infiltration capacity. The abandoned areas show high infiltration capacities in comparison to other areas (including the more or less natural areas). In combination with the relative low sensibility for splash (see above) these areas may be considered as the most stable regions within the study area.
In Table 5.2c we may see, that there are no significant splash differences between landunits with scattered herb vegetation (20-40%) and areas with denser herb and shrub vegetation (90-100%). An explanation is found in the previous Chapter (Figure 4.2). There it was shown that the effect of (herb) vegetation cover on splash erosion is particularly strong in the range of a 0% to 30% vegetation cover. Another interesting fact is that soils under a dense decideous forest cover with no herb vegetation have significantly higher splash values than the other areas with natural vegetation. They seem to be more sensitive to splash erosion as areas under recent crop cultivation.
Unfortunately we have limited information concerning these soils (see e.g. Appendix A3 site 2 and 9) but on the base of soil description we may assume that the absence of a herb vegetation cover in combination with a loose structure of the soil (low bulk density) explains the high splash sensibility.
Table 5.2d reveals that areas with a dense herb cover 50-100% show the highest infiltration capacities which points to a positive effect of the herb vegetation cover on the infiltration rate (see Figure 4.5, Chapter 4).
Table 5.3c shows that within the freshly ploughed areas we could not establish significant differences in splash erosion between soils derived from sandstone and from claystone. The differences in output between these two soil groups in areas under crop cultivation is not significant either. We would generally expect lower splash values for the more cohesive clay soils, but as we have already mentioned in Chapter 4, the swelling capacity of these clay minerals decreases the aggregate stability during wetting. Soils derived from metamorphic rocks and limestone show generally significant higher splash values within the agricultural areas. We could not find significant lower aggregate stabili-

ties and (or) bulk densities, for these groups of soils (see Figure 4.2 in Chapter 4). However, observations in the field, especially on the measuring plots (see below) show that particularly on clay soils and sandstone soils, in many spots traces of sealing may be discerned, which were not observed on soils on metamorphic rocks and on limestone soils. This might be an explanation for the lower splash values of the sandstone and claystone soils. The same trend in the differences between these groups of soils can be observed in areas with fallow land and in more or less natural areas. However, the differences are not always significant. As regard to the fc-values (Table 5.3d) no significant differences were measured between claystone and sandstone soils on freshly ploughed fields. Within areas under recent crop cultivation claystone and sandstone soils show significantly lower fc-values than soils derived from metamorphic rocks and limestone. We assume that the sealing which was observed on the sandstone and claystone soils also has a negative effect on the infiltration rate.

Sandstone soils show remarkable high infiltration rates within areas with no tillage and in areas with scattered vegetation (see Table 5.4b). This might be due to the high porosity (low bulk density) of some natural sandstone soils (see Figure 4.2 Chapter 4). We must keep in mind, however, that particularly on calcareous sandstone soils (Mar) clear traces of sealing with surface crusts of 0.5 mm with very low infiltration capacities were found.

We will now investigate whether the relative importance of the classification criteria, based on differences in output and measured with the rainfall simulator, is supported by the differences in the final output of the water erosion cascade and also the hydrological cascade measured on the erosion plots.

Table 5.1 shows that in 9 of the 13 basic landscape units, which were described in the previous Paragraphs, measuring plots were installed. Since the Gerlach throughs were concentrated in a certain area of maximal 20 x 50 mtr the samples are not randomly distributed within a certain landscape unit. We must therefore be very careful with the conclusions drawn from statistical tests and with the comparison of rainfall simulator results with plot results. However, we may assume that clear differences in the mean output of the erosion plots over a period of 3 months forms a good indication whether the distinction of landunits on the base of certain criteria is significant or not.

We first give the following comments on the differences in output: Table 5.5a gives the total output of the water erosion cascade (= splash + overlandflow) (x). The amount of material which was transported by splash over a unit distance of slope (50 cm) during that period, is given as a percentage of the total output (% Sp). We may conclude that on slopes with various slope lengths a great deal of the totally transported material varying from 40 - 80% passes a unit width of slope in a given period via splash transport.

This is explained by 2 reasons:

- Splash transport occurs on the slopes while there is (still) no overlandflow on the slopes during a rain storm.
- The catchment area of the overlandflow is local and limited (see Chapter 4) and may have the same size as the source area of splashed material (1-2 mtr according to Mosley 1974; Van Asch & Roels 1979).

Table 5.5 shows that the relative importance of splash in agricultural areas with meta-

Table 5.5 Water erosion, splash erosion and overlandflow values of landunits distinguished according to 1: degree of agricultural activity of man 2. vegetation structure 3. the parent rock of soils, measured on erosion plots. The significance of differences between the mean values of landunits.

OVERLANDFLOW (a)

Degree of agricultural activity	Vegetation structure	Soils on	MP	% Sp	n	x	s		1	2	3	4	5	6	7	8	9
Freshly ploughed	bare	claystone	12	76.9	2	0.823	0.124	1		T F	T −	T F	T −	T −	T F	T −	T −
		metamorphic rocks	11	3.3	2	9.589	2.786	2			− −	T F	T F	T F	T F	T F	T F
		sandstone	10	18.4	2	3.921	0.561	3				T F	T F	T F	T F	T F	T F
No tillage	scattered herbs	claystone	1	46.2	4	0.019	0.011	4					T F	T F	T −	T F	T F
		metamorphic rocks	3,4	45.7	8	0.191	0.092	5						T F	T F	T F	T −
		sandstone	5, 6, 7	56.5	10	0.241	0.091	6		D = 86%					− F	T F	− −
	dense herbs and shrubs	sandstone	9	82.5	3	0.039	0.016	7								T F	T F
	dense forest	metamorphic rocks	2	68.4	5	0.485	0.205	8									− −
		sandstone	8	82.5	5	0.317	0.096	9									

OVERLANDFLOW (b)

Degree of agricultural activity	Vegetation structure	Soils on	MP	n	z	s		1	2	3	4	5	6	7	8	9
Freshly ploughed	bare	claystone	12	2	15.83	4.76	1		T −	T −	− −	− −	− F	− −	− −	− −
		metamorphic rocks	11	2	321.32	10.38	2			T −	T −	T −	T −	T −	T −	T F
		sandstone	10	2	68.86	6.67	3				T −	T	T F	T −	T −	T −
No tillage	scattered herbs	claystone	1	3	22.14	11.36	4					− −	− −	− F	− −	− −
		metamorphic rocks	3, 4	6	18.31	7.43	5						− −	− F	− −	− −
		sandstone	5, 6, 7	7	30.05	20.07	6		D = 50%					− F	− F	− F
	dense herbs and shrubs	sandstone	9	2	5.17	2.50	7								− −	T −
	dense forest	metamorphic rocks	2	4	13.64	4.09	8									− −
		sandstone	8	5	13.60	3.57	9									

MP: Identification of measuring plots; n: number of measuring points; Sp: splash erosion as a percentage of total water erosion (x); x: mean water erosion in gr mm^{-1} rain (unit width of slope = 50 cm) measured over three months; z: mean overlandflow in ml mm^{-1} rain (unit width of slope = 50 cm) measured over three months; s: standard deviation; T: the difference between two compared means is significant ($\mu_1 \neq \mu_2$, α = 2.5%) according to Student's t-test or t-test of Welch; F: Samples are drawn from two populations with no equality of variances $\sigma_1^2 \neq \sigma_2^2$, α = 2.5%); −: $\mu_1 = \mu_2$; −: $\sigma_1^2 = \sigma_2^2$ (α = 2.5%); D: percentage of cases showing significant differences between the mean values ($\mu_1 \neq \mu_2$) of two landunits.

morphic rocks and sandstone is relatively low. On these plots a high overlandflow production was measured and in combination with the low shear strengths of the freshly ploughed soils, detachment by overlandflow shear is thought to be relatively large.
We can further conclude from Table 5.5a that the total water erosion (splash + overlandflow) on freshly ploughed field is generally 10 to 20 times higher than the more or less natural areas with no tillage. An interesting point is that the water erosion output, measured during the winter period in the decideous forest areas, is significantly higher than areas with scattered and dense herbs and shrubs (compare with Table 5.3a).
The output, measured on the erosion plots, also shows interesting differences between soil types. The soils on metamorphic rocks in the freshly ploughed areas show a very high production of overlandflow erosion, while the portion of splash output is relatively low. This is due to the fact that in these plots we measured a relatively high overlandflow production. Observations in the field revealed that during rain storms strong overlandflow occurred in the lowest part of the measuring plot and we concluded that in these areas with a shallow soil up to 30 cm and an impermeable rock, conditions of saturated overlandflow (Chapter 3) must have existed (see Plate 2).

The high amount of overlandflow in combination with the low shear strength of the soil, due to ploughing and the relatively high silt content might indicate that the amount of detachment by overlandflow shear is very large.
Furthermore an interesting point is that claystone soils on the freshly ploughed fields show a very low overlandflow erosion output. As we will see below, on these soils the amount of overlandflow production is also very low. Particularly in the first measuring periods, shortly after the soils were ploughed (± one month) no overlandflow was measured even after high rain storms, whereas the other plots (10 and 11) gave large amounts of overlandflow (see Appendix A4). During the last periods we found that overlandflow production began and this was due to a certain sealing of the soil surface. This also explains why the percentage of splash is high in relation to the other agricultural plots (76.9% of the total water erosion output). In areas with scattered vegetation we can observe in Table 5.5a that the overlandflow erosion output in claystone soils is relatively low. The rainfall simulator test also showed low values for splash detachment. These claystone soils under scattered vegetation are compact and have high bulk densities. In many cases they also show traces of sealing. We observed in these plots that the infiltration capacity of these soils increases due to the formation of cracks. This decreases the mean amount of overlandflow production and hence the overlandflow erosion. The relatively high overlandflow erosion output in areas with scattered vegetation on sandstone soils, was unexpected in view of the splash results with the rainfall simulator (see e.g. Table 5.4a). But also in this case the final output of the overlandflow erosion cascade is connected with a high input from the hydrological cascade, which was relatively high at least on one plot (Site no 5, Appendix A4).
Table 5.5b shows the differences in overlandflow production between the different basic landunits. It becomes obvious that overlandflow production in freshly ploughed areas, particularly on sandstone and metamorphic rocks, is relative high in comparison with more or less natural areas. This is not quite in accordance with the rainfall simu-

lator results which show a relative high infiltration rate on freshly ploughed soils (Table 5.3b and d).

The following explanations can be given:

- On the freshly ploughed measuring plots lying in sandstone soils, we could observe a rapid sealing after some heavy showers (see Plate 3). We already mentioned that the rainfall simulator test also generally showed a decrease in infiltration rate between freshly ploughed soils and soils under crop vegetation.
- On the measuring plot, lying in metamorphic rocks, saturated overlandflow could be observed which was due to a locally shallower soilcover lying on the relative impermeable metamorphic rocks.

We also mentioned already the remarkably low overlandflow production on the measuring plot lying in freshly ploughed claystone soils (plot 12 see Appendix A4). Apart from the effect of the large cracks (which could not be measured with the rainfall simulator due to the small infiltration surface) on the infiltration rate, we will point to the fact that the upper 30 cm of these freshly ploughed claystone soils must be considered as a loose package of strong cohesive clods (under dry circumstances) with many large fissures and non-capillary spaces connected to each other. The water rapidly infiltrated in this upper layer and a rapid sub-surface flow may develop along the slope. Unfortunately we did not measure this rapid sub-surface flow which might also produce a sort of sub-surface erosion.

Within the areas with scattered vegetation the sandstone soils on the plots show a relatively high run-off production which also results in a high output of overlandflow erosion. This contradicts the mean high fc-values measured with the rainfall simulator. We must stress again here the fact that particularly in calcareous sandstone (Mar), a crust can be formed locally especially after dry periods, which makes the soil impermeable. This could be observed on plot 5 (see Appendix A4) . Here a high overlandflow production was measured (56.04 ml/mm rain). On plot 6 with a somewhat denser herb vegetation on the contrary, the mean overlandflow production was relatively low (4.05 ml/mm rain).

Table 5.5 shows that a landscape sub-division based on (1) degree of agricultural activity of man (2) vegetation structure and (3) soil type related to parent material results in a number of landunits showing a high degree of differentiation between the units (86%) regarding the total output of the water erosion cascade. The question arises whether slope length and slope angle are also important differentiating landscape variables on a certain hierarchic level. The results given in Table 5.2a, b, 5.3a, b from the rainfall simulator and in Table 5.5 from the measuring plots showed that the activity of man and the vegetation structure are the best differentiating criteria on the first and second level. If we introduce slope angle or slope length at the second level the degree of differentiation as regard to the total output of the water erosion cascade is much lower (60% and 30% respect.). The question remains whether on the third hierarchical level slope angle and slope length give a better degree of differentiation than a sub-division according to soil type related to parent material. We can learn from Table 5.6 and 5.7 compared with Table 5.5 that a sub-division according to slope angle (range 25-35°), leads to approxi-

Table 5.6 Water erosion values of landunits distinguished according to 1. degree of agricultural activity of man; 2. vegetation structure; 3. slope length, measured on erosion plots. The significance of differences between the mean values of landunits

Degree of agricultural activity	Vegetation structure	L	MP	n	x	s		1	2	3	4	5	6	7
Freshly ploughed	bare	1	10, 11, 12	6	4.78	1.79	1		T F	T F	T F	T F	T F	T F
No tillage	scattered herbs	4	1	4	0.02	0.01	2			−F	T F	T F	−F	T F
		3	3, 4	8	0.19	0.10	3				−−	−F	T −	T −
		2	5, 6	8	0.26	0.10	4					−F	T −	−−
	dense herbs	1	9	3	0.04	0.02	5		D = 62%				−F	T F
	dense forest	4	2	4	0.49	0.22	6							−−
		2	8	5	0.32	0.10	7							

(For the explanation of symbols, see page 101)

Table 5.7 Water erosion values of landunits distinguished according to 1, degree of agricultural activity ofman: 2. vegetation structure; 3. slope angle, measured on erosion plots. The significance of differences between these values.

Degree of agricultural activity	Vegetation structure	A	MP	n	x	s		1	2	3	4	5	6	7	8
Freshly ploughed	bare	1	11	2	9.589	2.786	1		T F	T F	T F	T F	T F	T F	T F
		2	10, 12	4	2.372	0.342	2			T F	T F	T F	T –	T –	T –
No tillage	scattered herbs	2	1	4	0.019	0.011	3				T F	T F	T F	T F	T F
		3	3, 4 7	10	0.190	0.098	4					– –	– –	T –	T –
		4	5, 6	8	0.258	0.098	5						– –	T –	– –
	dense herbs and shrubs	3	9	3	0.317	0.132	6							– –	– –
	dense forest	2	2	5	0.485	0.205	7			D = 75%					– –
		4	8	5	0.317	0.096	8								

MP: Identification of measuring plots; L: slope class; A slope angle class n: number of measuring points; x: mean water erosion in gr mm^{-1} rain (unit width of slope = 50 cm) measured over three months; s: standard deviation; T: the difference between two compared means is significant ($\mu_1 = \mu_2, \alpha = 2.5\%$) according to Student's t-test or t-test of Welch; F: Samples are drawn from two populations with no equality of variances ($\sigma_1^2 \neq \sigma_2^2, \alpha = 2.5\%$); –: $\mu_1 = \mu_1$; –: $\sigma_1^2 = \sigma_2^2$ ($\alpha = 2.5\%$); D = percentage of cases showing significant differences between the mean values ($\mu_1 \neq \mu_2$) of two landunits.

mately a lower degree of differentiation (75%) while slope length is also a lesser important differentiating factor (62%).
We may conclude that the analysis of the output of the rainfall simulator and the measuring plots proves that the following sequence of mapping criteria leads to the best differentiation between landunits on each hierarchical level: 1. activity of man, 2. vegetation structure, 3. soil/parent material, 4. slope angle, 5. slope length.

In Table 5.8 the output of splash erosion and total water erosion of landunits subdivided according landuse and vegetation structure are compared with some data from measuring plots in other parts of the world. Our data must be handled with care because they are extrapolated from three month's measuring periods in the rain season. It is obvious that the data from the agricultural areas are high in comparison with the data from the natural areas in other parts of the world. Probably the measured transport rates on the more or less natural slopes in our area are comparable with transport rates of water erosion under semi-arid conditions. Young (1973) stated that in order to get an insight in the rate of slope retreat in different parts of the world more stratified sampling is needed. The region under study has to be subdivided on the basis of slope – vegetation – and soil characteristics. In addition we can state that in order to get also insight in the way of slope development the output of splash erosion and overlandflow erosion has to be measured separately. Table 5.8 shows that splash erosion is very important on more or less natural slopes.

Table 5.8 Output of water- and splash erosion from all measuring plots compared with water erosion date from other climatological regions (Data assembled by Young 1973)

Climate	Vegetation	Slope	Erosion[a] ($cm^3cm^{-1}yr^{-1}$)		Source	
			Water-	Splash-		
Arid	bare	–	0.3	–	Carson & Kirkby	1972
Semi-arid	bare	–	4.2	–	Carson & Kirkby	1972
Mediterranean	bare[b]	21°	36.9	3.8	Van Asch	1980
Temperate maritime	bare	–	1.5	–	Slaymaker	1972
Mediterranean	herbs	28°	0.5	0.4	Van Asch	1980
Savanna	herbs	8°	20	–	Riezebos	1979
Savanna	herbs	–	5	–	Townshend	1970
Temperate maritime	herbs	27°	0.1	–	Soons	1971
Temperate maritime	herbs	36°	5.6	–	Soons	1971
Mediterranean	shrubs	30°	2.9	2.4	Van Asch	1980
Mediterranean	trees	28°	4.9	3.4	Van Asch	1980
Savanna	trees	5°	20	–	Riezebos	1979

a Data of Riezebos and Van Asch extrapolated on year basis
b Ploughed fields

5.3 Summary and conclusions

In this Chapter the differences in output of the hydrological cascade and the water erosion cascade of landunits on different classification levels were compared in order to find a sequence of mapping criteria for the classification of the landscape in units, which show a maximum degree of differentiation in erosion output on each level. The results of the rainfall simulator and erosion plots indicated that the following sequence of criteria leads to an optimum differentiation between units on different hierarchical levels:
1. Degree of agricultural activity of man, 2. vegetation structure, 3. soil type related to parent material, 4. slope angle, 5. slope length.
With respect to the primary sub-division based upon the degree of agricultural activity of man it was found that the units with recent agricultural activity show a high water erosion output compared to that of the other units. The highest splash detachment output was measured with the rainfall stimulator on freshly ploughed plots. We found also the highest output of total water erosion on these plots. This is generally due to the low soil resistance against splash and overlandflow detachment, the high overlandflow production on some of these plots and the scarce vegetation cover. The results of the rainfall simulator and, to some extent less obvious, the output results on the measuring plots show that there is a relatively large decrease of the soil sensibility towards splash and overlandflow detachment in the period between the ploughing of soil and the growing of the crops. In this period the infiltration capacity of the soils decreases. This is generally caused by a consolidation and sealing of the soil by the impact of rain. In the areas with fallow land and abandoned fields the results of the rainfall simulator showed a further decrease of the sensibility against splash erosion in comparison to the areas under crop cultivation. The infiltration capacity is relatively high in the abandoned areas, and this is probably due to the strong growth of the herb vegetation. It may therefore be concluded that the decrease in the agricultural population, particularly after World War 2 (see Chapter 2), has generally led to a stabilisation of the erosion.
With respect to the vegetation structure which we selected in the base of the output results of the different landunits as a second classification criterium, we found that in the more or less natural areas a dense vegetation cover (80 - 100%) shows the lowest output of splash detachment and total water erosion and the highest infiltration capacities. However, particularly with regard to splash detachment, we found that the differences are not large or significant in relation to areas with a more scattered vegetation cover of about 20-40%. Chapter 4 has revealed that the effect of the vegetation cover rapidly decreases above a 30% vegetation cover. An interesting fact is that the soils under a dense decideous forest cover with no shrub and herb vegetation show a relatively high output of splash and total water erosion which can reach an amount comparable to the landunits under recent crop cultivation. The infiltration capacity in these units is much lower than the values measured in areas with a dense herb vegetation cover (30-100%).
The differences between units with different soil type and related parent material are not always significant and sometimes contradicting, when the results of the rainfall simulator are compared with the results of the erosion plots. Rainfall simulator output

shows lower splash values for sandstone and claystone than for soils on metamorphic rocks, while on the freshly ploughed plots metamorphic rock and sandstone soils give a high overlandflow erosion output in relation to claystone. We found that particularly the high production of overlandflow on the sandstone and metamorphic plots produced a large overlandflow erosion, whereas in claystone soils the overlandflow production and related erosion is low, due to the formation of large cracks in dry periods.
The output of data from the plots showed that excepting cases with a very high overlandflow production and a low soil erodibility (plot 10 and 11), the amount of material which is transported by splash erosion over a certain unit width of slope length during a given period is relatively large (2 to 4 times) in comparison to the amount of material, transported by overlandflow. In Chapter 4 we have stated that an important part of the sediment is delivered by splash towards the overlandflow. Furthermore we found that on natural slopes the amount of sediment transport by overlandflow is not positively correlated to the slope length. We must conclude that on natural slopes transport by splash is the dominant factor in the water erosion cascade. The amount of sediment transport by water is positively correlated to slope angle but not to the length of slope.

NOTES

1 The F-test is described in Davis (1973) pp. 99-105. If the variances of data of two landunits, tested with the F-test proved to be equal a T-test was used, described in Davis (1973), to test the significance of the differences between the means. In case the variances of data of two landunits are not equal, a T-test developed by Welch (1937) was used.

6

THE SPECIFICATION OF THE MASSMOVEMENT CASCADING SYSTEM

In the next Chapters attention will be paid to the relation of output of the massmovement cascading system to different landscape units. Firstly, a study was made of the landscape variables building up the massmovement cascading system. Mapping criteria will be defined on the base of the study of these variables, and an analysis will be given of these criteria eventually leading to a differentiation in output between the distinguished units.
In this Chapter the effect of landscape variables on the degree of stability (F-value) of a given slope will be considered. In the next Paragraph we will show how a combination of landscape variables determine the type of initial failure and the amount of mass which will be involved in the movement. In the last Paragraph we will discuss the effect of landscape variables on the transport of the moving mass.

6.1 The influence of landscape variables on the degree of stability of soil and rock mass

As we have stated in Chapter 1 the degree of stability is determined by the total shear strength S(kg/m^2) along a given shear surface and the amount of total shear stress T(kg/m^2) developed along this surface:

$$F = \frac{S}{T} \qquad (F \geqslant 1) \tag{1}$$

The mass reaches the state of initial failure when F = 1.
We will first discuss the influence of soil and rock variables on the shear strength and also the shear stresses. In the study of massmovements "rock" defined as a natural aggregate of minerals connected by strong and permanent cohesive forces whereas "soil" is an aggregate of mineral grains that can be separated by such gentle means as agitation in water. Since the terms "strong" and "permanent" are subjective to different interpretations the boundary between soil and rock is necessarily an arbitrary one (Terzaghi & Peck, 1967).
The shear strength of the rock and soil mass is made up of 2 components: the cohesion of the material and the amount of internal friction between grains. The amount of internal friction is expressed by a coefficient of internal friction (φ), which is the ratio between the frictional strength along a certain shear surface and the effective normal stress (σ) on this plane which tends to push the particles together. This ratio is assumed to be constant for a certain soil type in the case that the range of normal stress values is not too wide. The ratio is expressed as tan φ in which φ is called the angle of internal friction of the material. An agglomeration of soil or rock particles has a frictional re-

sistance along a certain shear surface which is built up by a certain plane friction produced where one grain attempts to slide past another and a structural resistance due to the interlocking of the particles. This interlocking effect determines the amount of force necessary for the lifting of one grain over another in order to move (Kézdi 1974). In addition to the frictional strength between grain particles there may be forces which pull the particles together and this source of strength, which is independent of the normal effective stress on a given shear plane is called the cohesion (c). The total strength is given by the most common empirical equation of Coulomb:

$$s = c + \sigma \tan \varphi \tag{2a}$$

in which s = the total shear strength (kg/m^2), c = the cohesion (kg/m^2), σ = the normal stress (kg/m^2) and $\tan \varphi$ = the coefficient of internal friction. The total strength of the material decreases with an increasing pore pressure of water (or air) in the pores. The pore pressure reduces the amount of effective normal stress (σ') on a given shear surface and when a positive pore pressure u(kg/m^2) exists equation (2) can be written as

$$s = c' + (\sigma - u) \tan \varphi' \tag{2b}$$

in which σ = the total normal stress (kg/m^2), u = the pore pressure (kg/m^2) and (σ - u) = the effective stress, also written as σ' and c' the effective cohesion. As far as the rock material is concerned we can state that the cohesive strength of an intact rock mass due to cementing and fusion of the mineral particles, is very important. In many cases the strength of the intact rock mass is not as important as the mechanical structure of the many discontinuities in the rock mass (joints, cleavage-, shear-, and bedding planes, faults fissures, but also dikes, cavaties and contact zones between different rocks). Generally the pattern of these discontinuities, combined with the orientation of the shear surface determines the shear strength of the rock material. (See references given in Yatsu 1966, Carson & Kirkby 1972 and Sowers 1979).
Terzaghi (1962) introduced the term effective cohesion (Ci) in a rock mass which is given by

$$Ci = \frac{(A - Ag)}{A} \tag{3}$$

where Ci = the cohesion of the intact rock, A = the total area of the section through the rock and Ag = the total area of joints and other gaps in the considered section. Due to a severe tectonic activity in the past or an increasing stress within the rock mass, the rock can be fractured in such a degree that it must be considered, according to Terzaghi, as an agglomerate of cohesionless angular rock fragments with a high degree of interlocking and hence a high angle of internal friction. With respect to sedimentary rocks, the alternation in mechanical characteristics must be investigated between layers, the thickness of the different layers, the character of the interface between layers, and the orientation of the bedding planes in relation to the potential shear surface (Sowers 1979). Another important factor is the strength of the weathering products that fill up the joints or the breccious material which fill up the faults (Pitau, 1970). The system of joints and other discontinuities is also of importance to the building up of an excessive pore water pressure, which decreases the shear strength (equation 2b). A system of continuous joints favours a free water flow and prevents the building up of locally excessive water pressure. However, a system of continuous joints also decreases the mechanical strength of the rocks (Terzaghi, 1962). In rocks with soluble minerals, the water in the joints dissolves the material and the widening of the joints leads to a gradual decrease in the shear strength.

An important component of the soil which determines the strength is the content of clay minerals. Between the clay mineral particles there are attractive and repulsive physicochemical forces and the net force determines the amount of cohesion and thus the strength within the soil mass (see a.o. Kézdi 1974). The attractive forces consist of the so-called v.d. Waals' forces which increase as the size of the particles decrease and thus the area of contact between mineral particles (Sowers 1979). The repulsive forces are related to an electric potential which exists between the clay particles. The electric potential is determined by the amount of negative charge of the clay minerals at the contact surface and the amount of water molecules and cat-ions which surround the clay particles. The type of clay minerals and the type and concentration of cat-ions determine the thickness of the film of water absorbed around the clay particles. This waterfilm plays a major role in the development of the cohesive strength of the clayrich soil mass. Sullivan (1939) (in Kézdi 1974) investigated the strength of the soil in relation to the various cat-ions absorbed and he found a decreasing strength in the following order: $NH_4^+ > H^+ > K^+ > Fe^{3+} > Al^{3+} > Mg^{2+} > Ba^{2+} > Ca^{2+} > Na^+ > Li^+$. It is likely that the absorbed layer is of considerable thickness in the case of Li^+ or Na^+ whereas it is very thin in the case of H^+-ions. (Kézdi 1974). The type of clay minerals and cat-ions absorbed also determines the empirical parameters known as the Atterberg limits. These Atterberg limits give indirect qualitative information concerning the strength characteristics of the soil in relation to the soil moisture content. The most common limits are the Plastic limit (Wp) and the Liquid limit (Wl). At moisture contents lower than given by the plastic limit the soil is brittle and will show a given finite strain deformation (ϵ) at a given applied stress (τ) and will finally fail at a given shear stress τo (see Figure 6.1).

The soil has a viscous component at a water content between these two limits. At a certain applied shear stress τ (kg/m^2) (called the yield stress, see Figure 6.1b), which is lower than τo the soil begins to deform continuously and the velocity of deformation $\dot{\epsilon}^1$. (= strain rate) depends on the applied stress. When the soil has reached the liquid limit the soil has no strength and is in a completely viscous state. It starts to deform under any applied stress (Figure 6.1a). The difference between the Liquid limit and the Plastic limit is called the Plasticity index (Ip). The Plasticity index represents the range in water content in which the soil has a plastic character with a certain yield stress. According to Kézdi (1974) it is a measure for the cohesiveness of the soil: the greater the Plasticity index the higher, generally, the attraction between particles of the soil. At

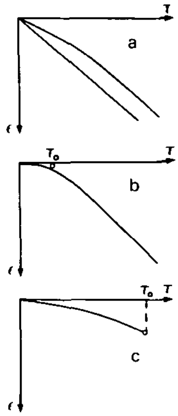


Figure 6.1 Stress-strain relationships at different moisture contents (m) of the soil. a): $m > W_l$; b): $W_p < m < W_l$; c): $m < W_p$ (after Kezdi 1974).

this point we must state that the Atterberg limits only give a rough indication towards the stress-strain characteristics of the soil and that they are used to classify soils with a wide range of properties (Terzaghi & Peck 1967). Apart from the effect of clay minerals and the absorbed cat-ions and water content on the strength (cohesion), we must consider the effect of the coarser particles on especially the internal friction of the soil. In general the frictional resistance between the grain particles is determined by the following soil variables (Lambe & Whitman 1969):

- The bulk density or porosity of the soil which is related to the degree of interlocking of the particles (see above). Therefore a higher bulk density has a higher degree of interlocking and by a given normall stress a higher strength.
- By a given porosity the frictional angle decreases by an increasing average particle size (varying from 16 - 0.6 mm). This is explained by the greater degree of grain crushing and fracturing that occur with larger particles due to the greater force per contact. The crushing of the grains reduces the strength.
- The grading of the particles: soils with the same smallest particle size (e.g. 0.5 mm) but different maximum sizes (6-50 mm) show by comparable compactive efforts a smaller initial void ratio and hence a larger friction angle. It is apparent that a wider distribution of particle sizes produces a higher degree of interlocking.
  Experimental work carried out by Stathem (1977) shows that soil samples consisting of a mixture of 2 grain size distributions (coarse/fine size mixtures) have a peak strength corresponding to a coarse fabric, with its pore spaces completely filled with the finer grain size material.
- As would be expected, the angularity of the grains is also of importance because angular particles interlock more thoroughly than rounded particles.

- The type of minerals seems to be of minor importance excepting micas which generally show a low degree of interlocking.
  As far as gravelly material is concerned the hardness of the gravel may influence frictional angle.

Sofar we have discussed the influence of rock and soil variables on the shear strength of the material. We have mentioned the effect of the pore water pressure on the effective normal stress and hence the strength along a given shear surface. The pore pressure is determined e.g. by the height of the groundwater in the soil or rock mass. Apart from the input by rain, the height of the ground water level reached in the soil or rock at a given time is determined e.g. by the infiltration capacity, the hydrological conductivity and the presence of more impermeable layers in the sub-surface.
Apart from the shear strength, we must consider the shear stresses within the soil mass in order to determine the state of equilibrium (F-value) for a given plane within the soil mass. The shear stresses working at a given plane generally depend on the bulk weight of a unit volume of soil or rock mass (including the water content within the mass).
The vegetation variables influence the stability (F-factor) of the cascading system in two ways:
- The density and structure of the roots influence the strength of the soil (Eyles 1971, Carson & Kirkby 1972).
- The vegetation is an important regulator in the hydrological cascade (see Chapter 3) and therefore influences the ground water level and hence the maximum pore pressure values in the soil via the process of evapotranspiration. The vegetation also has an influence upon the infiltration capacity of the soil and hence regulates the supply of water to the sub-soil (Eyles 1971, Crozier 1969, Pain 1971).

The topographical variables influence the amount of shear stress developed along a potential shear surface. An increase in slope angle and height of the slope generally increases the shear stress and therefore decreases the F-value. The form of the slope is also of importance, e.g. profile concavity and contour concavity lead to a concentration of waterflow and hence an increase of the pore pressure.
Apart from the landscape variables we discussed above, there are process variables which can increase or decrease the F-value in the course of time.

In Chapter 1 we have mentioned the erosion system of the rivers (or sea) which leads to an undercutting and steepening of the slope, thus increasing the shear stresses in the soil or rock mass. After a long period the weathering system leads to a weakening of the rocks along the discontinuities and also a change in the grain size distribution in the soil and a decreasing in the strength. Man can influence the landscape variables in many ways by changing the topography of the slope, loading of the slope due to artificial construction and by changing the hydrology of the slope. Furthermore, traffic induces transitory stresses (Eckel 1958) in the ground and this increases the shear stresses and sometimes decreases the shear strength of the soil. These transitory stresses are also induced by earthquakes which often function as a trigger for many land slides.

6.2 The influence of landscape variables on the type of initial failure of landslides

We discussed the influence of landscape variables on the stability regulator in the massmovement cascading system. We will now discuss how different landscape variables determine the initial type of failure and the amount of soil or rock mass which is involved in the movement. Further, we will discuss the landscape variables in relation to the transport of the material. The type of failure and transport of a soil or rock mass is characteristic for a certain landslide type. Various criteria have been used to classify massmovement phenomena: parent material: Yatsu (1967) Zaruba and Meckl (1969); the mechanics and cause of failure: Terzaghi (1960); slope and landslide geometry; Ward (1945), Skempton (1953), Crozier (1973), and the most well known classification using different criteria (type of material, shape of failure surface, mechanism of movement, soil moisture content and velocity of the movement): Sharpe (1938), Varnes (1958). The complex and variable classification method of Varnes (1958) is generally accepted, but particular movements do not always fit into the distinguished categories. Due to a great variation in landscape variables: geology, climate, hydrology, slope geometry and vegetation, there is an infinite variety of massmovement forms and a rigorous classification may never be possible or desirable (Brunsden 1979).
In this study we will use the following classification characteristics of the land slides (see also next Chapter): 1. The mechanism of movement at failure, 2. the amount of mass involved at failure, 3. the mechanism and velocity of movement at the further transport of the mass, 4. the travelling distance of the transported material.
The study of the great variety of land slides reveals that, with regard to the mechanism of movement, there are 4 main types: falls, slides, flows, and heaves (Sharpe 1938, Varnes 1958, Carson & Kirkby 1972). Falls involve the free movement of material away from a steep slope mainly through the air. Sliding is the movement of a soil or rock mass along a well defined thin surface. The mass above the slide surface moves as a block with no internal shear. When the mass is flowing there is no sharply defined failure surface, but on the contrary the shear is distributed throughout the moving mass. In case of heave the soil expands perpendicularly to the surface and subsequently contracts.

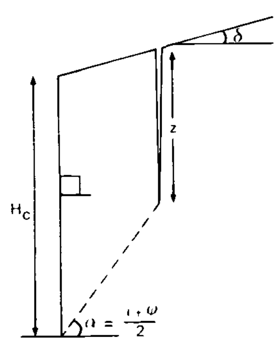


Figure 6.2 Stability of a cliff and the influence of tension cracks (after Carson, 1971).

In some slow massmovement processes the latter motion is the basic mechanism, particularly seasonal creep. We will not deal with this latter type of massmovement in this study but will refer to a seperate publication.
In case of *very steep slopes* (70-90°) which occur in *rocks and cohesive soils* (clay, clay-rich and silty material e.g. loess) *rockslides* develop when the height of the cliff or very steep slope has reached a critical value. Theoretically, under these conditions a more or less straight sliding surface develops which passes through the toe of the slope with an angle (see Figure 6.2).

$$a = \frac{i + \varphi}{2} \quad (4)$$

Tension cracks may develop parallel to the free rock or soil face, due to the release of lateral pressure of the free face (Terzaghi 1943 in: Carson 1971). Based on the Culmann approach for limiting equilibrium, the critical height for an intact rock or soil mass with a vertical slope ($i = 90°$) is:

$$H_c = \frac{4c}{\gamma} \tan (45° + ½\varphi) \quad (5)$$

in which H_c = the critical height of the cliff or steep slope, c = the cohesion of the material, γ = the bulk unit weight of the rock or soil mass and φ = the angle of internal friction. In this rock cliff tension cracks can develop at a depth z and the critical height becomes: (Carson 1971)

$$H_c = \frac{4c}{\gamma} \tan (45° + ½\varphi) - z \quad (6)$$

Theoretically z can reach a maximum depth z_o which is given by: (Carson 1971)

$$z_o = \frac{2c}{\gamma} \tan (45° + ½\varphi) \quad (7)$$

If we substitute equation (7) for equation (6) we obtain at a maximum development of the cracks

$$H_c = \frac{2c}{\gamma} \tan (45° + ½\varphi) \text{ or:} \quad (8a)$$

$$H_c = \frac{qu}{\gamma} \quad (8b)$$

in which qu = the unconfined compression strength of the soil or rock material (see Carson 1971).

In the foregoing Paragraph we discussed the effect of rock and soil variables on cohesion and internal friction and from the model which is presented here, we can conclude that an increase in c and (or) φ leads to an increase in the critical height H_c according to equation (8) and hence the stability of a certain cliff with height H. An increase in φ leads to an increase of the slip plane angle (a) (equation (4), see Figure 6.2) which means a relative decrease of the total volume of failing mass. However, if equation (4) and (8) are used, it follows from Figure 6.2 that an increase of the critical height (H_c), due to increasing c and (or) φ leads to an absolute increase of the totale volume of mass at failure.
The theoretical discussion given above was confirmed by the work of Lohnes & Hardy (1968) who investigated the critical height of cliffs which were developed in loess. In general, the type of failure which occurs when the threshold of instability is reached, can be described as a rock or soil slide along a more or less straight failure plane. Carson & Kirkby (1972) described this type of failure as "slab" failure in case that the blocks or slabs subside or "sag" down due to the weakening at the base of the slope by e.g. a large water concentration. Furthermore "toppling" failure can take place in cases where the rock plate is thin in relation to the height or length of the slope (Brunsden 1979).
A number of other processes or variables leads to an increase in instability of the equilibrium system described above (see e.g. Koons 1955, Schumm & Chorley 1964, Bjerrum & Jørstad 1968, Hutchinson 1968): a) undercutting by the slope, due to river erosion, b) weathering along cracks and joints (6.1), c) frost action widening and extending the joints and cracks, d) changing of the water pressure built up in the joints, widening the joints and pressing the slab outwards or diminishing the strength along the potential failure plane.
In case of a *well developed system* of highly ordered *discontinuities in the rock*, which are inclined towards the exposed free face (see Figure 6.3) so called *plane failure* can develop and this can be considered as a type of rock slide (Brunsden 1973). The stability of these systems depends, according to Coulomb's law, on the cohesion (c) and the coefficient of internal friction (φ) along these discontinuities, the normal stress on these planes and the pore water pressure. When there is a system of discontinuities with a constant cohesion and coefficient of internal friction we can use the stability model developed by Culmann (in Carson 1971, pp. 100-102), in this case along a predisposed

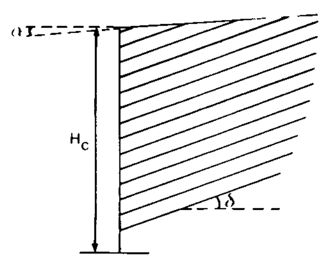


Figure 6.3 Stability of a cliff with bedding planes towards the free face.

shear plane with an angle α (see Figure 6.3). The critical height of the slab at dry conditions is than given by

$$H_c = \frac{2c}{\gamma} \frac{1}{\cos\alpha\,(\sin\alpha - \cos\alpha\tan\varphi)} \qquad (9)$$

It will become clear from equation (9) that H_c and hence the degree of stability of a cliff with height H increases with increasing c and φ and decreases with increasing γ and α. We can conclude from Figure 6.3 and equation (9) that the amount of mass which is involved in the movement at the threshold of failure increases with c and φ and decreases with γ. Calculations with equation (9) in Figure 6.3 will also show than an increase in the bedding plane angle α leads to a decrease in volume of moving mass at the point of failure.
Apart from the major pattern of discontinuities in soil and rock masses, described above, we must consider the fact that also a micro pattern of joints and cracks has developed, particularly in rock masses which is superimposed on this large network. Terzaghi (1962) points to the fact that the discontinuities on a small scale in the rock reduces the strength of the rock and therefore the critical height of the steep slopes and cliffs. Along the pre-existing planes the cohesive strength is considerably reduced and hence the strength along a potential slip surface is made up of the plane friction along the joints and the cohesion in the intact rock fragments. When the slope increases in height more shear stress is concentrated on the intact rock particles and this leads to more fracturing of the rock and a decrease of the strength. In an ultimate state the rock can be considered as a densely packed aggregate of cohesionless coarse rock fragments with an angle of internal friction of 70° and under these cohesionless dry conditions the slope angle can not surpass the critical angle of 70° (Carson 1971).
These *micro-patterns of discontinuities* within the rock mass also leads to a type of rock failure on a much smaller scale in comparison to the above described types. Small blocks or rock fragments can fall from the cliff face, sometimes separately and sometimes in large numbers, but always from a local part of the free face. The failure process is confined to a layer immediately behind the cliff and eventually leads to a parallel stripping of the rock surface. A number of process systems leads to the extension and enlargement of the cracks and the final failure of the rock fragments. According to several investigators (a.o. Rapp 1960, Terzaghi 1962, Hutchinson 1967, Bjerrum & Jørstad 1968). The following process systems are of importance: a) the freezing and thawing of water which seeps into cracks, b) the creation of positive pore water pressure and c) the extension of plant roots. A granular disintegration of the free rock face particularly in weakly consolidated rocks, occur due to the destruction of the cemented bonds by solution, frost action and even raindrop impact (Carson & Kirkby 1972).
We will now discuss the type of initial failure which occurs on *less steeper slopes* with variable slope angles (< 70°) in *rock material*. Under these conditions the initial movement of these rock masses depends on the development or presence of *large joints and bedding planes* which dip in the same direction of the slope angle (a.o. Terzaghi 1962, Müller 1964). These conditions lead to a common type of failure along these discontinuities which is called *rock slide* or more specified: *planar translational rock slides.*

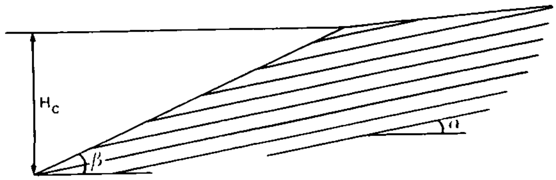


Figure 6.4 Stability of a rock slope with bedding planes towards the free face (α<β).

In case that the angle α of the joints or strata is lower than the slope angle β (Figure 6.4) and using the Culmann method with a predisposed shear surface, we arrive at the following expression for H_C: (see Carson 1971, p. 100).

$$H_C = \frac{2c}{\gamma} \frac{\sin\beta}{\sin(\beta-\alpha)(\sin\alpha - \cos\alpha \tan \varphi)} \tag{10}$$

In this case H_C, thus the stability and also the amount of failure mass decreases with an increasing slope angle β and increases with the cohesion (c) and the angle of internal friction (φ). Calculations will show that by an increasing angle of the bedding planes (α) the total volume of moving mass at failure decreases.
In case that the bedding plane angle is larger than the general slope angle, failure can only take place if a cliff has developed (due to undercutting at the foot of the slope (see Figure 6.5). In this case equilibrium conditions are the same as those given by equation (9) (Figure 6.3).

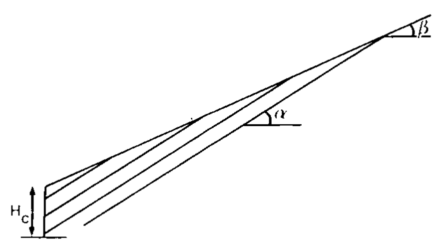


Figure 6.5 Stability of a rock slope with bedding planes towards the free face (α>β).

As was stated above the amount of mass at failure is positively correlated with the c and φ-value and negatively with γ. The slope angle δ is not of importance (see Carson 1971, p. 101). The strength along the potential failure plane and hence the amount of mass involved at failure is decreased by the development of a positive pore pressure. The weakening of the strength along these discontinuities by weathering and solution has already been discussed. Brunsden (1979) stated that especially solution in calcareous material is the cause of many rockslides. In all types of *cohesive materials* (rocks and soils) generally *deep seated failures* may occur depending on the length and steepness of the slope and the strength of the material involved.

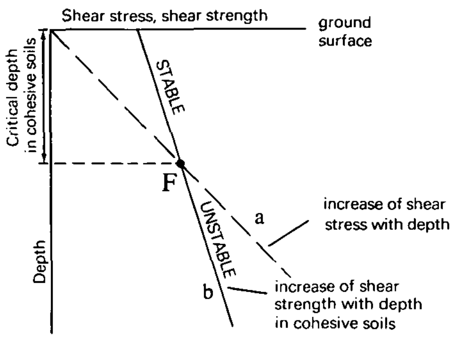


Figure 6.6 Increase of shear strength and shear stress with depth beneath a slope in cohesive material (after Carson & Kirkby, 1971).

The development of deep seated slides (deep in relation to the length) is explained by the fact that by a given slope angle the cohesive soils always have a certain strength at the surface, while the shear stress at the surface is zero. If the increase of shear strength of the material with depth (line a Figure 6.6) is less than the increase in shear stress with depth (line b Figure 6.6) – which is mostly the case – failure always takes place at a certain depth (F), where the shear stress values equal the shear strength values (see Figure 6.6) (Carson & Kirkby 1972).
The slip surfaces of these deep seated slope failures have a more or less circular form which is explained by a.o. Lambe & Whitman (1969), Carson & Kirkby (1972). All points in the sliding block make a more or less rotational movement and therefore this type of movement is called *rotational slide or slump* (see Figure 6.7). Three types of failure may occur in these cohesive materials: a) base failure b) toe faillure c) slope failure (Terzaghi & Peck 1967, Sowers 1979, see Figure 6.7). Here we will consider deep

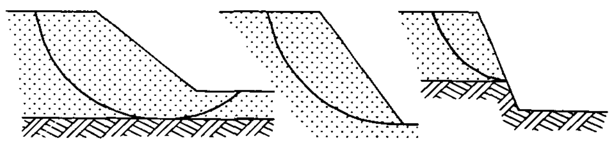


Figure 6.7 Three types of slumping: a) base failure; b) toe failure; c) face failure. Cross sections aproximated by circular arcs. (after Sowers, 1970).

scated failure under drained conditions in material which has an appreciable angle of internal friction (φ) and cohesion (c). In this material toe failure usually occurs whereas in the presence of harder rocks slope failure may occur (Terzaghi & Peck 1967, Sowers 1979, see Figure 6.7). Base failure may occur under certain conditions in very soft homogeneous clay ($\varphi < 3°$) or clay under undrained conditions ($\varphi = 0°$) (Terzaghi & Peck 1967, Sowers 1979). The critical height (see Figure 6.7) for the much stronger clays under drained conditions is given by

$$H_c = Ns \frac{c}{\gamma} \tag{11}$$

in which N_S = the stability factor (dimensionless), H_C = the critical height of the slope (see Figure 6.7), c = the cohesion and γ = the bulk unit weight of the soil mass. Taylor (1937) calculated the values of Ns for different slope angle (β) and friction angle (φ) of the material. The calculations were based on a model for limited equilibrium condition of rotational slides with a circular slip surface. Figure 6.8 gives a stability chart which was developed by Taylor (1937) and based on his equilibrium model of circular friction. In this diagram Ns can be read by a given slope angle β and the friction angle φ. If the cohesion is also known, the critical height of the slope can also be calculated. Ns values were also calculated with other equilibrium models of Culmann and Fellenius (in Taylor 1937). The stability chart given in Figure 6.8 shows that H_C and therefore the degree of stability for a slope with a given height H increases with c and φ and decreases with increasing

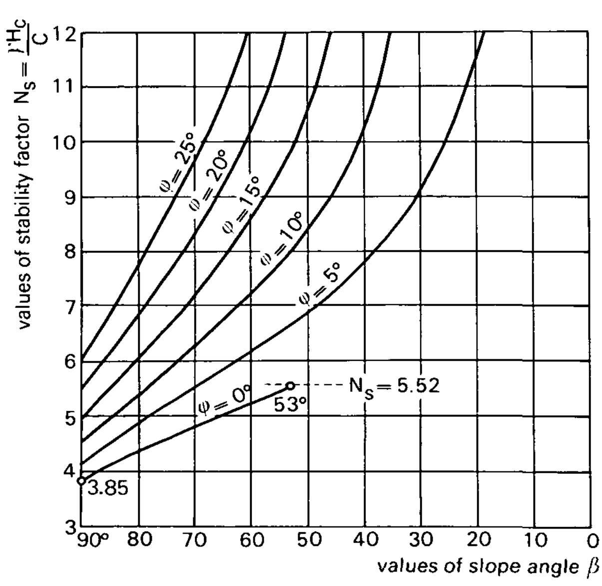


Figure 6.8 Relation between slope angle and the stability factor Ns for various values of φ (after Taylor, 1937).

slope angle β and γ. Bishop & Morgenstern (1960) have expanded the stability diagrams of Taylor to accomodate various pore pressure conditions.

For the purpose of our study we are interested in the question how the cohesion (c) and internal friction φ of the material, the pore pressure u and the slope angle β influence the amount of mass production for these rotational slides. The mathematical relationship between these values and the amount of mass production can be determined by using different equilibrium models which can also be used for heterogeneous soil masses, different hydrological and more complex topographical conditions. The circular arc-method of Petterson (in: Sowers 1979), the method of slices developed by Fellenius (1936), Bishop (1955), Janbu (1956) and the friction circle method developed by Taylor (1937) are worth mentioning (Terzaghi & Peck 1967, Lambe & Whitman 1969). Since no diagram charts, expressing such mathematical relationships are available, we will try to explain the general relation which exists between these variables and the output of mass. We will use the general relationship between shear strength and shear stress with depth given in Figure 6.6, the stability chart given in Figure 6.8 and the equilibrium equation given by Fellenius for homogeneous soils. The assumptions for the use of this model are given by Lambe & Whitman (1969, p. 364). The equation is given by:

$$F = \frac{c'L + \sum_{i=1}^{i=n} (W_i \cos \alpha_i - U_i) \tan\varphi}{\sum_{i=1}^{i=n} W_i \sin \alpha_i} \qquad (12)$$

in which F = stability factor (dimensionless), c' = cohesion in kg/m^{-2} along the slip surface, L = length of slip circle in m, W_i = the weight of slice in kg., α_i = slip surface angle of slice in degrees, U_i = pore pressure on slip surface in kg of slice i, φ = angle of internal friction in degrees (see also Figure 6.9). This equation is widely used for stability problems because of its simplicity and the fact that the calculations are feasible. For the exact calculation of the safety factor it will give errors from 10%-60% (on the safe side) (Lambe & Whitman 1969). This sample equation is, however, appropriate for the demonstration of the general correlation between soil mechanical parameters and the amount of moving material.

Figure 6.8 shows that an increase in c and φ means an increase in the critical height of the slope and thus the length of the sliding mass. It can be inferred from Figure 6.6 that an increase in φ- and c-values means an increase of the depth of the potential slip surface and therefore of the slice W_i depicted in Figure 6.9. We may therefore conclude that at increasing c- and φ-values the potential slip surface develop at a greater depth which means, when the point of instability is reached there is a larger amount of mass production. The depth of the material in which the sliding is assumed to take place forms a threshold value under these conditions: if the calculated potential slip circle passes to an underlying stronger rock mass, theoretically no failure can take place.

An increasing pore pressure u results in a decrease $(\sigma-\mu)$ tang φ (see equation (3) and this has the same effect as a decrease in the φ-value. Figure 6.9 depicts two rotational slides with different slope angles $\beta 1$ and $\beta 2$. Figure 6.9a gives the slip surface at limiting equilibrium conditions. The stability chart (Figure 6.8) shows that a decrease in the slope angle β leads to an increase in the critical height (H_{c2}) and hence the length of the slide (Figure 6.9b). If we assume that the amount of mass which fails remains the same, the length (L) of the slip surface (1 in Figure 6.9b) increases while the angle of the slip-surface (i) of most slices is decreased. According to equation (12) the stability factor (F) in this case must increase ($F > 1$), which means that we do not have the potential slip surface. In this equilibrium model a trial and error method will show that the point of limited equilibrium ($F=1$) is reached again, if we construct a slip circle at a greater depth (circle 2). Therefore a decrease in β means an increase in length and volume of the rotational slide.

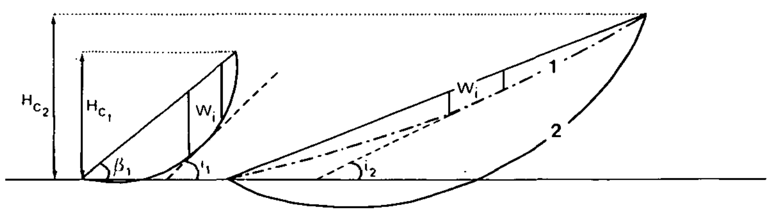


Figure 6.9 The stability of a slump in relation to slope angle.

It becomes obvious (Figure 6.8) that β forms a threshold determining whether sliding can take place or not. The depth of the material also determines whether the potential slip circle can develop up to a certain depth and therefore forms a second threshold. The above described correlationships between the landscape variables and production of sliding mass will be proved below with the equilibrium equations for a sliding mass along a plane surface which can be considered as a special type of the rotational slide (Carson 1971).

By a given critical height and slope angle a rotational slip (called slump) may develop along a curved surface which may be approached by a circle arc or logarithmic spiral. In reality the slip surface can be deformed due to the presence of faults, joints or weaker layers. The depth-length ratio generally varies from 0.15-0.33 (Brunsden 1979). Figure 6.10 gives the most characteristics features of a slump. Note the main scarp which is more or less concave, steep to vertical and bare; the head area with more gentle slopes or reserved slopes creating depressions which can collect water, transverse cracks and minor scarps. The trees lean uphill. Downslope, transverse cracks or minor scarps can be formed due to irregularities in the slip surface or slope topography. In the foot area pressure ridges and cracks develop; it is a zone of uplift with trees leaning downhill. The toe has often become a zone of flow with a lobate form with radial cracks due to a

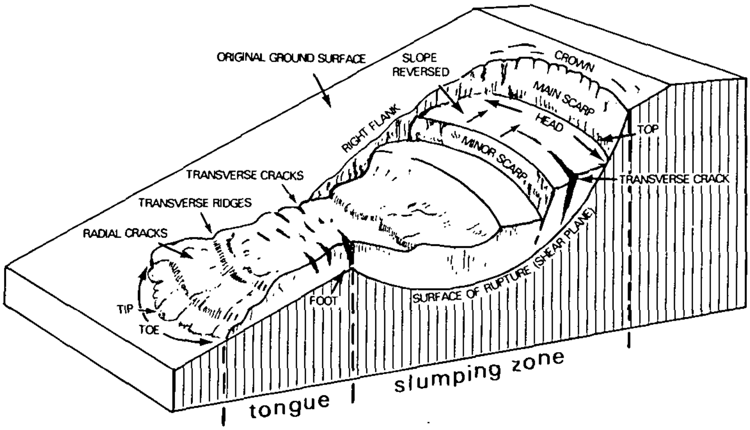


Figure 6.10 Features of a rotational slide (slump) (after Varnes 1958)

lateral spread and transverse ridges resulting from a pushing of the upperpart of the slide (Ritchie 1958).

Slump failure is very common as an initial failure type in all sorts of cohesive material (see a.o. Hutchinson 1968, Brunsden 1979).

If the movement of the slumped block continues and the material is totally transported out of the sliding area a steep unsupported scarp remains, leading in many cases to new slumping. In this case multiple rotational slumping occurs as a retrogressive serie of

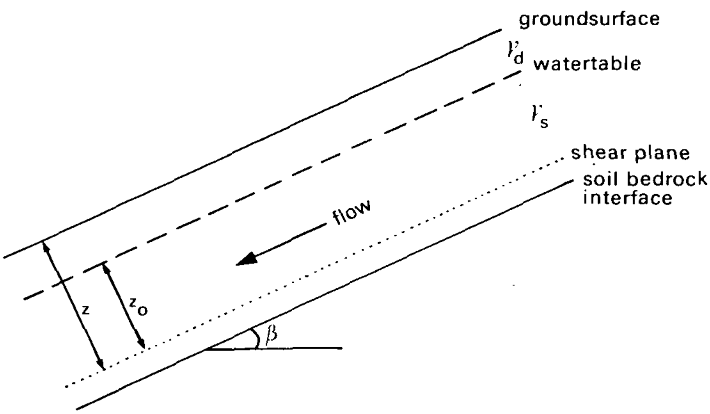


Figure 6.11 The stability of a translational slide. γ_d: bulk unit weight of unsaturated zone in kg m^{-3}; γ_s: bulk unit weight of water in kg m^{-3}; φ: angle of friction in degrees; z: thickness of regolith above shear plane in m; z_0: height of groundwater above shear plane in m; β: slope angle in degrees

failures (see a.o. Hutchinson 1969, Brunsden & Jones 1974). Hutchinson (1967) described small shallow successive rotational slips, on steep slopes in fissured clays. These fissures form a regular or irregular pattern of stepped terraces or mosaics of small benches on the slope. Rouse (1975) suggested that the complex of these shallow rotational slips may be considered as a shallow tranlational slide, which also develop in more frictional material (see below).

Slope failure can also occur under the most common natural conditions where a *relatively thin weak regolith* cover is *lying upon stronger rock material*. In most climatic zones the regolith cover is usually thin (1-2 mtr.) and in case of instability failure takes place along a flat surface parallel to the slope. They are called *translational slides* because the points in the sliding mass are moving parallel to each other in a more or less straight line. Assuming that 1, the length of slope can be considered as infinite, compared with the depth of regolith, 2. the regolith is homogeneous with depth and slope length, 3. the slip surface is plane and runs approximately parallel to the ground surface and 4. the groundwater in the regolith is flowing parallel to the surface at a depth z_o (see Figure 6.11), the stability conditions can be given by the following equation: (Lambe & Whitman (1969), Van Asch (in prep.).

$$F = \frac{\frac{c}{z\cos^2\beta} + \left\{\gamma_d - m(\gamma_d - \gamma_s + \gamma_w)\right\}\tan\varphi}{\left\{\gamma_d - m(\gamma_d - \gamma_s)\right\}\tan\beta} \qquad (13)$$

(For notation see Figure 6.11).

Under these boundary conditions and for a cohesionless regolith (c = 0) without groundwater (m = 0) at the threshold of failure (F = 1) equation (13) reduces to the simple form:

$$\tan\beta_{crit} = \tan\varphi \qquad (14a)$$

If the groundwater level reaches the surface (m = 1) the critical slope angle (β_{crit}) for a cohesionless regolith reduces to:

$$\mathrm{tg}\,\beta_{crit} = \frac{\gamma_s - \gamma_w}{\gamma_s}\tan\varphi \qquad (14b)$$

which approximates for most regoliths to $\mathrm{tg}\varphi_{crit} \approx \frac{1}{2}\tan\varphi$ since $\gamma_s \approx 2\gamma_w$ for many natural soils (Carson 1971). We will point to the fact that for cohesionless regoliths the depth of the slide is undetermined, which means that at the point of failure sliding takes place at every depth in the regolith. In this case the amount of moving mass always depends on the maximum thickness of the regolith. At the threshold of failure (F = 1) equation (13) can be written in the following form:

$$\frac{c}{z} = \cos^2\beta\,(N \tan\beta - M \tan\varphi) \qquad (15)$$

in which $M = \gamma_d - m(\gamma_d - \gamma_s + \gamma_w)$ and (15a)

$$N = \gamma_d - m(\gamma_d - \gamma_s) \qquad (15b)$$

Equation (15) must be seen as an equilibrium equation for this type of landslide with varying hydrological conditions, slope angle β and c- and φ- values of the material, at the point of failure (F = 1). We can conclude from this equation (15) that:

- A solution for the depth of sliding (z) is only possible if $N \tan\beta > M \tan\varphi$. Therefore if $N \tan\beta < M \tan\varphi$ there exists always stability conditions on the slopes.
- The calculated value of the depth of sliding (z) for failure must be smaller than the thickness of the regolith cover, otherwise the potential slipsurface lies under the regolith cover in the hard rock. In this case no failure takes place.
- It follows from the two conclusions above that the slope angle β and the thickness of the regolith can be considered as threshold for failure.
- If M and N are constant (constant unit weight and hydrological conditions see equation (13) the depth of sliding (and thus the amount of mass production) increases with increasing c- and φ-values and decreases with increasing slope angle β (see equation (15). This was also stated for the rotational landslides.
- If by a rise of the groundwater level the pore pressure increases (m increases in equation (13) M and N decrease in equation (15). A comparison of equation (15a) and (15b) shows that M decreases more than N and this means, in equation (15), that at the point of failure (F = 1) z must decrease. In other words: at higher pore pressure conditions failure take place at a lower depth in cohesive regolith, which have a certain depth.

In the field these shallow translational slides (also called shallow debris slides or soilslips) can be recognized by narrow long tracks along the slopes in which parts of the regolith mantle are slipped away. They are concentrated on places where there is an active undercutting by a river and a concentration of groundwater leading to a maximum level of the groundwater in the regolith: e.g. in the valley heads. As can be seen from equation (13) a rising of the groundwater level (m) leads to a decrease in the F-value and the possibility of sliding increases. In general a groundwater subsurface flow is possible due to impermeable soil horizons or bedrocks (Carson & Petley 1970) or even a permafrost boundary (Chandler 1970). Shallow slides have also been found in deep stiff fissured clays (Henkel & Skempton 1955, Skempton & De Lory 1957, Hutchinson 1967). According to these investigators the shallow slides occur in these thick clay layers due to the formation of cracks in the upper layer, thus reducing the strength and especially the cohesion of the clay (Skempton, 1964).

Table 6.1 A summary of limited equilibrium conditions for different type of landslides.

Natural conditions	Type of failure	Equilibrium equation at failure (F = 1)	Type of transport
Cliffs (90°) in rocks and cohisive soils	rockslides (slab failure)	$Hc = \frac{2c}{\gamma_d} \tan (45° + \frac{1}{2} \varphi)$	debris flows rockfalls
Cliffs (90°) in rocks and cohesive soils with joint- or beddingplanes exposed towards the free face	rockslides (plane failure) (wedge failure)	$H_c = \frac{2c}{\gamma_d} \frac{1}{\cos \alpha (\sin \alpha - \cos \alpha \tan \varphi)}$	debris flows rockfalls
Slopes in rocks with beddingplanes dipping towards the slope	rockslides (plane failure)	$H_s = \frac{2c}{\gamma_d} \frac{\sin \beta^c}{\sin (\beta_c - \alpha)(\sin\alpha - \cos \alpha \tan \varphi)}$ $(\alpha < \beta_c)$	debris slides debris flows
		$H_c = \frac{2c}{\gamma_d} \frac{1}{\cos \alpha (\sin \alpha - \cos \alpha \tan \varphi)}$ $(\alpha > \beta_c)$	
Slopes in cohesive soils	rotational slides	$\sum_{i=1}^{i=n} W_i \sin \alpha_i = c'L + \sum_{i=1}^{i=n} (W_i \cos \alpha_i - U_i) \tan \varphi$	debris flows mudflows or mudslides
		$H_s = N_s \frac{c}{\gamma_d}$	
Slopes with thin soil (regolith) cover	translational slides	$\tan \beta_c = \frac{\frac{c}{z\cos^2\beta_c} + \left\{ \gamma_d - m(\gamma_d - \gamma_s + \gamma_w) \right\} \tan \varphi}{\left\{ \gamma_d - m(\gamma_d - \gamma_s) \right\}}$	debris flows mudflows

H_c: critical height of cliff in m. H_s: critical height of slope in m, c: cohesion in kg m^{-2}, φ: angle of internal friction in degrees, γ_d: dry bulkdensity in kg m^{-3}, γ_s: wet bulkdensity in kg m^{-3}, γ_w:unit weight of water in kg m^{-3}, α: angle of bedding plane or slip plane in degrees, β_c: critical slope angle in degrees, W_i weight of slice i in kg, U_i: pore pressure on slip plane of slice i in kg, α_i: angle of slip plane of slice i in degrees, N_s: stability factor, z: depth of regolith cover in m, m: ratio between depth of groundwater and depth of regolith.

In the foregoing we have discussed the influence of soil and rock variables and topographical variables on the initial state of equilibrium and the amount of mass which is involved at sliding for different types. Table 6.1 summarizes the equilibrium equations for the different landslide types discussed above. We can deduce from the equations that for all the types an increase in c- and φ-value leads to an increase of stability. Since the pore pressure (u) in all these equations are related to tan φ (according to Coulomb's equation), an increase in pore pressure always leads to a decrease in strength and therefore the stability of the system. The equation will also show that an increasing slope angle and bulkdensity decreases the stability of the system. In other words in an area with variable slope angles and different materials, the chance or frequency of landsliding must increase with increasing slope angles and decrease with increasing strength values of the material. In cohesive materials the depth of the material in which potential sliding takes place is an important threshold (see e.g.: equation (13).
At the threshold of failure the F-value is 1 or the height of the slope is critical (H_C). We can deduce from the discussions given above and the equations summarized in Table 6.1 that at the point of failure the amount of sliding mass is determined by various variables. Steeper slope angles and a rising bulkdensity at failure lead to a decrease of sliding mass, whereas higher c- and φ-values at failure lead to an increase in sliding mass. Since (u) is related to (φ) (see above) we can also conclude that rising pore pressure lowers the value (σ-u) tan φ and therefore leads to a decrease of mass at failure. The depth of weathered regoliths determines the maximum depth at which sliding can take place and it is therefore also a variable which determines the potential maximum amount of mass production at failure.

6.3 The influence of landscape variables on the type of transport of landslides

In this Paragraph the influence of landscape variables on the transport of the material after failure has taken place, will be discussed. In the massmovement cascading system the distance and velocity of transport of the moving material are subjects of particular interest. We have already stated that the type of initial failure may influence the further transportation of the material and therefore the main type of transport in relation to different types of initial failure will be discussed here.
First the mobilisation of debris after the initial failure of a rock mass (rock slides) will be discussed. Heim (1936) found from empirical evidence that the travelling distance of a slab along the slope depends on the initial height of fall, the irregularity of the terrain and the size (volume) of the slide. During the movement the rock slab can be fractured along the sliding path in a mass of loose debris which, due to a change in physical characteristics, increases the mobility of the mass. The data collected by Brunsden (1979) from different authors reveal that the material travels many kilometers beyond the point that might be expected of a rigid mass sliding down an inclined plane. During movement of the fractured rock material air may be trapped. The effective stress between particles suddenly decreases, resulting in a high fluidity of the material and catastrophic rapid flows (Kent 1966). Shreve (1968) hypothised that a cushion of air is

trapped at the base of the flow thus forming a near frictionless surface for the moving mass, which in this case behaves as sliding blocks with a slip surface at the base. Hsü (1975) proposed that the frictional resistance is reduced by the boyunt effect of dust suspensions acting as a fluid medium between the "floating" blocks.
The velocity of the above *debris flow (or slide)*-transport process is very fast, i.e. 150-300 km/hour (Brunsden 1979). These flows have the features of a lavaflow or glacier in planform, sometimes with a wide lobe as it extends over a wide flat riverplain. The flow may sometimes run up the opposite valley side (see Brunsden 1979 pp. 156-157). The longitudinal profile slopes gently. A trough can be found between the head and scar and the surface of the flow shows a humockly topography with ponds and enclosed depressions, transverse ridges and longitudinal ridges. The material is very heterogeneous, with a tendency towards a concentration of coarser material on the surface. In the flow large blocks up to several meters can be transported. In thick soil and regolith of variable grainsizes shallow slides and also rotational slides can develop (see above). If failure takes place under the influence of a high water table and high pore water pressure and if the material disintegrates after initial failure, the moving material changes into a rapid viscous flow. These flows are described *as debrisflow, debris avalanche, mudflow* or *mud-avalanche* or *flowslide* (a.o. Rapp 1960, Johnson & Rahn 1970, Prior et al. 1970, Bishop 1973 and Blong 1973). The travelling distance may be related to the slope angle and the thickness of the mass, (Curly 1966, Sulebak 1969, Cambel 1974) which determine the amount of shear stress. The water content of the material (varying from 15-40%) determines the viscosity and the topography within the track pass.

The flows, which may reach velocities from 1-14 mtr/sec. generally have a relatively large length-depth ratio varying from 9-270 (Brunsden 1979). The track of the flow may be widened downslope after the break up of the initial sliding material. Along the sides levees can be formed. These are characteristic for rapid and very wet flows. They show circular heads and in the toe area single or multiple lobes. Initial failure can take place by shallow slides and slope angles varying from 25-20°, while flow transport occurs on angles varying from 10-15° (Statham 1977).
Initial failure of soil material can also be followed by a much slower transportation of sliding material in the form of either flow or sliding movements. The initial rotated mass particularly in clay rich material can be broken and can assemble large quantities of water which give the clay a more viscous component with lower yield strength (see 6.1). When the topographical situation is appropriate the material can be further transported over a long distance, by means of flowing or sliding processes (Hutchinson 1970, Prior & Stephens 1972). The detailed investigations of Hutchinson & Bhandari (1971) show that mechanism of transport may be explained by the effect of the rapid loading of material falling from upslope at the flow which creates undrained pore water pressures and a loss of strength in the soil mass. This leads to a sliding movement of the whole block along a well defined slip surface (slope angles $\geqslant 14°$).
Another suggestion is that due to a high water content the material has a viscous component with a relatively low yield strength (see 6.1). In this case, at a certain depth and slope angle, shear stresses in the soil mass surpasses the yield strength of the material

and transport via viscous flow can take place (Yen 1969, Ter-Stephanian 1965). Therefore investigations on stress-strain behaviour under different water contents are very important to these types of flows. The morphometry of these so-called mudflows (or slides) is very characteristic. In general we can distinguish a supply area, in which slumping movements take place, a central neck or track, and a lobate toe area (Brunsden 1979). In the track the mudflow has very sharp shear surfaces on sides and base. In the track and toe area there are radial cracks (toe), transverse cracks (where the slide passes steeper slopes) and shear cracks along the sides. The flow may consist of unweathered material in a matrix of softened and weathered material. A dry crust may develop at the surface during dry periods in summer. The rate of movements is generally slow ± 5-25 mtr. per year (Brunsden 1979) on slopes averaging 7°. Movements occur seasonally and may be related to seasonal rainfall patterns.

NOTES

1 The amount of strain of a specimen of soil or rock can be defined as $\epsilon = dl/l_0$ where l_0 is the initial length of the specimen, $(l_0 - dl)$ in the length after compression. $\dot{\epsilon} = d\epsilon/dt$), which is a function of the stress.

7

THE INFLUENCE OF LANDSCAPE VARIABLES ON THE MASS-MOVEMENT CASCADING SYSTEM IN THE STUDY AREA

In this Chapter we will discuss the influence of landscape variables on the amount of production of soil and rock mass and the transport characteristics of the failed mass in the massmovement cascading system in the study area..

The amount of mass production by landslides in a given area is determined by the number of slides, and the amount of mass which is produced at each individual slide. In order to obtain an insight into the frequency of sliding within a certain area, we must determine the landscape variables giving the boundary conditions for failure by different types of slide. We will also analyse the influence of these landscape variables on the amount of mass production at each individual type of slide (see Chapter 6, Table 6.1).

Table 7.1 is a survey of the type of landslides which have been distinguished in the study area. The types are distinguished according to the following characteristics: a) the mechanism of movement at initial failure, b) the mechanism of movement at a further transport, c) the type of material involved at initial failure, d) the range of slope angle values at which failure took place, e) an indication of the amount of mass involved at failure, f) specific landscape – and process variables which have initiated movement and g) the stability conditions at present. A detailed description of the characteristics of the slides will be given below in the various typical examples. We will use the following terminology (with regard to the mechanism of movement):

- *planar rock or debris slides:* sliding of respectively a rock or soil (devris) mass along a more or less plane slip surface;
- *rotational rock or soil slides (slumps):* rotational sliding or soil (debris) mass along along a more or less circular slipsurface.
- *rapid debris flow:* rapid flowing of debris or (finer) soil mass from a sliding area.
- *slow mudflow:* slow flowing of fine soil material out of a sliding area into valley systems. Mechanism of movement can also take place via sliding processes.

As regard to the velocity of movement (Table 7.1 see: column 2), we propose, according to Varnes (1958) the following classification:

a) extremely rapid > 3 mtr/sec, b) very rapid 3 mtr/sec – 0.30 mtr/min, c) rapid 0.30 mtr/min – 2 mtr/day, d) moderate 2 mtr/day – 2 mtr/month, e) slow 2 mtr/month – 2 mtr/year, f) very slow 2 mtr/year – 0.30 mtr/5 year, g) extremely slow < 0.30 m/5 year.

In column 3 is indicated the dominant length, width and depth of the landslide type. Also is roughly indicated in this column the proportion of the surface of the sliding mass (T), which is lying out of the source area of the slide T is the distance from toe to source area for different characteristic landslide types, which gives also an indication of transport. In column 5 is indicated the type of material which was involved at initial

Table 7.1 Description of landslide types in the study area

type nr.	Type of initial failure	Type of transport	Morphometric characteristics L	W	D	T	LT	Slope angle
1	Rock slides (slab failure)	extremely rapid debris flows	100-200	50	-	1/1	100-200	90°
2	Rock slides (slope sagging)	extremely rapid accumulation at foot	50-70	30	5-10	1/1	10-30	70°
3	Rock slides (bedding failure)	very rapid debris flows	800	200-300	-	1/4-1/2	300	20°-30°
4	Rock slides (wedge failure)	very rapid debris flows	500	100	-	3/4-1/1	300	10°- 5°
5	Rock slides (wedge failure)	rapid to moderate debris or mudflows	200	50	10-20	1/8-7/8	100	20°-25°
6	Debris slides	rapid debris flows	500	50-200	-	3/4	300	20°-25°
7	Shallow debris slides	extremely rapid accumulation at foot	20-100	5-20	0.5-1	3/4-1/1	5	30°-40°
8	Shallow rotational slides	no transport by flow	40-60	30-50	4	1/2-3/4	10	25°-35°
9	Rotational slides	moderate to rapid initial flow at toe	10-30	5-10	2-5	1/4-3/4	20	20°-30°
10	Deep rotational slides	slow intermittant; no transport by flow	20-50	10-30	5-20	1/8-1/4	10	20°-25°
11	Rotational sliding area	slow intermittant flow	500	200	5-20	1/8-1/4	200-400	5° -30°
12	Badlands; rotational slides	slow to moderate flow in gullies	10-50	10-50	2-5	1/1	10	20°-30°

L: typical length of slide in m, W: typical width of slide in m, D: typical depth of slide in m, T: part of landslide mass which moved out of the source area. LT: typical distance from toe to source area in m.

ock and soil aterial	Characteristic factors affecting landslides	Activity
ındstones	retrogressive erosion by rivers; undercutting of the slope by rivers; earthquakes	not active
ındstones	undercutting of the slope by rivers; earthquakes	not active
ıetamorphic rocks and ınstones	fractured rock due to faulting; contact zones between rocks; retrogressive erosion by rivers; dip of rock layers towards slope	not active
lay- siltstones	weakening of the rock by joints and faults; supply of water from adjacent sandstones mass; dip of rock layers towards slope; earthquakes	not active
andstones	dip of rocklayers and joints towards slope; retrogressive erosion by rivers; impermeable clay-layers	active
ractured metamorphic ocks and claystones	fractured rock due to faulting; retrogressive erosion by rivers; accumulation of groundwater at riverhead	not active
egoliths on clay- and, andstones and sf-rocks	steepening of the foot of the slope and undercutting by rivers	active
egoliths on metaıorphic rocks	accumulation of water due to slope- and contour concavity; undercutting of the slope by man	active
veathered claystones and andstones	undercutting and retrogressive erosion by rivers; accumulation of groundwater at riverhead; impermeable rocks in subsurface: joints; terracing and irrigation	active
veathered claystones ınd metamorphic rocks	accumulation of groundwater at slope- and contour concavities and riverhead; presence of impermeable rock; steepening of the foot of the slope by rivers; weakening of the rock by joints and faults	active
veathered claystones ınd sandstones	water accumulation at riverhead;	active
veathered metamorphic ocks and sandstones	formation of gullies in scarps of landslides or in steep slip surfaces of shallow debris slides	active

failure. Column 4 gives the range of slope angles at which failure took place. The influence of the soil mechanical parameters are discussed below, while in column 6 special local landscape variable, which have initiated failure, are mentioned. In column 7 we have indicated, among other remarks, whether the landslides are stable, or whether transport (periodically) took place during the period of investigation (which was about 3 years).

7.1. Landscape variables in relation to different types of rockslides

We have distinguished 5 types of rockslides, which were found in 4 different types of rocks. The cohesive limy sandstones (Mar), the weakly cohesive sandstones (Mars), the metamorphic rocks (sf) and the claystones (Ma) (see Table 7.1).
Most landslides of these types have big sizes and are stable at present. They probably date from historical periods, which are characterized by many earthquakes.
In the valley of the Torrente Guarno and the Torrente Pescio, south and south-east of Ayello Calabrò and the Torrente La Fumerella, south east of San Pietro (see Appendix A 7) cliffs have developed in the cohesive limy sandstones (Mar). These sandstone packages are underlain by weak cohesive sandstones (Mars) in which lesser steep slopes have developed. The sandstone beds show almost no dip.
In these sandstones rockslides of type no 1. (see Table 7.1) have developed. The cliffs have a height of 70-80 mtr. The cliff planes have two directions which probably correspond to dominant directions of joint planes in this area. At some spots along these joint planes, the massive sandstone blocks have shifted away a little from the upper edge of the main scarp (see Plate 4). At some places at the foot of the cliff we observed an erosional slope developed in sandstone with an angle of 60°, which could be a slip surface. These slip surfaces are partly covered with blocks. They continue out of a wide and shallow upper valley end.
In this flat valley system (slope 25°-30°) lies a debris mass which is concentrated along this valley and extends far below up to 200 mtr. from the cliff. In this debris mass Mar-sandstone boulders up to 30 meters in size have been transported from the cliff. The debris mass consists of a sandy loam to sandy clay matrix. The debris mass is at present partly terraced, evidence that the slides are fossil. The blocks which are partly inbedded in the debris mass show, due to a difference in weathering at the sides, that the original surface of the debris mass must have lain at a higher level. Due to erosion of the original surface the blocks are further exposed in the mass. This also points to the fact that the activity of these landslides is not of a recent date. The cliff also shows a difference in weathering of the rock also indicating that the landslides are not recent. Parts of the cliff wall are affected by more recent processes. Due to the dissolving of the limy cementation material the sand looses its cohesion. The granular disintegration leads to the formation of hollows (see Plate 5).
Wherever the hard limy sandstone (Mar) and the soft cohesive Mars-sandstone crops out in the form of high steep valley walls these spectacular rockfalls were found (see map Appendix A7). The height of the Mar-sandstone cliffs has lead to instability.

Based on the Table given by Sowers (1979) the unconfined compressive strength of the intact Mar-sandstone varies between 175-560 kg/cm^2. Given a bulk density of these rocks of about 2 gr/cm^3, the theoretical height of an intact rockcliff can be calculated according to equation (8) given in Chapter 6. The theoretical height of intact rock under these conditions varies between 785 and 2800 meters. The joints within the cliff must have weakened the strength of the rock. Therefore the critical height is only 80 meters. If we assume that the material behaves as an isotropic continuum of discontinuities and assuming that tension cracks have developed upto the maximum depth (see Chapter 6), we can make a rough estimate of the cohesion and friction angle of these rock type cliffs for a dry condition. The friction angle can be calculated from equation (4) (in Chapter 6) in which (a) the angle of the slip surface is taken as 60° and (i), the angle of the cliff is 90°. In this case φ approximates to 30°. The cohesion can be estimated from equation (6) (in Chapter 6), if we take as critical height for the cliff 80 meters. The cohesion in this case is about 4.5 kg/cm^2.
Table 7.2 compares the strength characters of the Mar-sandstone with representative strength parameters for some rocks given in Statham (1977).

Table 7.2 The strength parameters of Mar-sandstone compared with representative strength parameters of some other rocks as given by Statham (1977).

Rock type	Intact rock			Rock with discontinuities		
	unit weight g cm^{-3}	compressive strength: x 10^3 kg cm^{-2}	critical height of vertical cliff: x 10^3 m	cohesion kg cm^{-2}	φ degrees	critical height: m
Mar-sandstone	2.0	0.2 - 0.6	0.8 - 2.8	4.0 - 5.0	30	80
Sandstone	1.95	0.2 - 1.7	1.0 - 9.0	0.5 - 1.5	30 - 45	9 - 40
Quartzite	2.61	1.5 - 3.0	6.0 -11.0	1.0 - 3.0	30 - 50	12 - 65
Shale	2.40	0.1 - 1.0	0.4 - 4.0	0.2 - 1.0	27 - 45	4 - 20
Limestone	3.17	3.0 - 2.5	0.9 - 8.0	0.2 - 1.0	30 - 50	5 - 25
Granite	2.61	10.0 - 2.5	4.0 -10.0	1.0 - 3.0	30 - 50	12 - 65

From the Table we can conclude that the friction angle of these rocks is representative for the common sandstone types. The cohesion, however, is about 4 times higher than most other rock types given in the Table. Based on the equation (3) given in Chapter 6 we may conclude that the development of discontinuities per unit volume of rock is relatively low which gives the rock a relatively strong cohesion. Therefore according to equation (6) in Chapter 6 the amount of mass involved at failure must be relatively high for these sandstones. Since the effect of frostweathering is relatively low in these areas (see Chapter 2) we may conclude that solution along the joints of limy material has been the main agent in weakening the strength of the rock. Instability may also be

induced by earthquakes, which increase the shear stresses in the rockmass. This means that the above calculated cohesive strength may even be higher. It is rather difficult to determinate the mechanism of transport downward along the slope, but since the flow is limited to the steepest part of the slope, the rock mass probably has tumbled down along the slope, which we will call a rapid dry debris flow (see Varnes 1958).
Sagging down of valley walls in rockmasses along well developed joints and faults (type no. 2) were found in the valley of Fiume Fumerella and the tributary valleys of Fiume Catacastro east and west of San Pietro (see map Appendix A7). The valley walls along which this type of failure (type no. 2 see Table 7.1) has taken place are very steep (up to 70°) and can reach a height of 100 meters. The slided material has accumulated at the foot of the slope. The material has been rapidly discharged down the river by water transport. The sagging of the slabs along the valley walls can be compared with a type of slabfalls (Carson & Kirkby, 1972, see Chapter 6).
The strong incision of the river and the undercutting action of the running water and the weakening of the rock by joint planes lead to the results that parts of the slope are sagging.
The valley head of the Torrente Collonci is dominated by a huge landslide, which may be described as a rockslide in which the slip surface has developed along a bedding plane of Mar-sandstone (type 3, Table 7.1). The landslide has a length of 800 m. and a width of 150 m. A volume of roughly 3×10^5 m^3 sandstone has started to move along a slope which averages about 25-30°. Large sandstone blocks rise up out of the debris mass at many spots. The upper part of the landslide is under cultivation and is intensively terraced. Downstream are many blocks on the surface an there can be no agriculture. The landslide has developed partly along a fault system of the flanc side of an anticline in Mar-sandstone.
The displacement of the material was not far. Investigations in the field reveal that at least ¾ to a ½ of the material stayed in the source area, while the travelling distance out of the sliding area is about 300 meters. Given the relative high slope angle and the fact that the slide did not reach the foot of the slope we must conclude that the rockslide passes into a dry debris flow with a low mobility. Possibly earthquakes in the past have functioned as a trigger to set the debris into motion.
A second example of this type no. 3 is formed above, Nocera Tirinese (Aqua Fredda) where traces of a large "fossilised" landslide has been found in metamorphic rocks (see map Appendix A7). In the terrain it can be seen how the slope is covered with blocks upto 5 mtr. in size which lie in a clay loamy matrix over a large area. Near the water divide lies a steep wall of 40-60 mtr. in height with a width of 300 mtr. which probably could have been the original scarp. In the blockfield with an irregular topography are many small springs. This whole process has taken place on a slope angle with an average of 25°. It is possible that here a weakened zone of rock, due to tectonic activities has started to slide, and that the schistosity of the material has contributed to develop a slip surface. In this case the displacement of the material was not great either, because the material stayed at the head of the slope and was not transported down the valley floor. Therefore we assume that, after failure, the moving mass was transformed in a dry debris flow with limited transport capacity.

On claystone we found 2 examples of large landslide areas which, at the present state, have the character of a debris flow (type 4, Table 7.1). They have probably started as rockslides. These "fossile" slide complexes were found in the valley Ruzza, which is a tributary of the Fiume Torbido, and in the riverbasin of the Torrente Scala (see Appendix A7). These slides have developed in unweathered claystone which dip into the direction of the slope. The material after failure must have had a greater mobility and probably had the character of a wet debrisflow. Indications for this greater mobility than the above described types are: a) the greater displacement from the source area on a lower slope angle, b) the elongate form and lobate forms in the toe area. The two landslides developed in both cases on the boundary of claystone lying above the sandstone (Mar) which forms a dipslope at the side of the slide. Apart from the fact that lithological boundaries are always weak zones, the many springs which have developed at the foot of the sandstone slope, due to ponding of water by the claystone formation, must have been of great importance to the development of the landslide complex. Furthermore, the development of faults and macrojoints can have contributed to the instability of the area. In the field the uneven topography (relief differences of an average of 5 meters over a distance of 20 mtr.), the closed depressions and the many springs are characteristic for the debrisflows. The area now used for agriculture and the small bricksheds, which were found in the landslide of the Valle Ruzza, are an indication for the fact that the complexes are stable now. Only the upper edge of this slide still extends by slumping, which is tied to a number of upper stream branches of the Valle Ruzza. At present slumping is still taking place in the most western branch of the complex and this will definitely form a threat to the newly made road within a few years.

We now come to a new type of rockslide (type 5, see Table 7.1), which could be studied in more detail, because we were able to follow the development during our stays in the field in 1972, '73 and '74. The landslide has developed at the head of a moderately incised part of the tributary of the valley of Angro near San Pietro (see map, Appendix A7) in a (Mars)-weakly cemented sandstone. This formation is characterized by the alternation of sandstone and siltstone with intercalations of thin beds of claystones.

In 1972, during the very heavy precipitation period of March 6 and 7, a part of the road to San Pietro sagged. Precipitation amounted to 40 mm in these days. A scarp ± 35 meters wide, could be observed due to the sagging of a large block of sandstone (see Plate 6). This sagging appeared to form part of the enormous blockslide complex whereby, over a 100 meters in the extension of a branch of the river, the rock had begun to move. The dense shrub and tree vegetation upholded itself as a fairly united whole over the moved mass. The movement of the rubble mass continued during the following days and as a result a gradually deepening hole arose with a scarp of 10-20 mtr., extending in a backward direction due to the effect of secondary rockfalls. A temporary road which had been built in a few days' time, about 10 meters behind the scarp, was therefore damaged again.
In February 1973 it appeared that the upper scarp had not developed any further. Since the dense tree and shrub vegetation had been, for the greatest part, carried away or "ploughed under", a debriss mass appeared which apparently had undergone a strong movement down towards the valley. The total length of the debriss mass was 220 meters. The width varied between 20 to 50 meters. The slope angle varied between 20-35°. The debris mass discharges into an older valley head cliff with an angle of 45° and a height of 50 meters, where the debris dropped down in

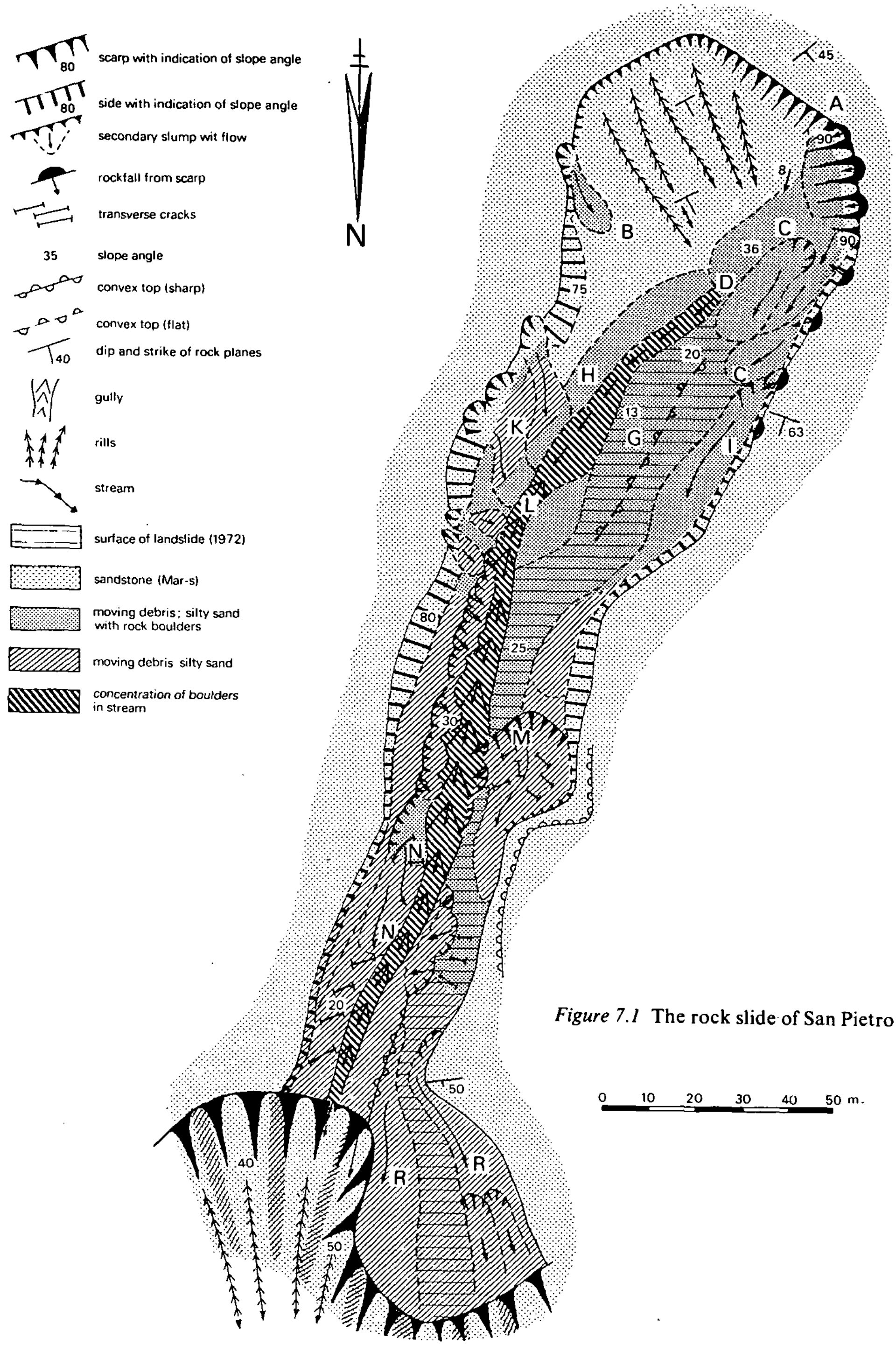


Figure 7.1 The rock slide of San Pietro

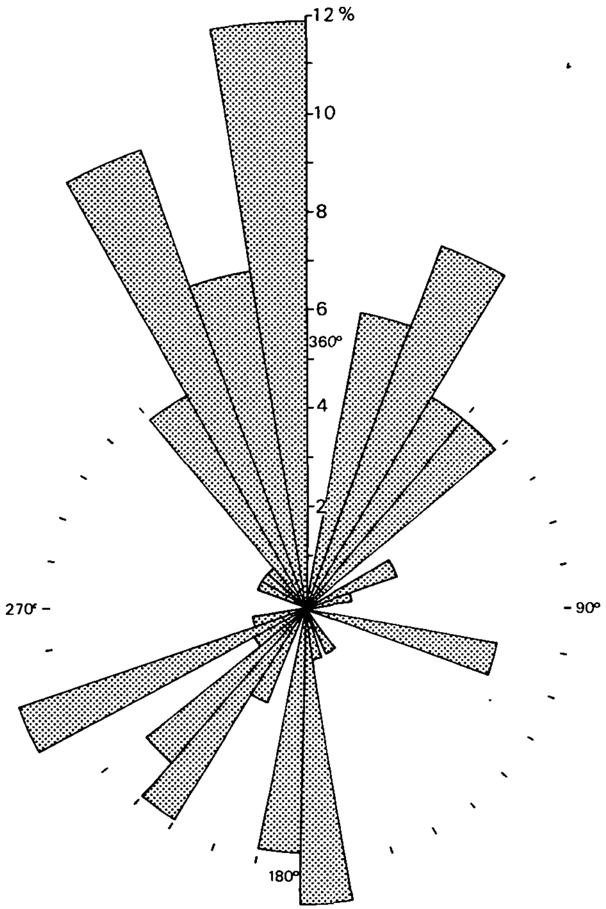


Figure 7.2 Frequency distribution of the strike of joint planes in weakly cohesive sandstones (Mars) near the rock slide of San Pietro.

the form of flows. The sandstone mass no longer showed cohesion. Along the whole landslide complex a scarp (varying in height from 10 mtr. at the head to 1 mtr. at the toe) could be seen. This meant that a large amount of debris had already been carried away from the complex (see below). On the landslide complex at respectively 2,5 mtr. and 135 mtr. (measured from the topscarp) two less obvious scarps were observed.

In June 1974 it appeared that even more debris had disappeared from the complex. Due to the dry season the relatively stable landslide was accessable so that it was possible to make a detailed map (Figure 7.1). During this mapping it appeared that the topscarp was not round but was composed of a set of straight segments which corresponds to certain joint planes. Figure 7.2, a frequency diagram, represents the strikes of about 150 joint planes which were measured in the surroundings of the landslide. Some of these directions of the strikes, namely 25°, 180°, 335°

and 360° correspond to the direction of parts of the scarps which are shown in Figure 7.1. The longitudinal axis of the landslide complex has developed in a direction which corresponds to a strike direction of 25° of a certain group of joint planes. The scarp is composed of vertical walls which vary in height from 7-13 meters (A, Figure 7.1). At (B) we found a dipslope of 40° forming a part of the slipplane of the landslide. The material is composed here of gray sandstone with thin layers of clay inbetween. Within a maximum of one year deep rills (10 cm deep) have been formed on this slope. Locally the scarpwall shows slidings which are obviously tied here to joint-planes and not to instability as a result of an "active Rankine State" of the sandstone mass (Terzaghi 1962). The debris which has tumbled down at the foot of the wall is so highly saturated with water that it can move on as a flow (C). At point (D) a semi-permanent stream begins, in which blocks of grey and brown sandstone are lying. Some boulder walls which supported the old road have also been found here. The small river follows the axis of the landslide along which the most rapid transport of material through water and via flow movements has taken place. A cross section drawn at point (D) (in Figure 7.3) clearly shows that the slipsurface is formed by the bedding and a well developed joint plane with a strike direction of 25° which can be distinguished on the map as scarp (EF). At point (G) (Figure 7.1) a higher lying ridge mainly composed of brown debris material was observed. This ridge still contains remains of the original vegetation and is a remnant of the old surface which had been found in February 1973. The ridge had moved very little since then. To the right and left of this (H and I), on a lower level (± 6 meters) active rapid flows are situated, composed of grey and brown sandy-clay material. In the centre the debris path with coarse sandstone blocks continues. The material of flow (I) has been partly delivered by the side scaro. At (K) it also appears that the freed walls of the scarp become unstable due to the deeper sagging of the debris material and eventually lead to the formation of a number of slump-flow landslide complexes. At level (L) the debris track changed into a gully of 4½ mtr. depth with walls of 60°. These walls are not stable and give rise to slump movements. The slumped material has been carried away by running water and flowprocesses. The gully has become wider downslope due to this slump-flow mechanism. At point (N) the old surface of 1973 has disappeared. (M) itself is an active flow with a clear scarp at the top, and can be regarded as a local reactivation in the debris in the form of a slump-flow mechanism. At (O) the slump-flow movements are clearly the results from the receding walls of the gully. A renewed incision of

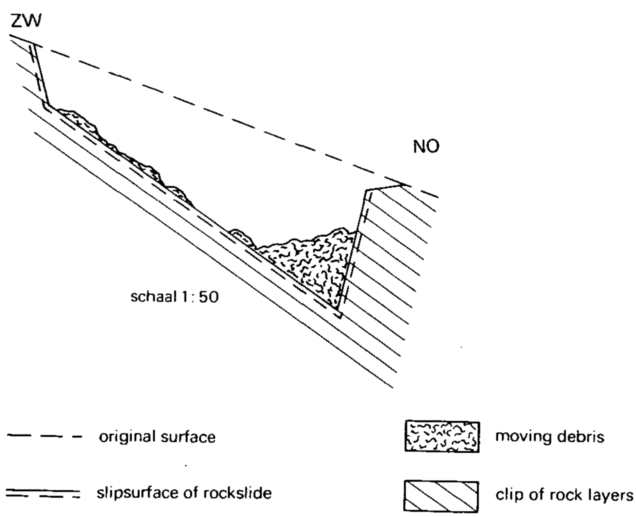


Figure 7.3 A cross section at the head of the rockslide of San Pietro.

the gully has taken place here. Two flows (R) are of a recent date. Inbetween them lies an older flow, somewhat covered by vegetation (apparently from 1973). At (P) asphalt from the road was found in this flow. The whole complex discharges over a steep wall of 40-60°; the river lies 60 meters deeper.

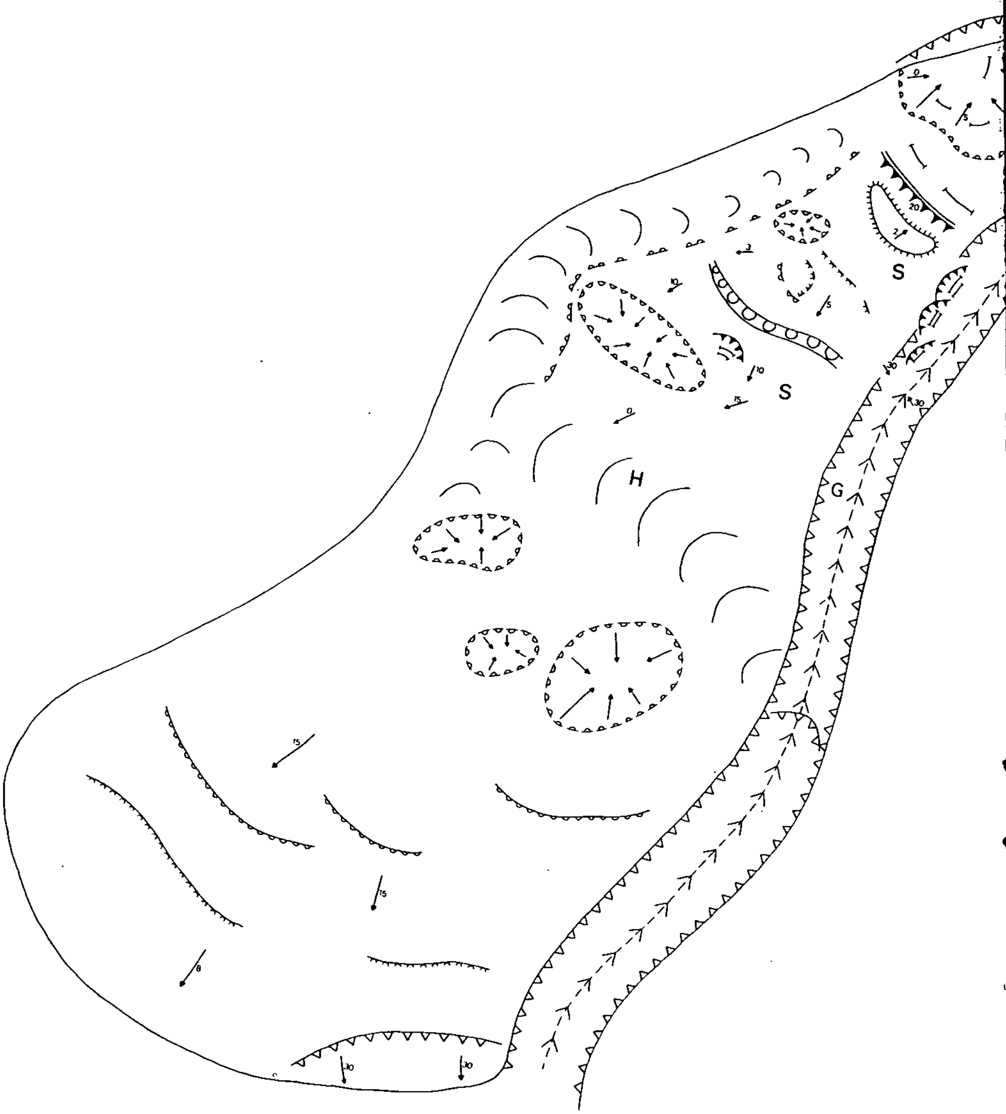
The detailed description given about showed that a number of landscape variables has influenced the type of initial failure of the landslide:

- The slightly cohesive sandstone rock, with well developed major joint planes and bedding planes dipping in the direction of the slope angle.
- A rapid retrogression and a deep downcutting of the branch of the river Angio, which has given rise to a severe steepening of the valleywall head, mainly by slabfalls (see Figure 7.1 at T) at the foot of the sliding area.
- A concentration of groundwater in the source area of this river-branch which could be partly ponded by impermeable clay layers in the sandstone mass.
- The heavy precipitation, which has been registrated in the period of March 4 to 7 1972, which in this case has functioned as a "trigger".

The intial movement which we could observe in March 1972 had the character of a wedge failure with a relative slight displacement of the moving mass (see Figure 7.3 and detailed description given above). However, due to the weak cementation of the sandstone, the rock mass was already disintegrated into a debris mass. The further displacement of these debris masses took place in later periods especially during the wintertime after heavy rainy periods. During this heavy rain-periods the debriss became saturated with water and the material must have reached the viscous state. The debris mass was carried away further via flows. The detailed mapping of 1974 revealed (see Figure 7.1) that at first, flow movements particularly took place in the underground: the vegetated surface was pushed along with it and partly sagged down due to the loss in mass in the underground. For this reason one can explain the fact that the partly intact and vegetated surface (G) (Figure 7.1) is still present.
The detailed mapping also showed, that new elements began to play a part in the transport of debris:

- Acceleration of the removal of debris, due to the development of a rapidly incising gully. The water in the gully was able to transport blocks from the damaged walls protecting the road over a distance of some tens of meters. This gully incised rapidly into some four meters of the debris with the result that the steep walls of these gullies became unstable and retreated rapidly via slump movements (O in Figure 7.1). It was established that the walls of the gully retreated, and that downstream a new incision in the lowered surface had begun. The rapid headward incision of the gully functions as a catalyst for an accelerated removal of debris via slump-flow movements.

  Since more debris disappears from the complex, the walls of the scarps and sides become increasingly more liberated. These walls become unstable and as a result rockfall (see B) and slump-flow movements (S) at the sides take place.
- The debris mass can also undergo a renewed movement without the influence of an incising gully. The still active (slump-flow) movements which have been observed at (L), (N) and (I) form an example (see detailed description). We may conclude from


S
S
H
G

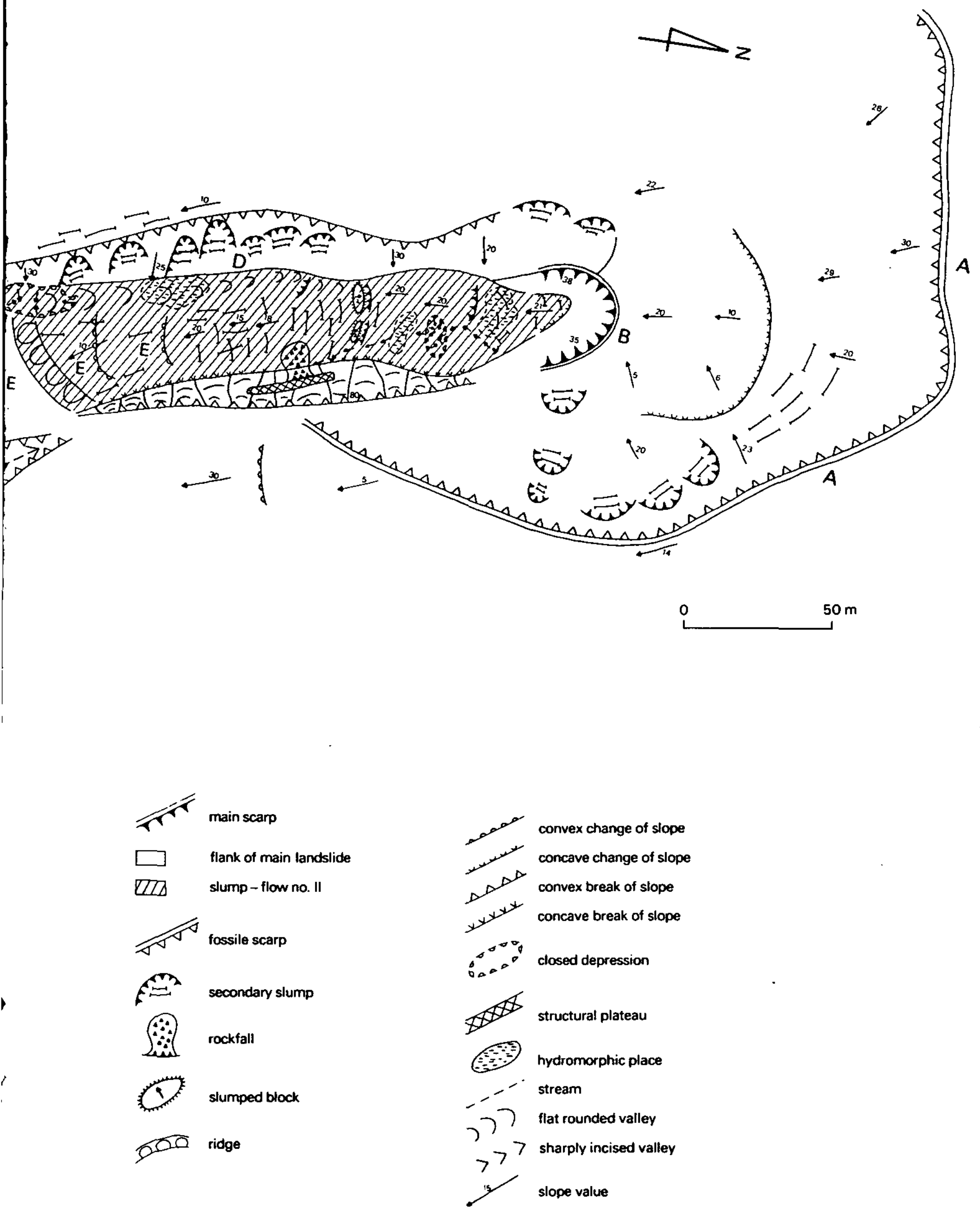


Figure 7.4 Debris flow of San Antonio.

this, that movements do not take place continuously over the whole surface but via a number of clearly differentiated slump-flow complexes.
- Movements can be activated by a local concentration of water of the continuously varying stream patterns of the groundwater. The differentiated movements may also be activated by a rapid loss of debris downstream (see (N) in Figure 7.1).

The original topographical surface before the mass movements took place can be reconstructed with the aid of a number of cross sections, which have been measured in the field. The topographical surface of the slide of 1973 may also be reconstructed (although less accurately), and also the relief of the measurements carried out in 1974. This enables us to estimate the loss of debris out of the sliding area. For the period of 1972-1973 it amounts to ± 62.000 m^3 and for the period 1973-1974 to ± 13.500 m^3 which gives a total loss of ± 75.500 m^3.

7.2 The influence of landscape variables on the development of debris slides

In the foregoing paragraph, we discussed different types of slide and related transport phenomena, which started in a more or less cohesive rock mass, along more or less, straight dipping surfaces. In this Paragraph two types of landslides (no. 6 and 7, Table 7.1) will be discussed, which started in weathered material or in very fine fractured rock along more or less flat slip surfaces. In general, there is a larger displacement of material out of the source area of the slide. Two landslides of type no. 6 were observed on the steeper northwestern slope, averaging 25°, of the Fiume Torbido, in the neighbourhood of St. Antonio and Casino Vespario (see map Appendix A7). These landslides, which have a elongated form, have developed in fine layered, and fractured claystone. The claybeds dip with an angle of 20° in the opposite direction of the topographical slope. The slides are situated at the head of the tributary valley of the Fiume Torbido, which has sharply incised this valley slope.

A detailed description of the complex of St. Antonio is given here as an example (see Figure 7.4). The complex was bounded at the top by scarp (A), which has the form of an amphitheatre with slopes, averaging 30°. They have been affected by recent slump processes. Slightly further downstream was a relative small round scarp (B), with an angle of 35°. Even further downstream a bare cliff (C), with a height reaching 40 mtrs. could be observed. The slided mass showed transverse cracks with steps upto 3 mtrs. It is possible that these steps at the head of the slide, still reveal the sliding in blocks at initial failure of the debris mass. The western side (D) averages 20 mtrs. height, with a slope angle of 20-30°. On the steepest parts of these sides (>25°) shallow planar debris slides (type no. 7) has taken place. At (E) the toe of a secondary flow complex could be observed, which was limited by a distinct front, with a slope angle of 20° (F). The debris mass lying above this front had a dense shrub vegetation, a greater density of cracks and a more irrigular topography. The landslide complex further downstream was used for pastures and still further downstream for agriculture. This part consisted of a soft undulating landscape with close depressions and slopes varying from 0 to 5°. In this area reverse slopes (for instance under (S)) were measured, which were interpreted as parts of transverse ridges. The olive trees in this area were all crooked, pointing to a displacement of the surface. The fairly flat valley (H) cuts the complex in two parts. The valley system (G) with rather steep walls, also affected the complex. Landslides were also found along the steep sides of this valley. The lower part of the landslide spreads out in a wide fanshape towards the main valley floor. According to the descriptions, from a number of inhabitants, movements must have taken place during the Fifties. The greatest part of the displacement of the material must have occurred within a few hours. The house (see Figure 7.4) was just saved. After the movement scarp (D) and supposedly also a part of scarp (C) developed. It took about seven days for the landslide complex to stabilize completely. The secondary flow with scarpwall (B) and a different topography and vegetation could have been developed in later years. During the beginning of 1960 the toe area below depression (H) was cultivated again.

An analysis of the landscape variables reveals that these relative steep slopes in very fracturated clay probably in combination with the development of high pore pressures at the head of the tributary rivers, have lead to the development of debris slides which must have rapidly passes into a debris flow. The transverse steps (minor scarps), the arcuate head scarp and the marked sides at the head of the complex form diagnostic features for the fact that initial movement might have taken place in the form of a debris slide (see Chapter 7, Varnes 1958, Brunsden 1979). The high water content of this sliding debris mass, has changed the mass into a viscous state and further transport of the material must have occurred via flow processes (see Appendix A5). The flowing character of this landslide is accentuated by (see detailed description above and Varnes (1958), Brunsden (1979):

- The large distance of transport from the source area towards the valley floor.
- The elongated form of the complex and the lobated form at the foot of the slide.
- The hummocky topography, with many close depressions and transverse ridges in the lower part of the slide.

Since eyewitnesses havè stated, that the greatest displacement occurred in a few hours, we can estimate that the velocity of the mass must have been in the order of 2-5 mtr./min., which is relative low in relation to the mean velocities of debris flows, given by Brunsden (1979) which amount to 1-100 mtr./sec.

The second type of debris slide is the most common type of slide which occurs in the study area on the steepest slopes with a relative thin regolith cover (type no. 7 Table 7.1). They were found on weathered regolith derived from sandstone (Mars) at the steepened foot of the slope (angle 35°) in the Valley of the Fiume Sante Maria. This type of slide was also found in weathered regolith on claystone along the steepened valley walls of the tributary rivers of the Fiume Torbido, e.g. the Valle Irroiti. On the eastern side of this valley on slopes varying from 32-36°, shallow planar slides developed at a mean depth of 80 cm (Figure 7.5, a, b, c, d). The slipsurface developed well below the rootzone, of tussock grasses, which reaches to a depth of ± 50 cm. It developed just above the transition zone of weathered regolith to non-weathered regolith. Four samples were taken from the regolith at a depth of 60 cm. In these samples no roots were present. Direct shear tests in the laboratory under wet conditions show a mean angle of internal friction of 31.8° and a mean cohesive strength of 260 kg/m^2. The mean bulk density of the saturated soil was 2.27×10^3 kg/m^3 and the unit weight of dry clay regolith was 1.98×10^3 kg/m^3. The slip surface developed at the maximum depth within the regolith (80 cm) and, given the soil mechanical and topographical values mentioned above, we can calculate from equation (13) (in Chapter 6) that the groundwater

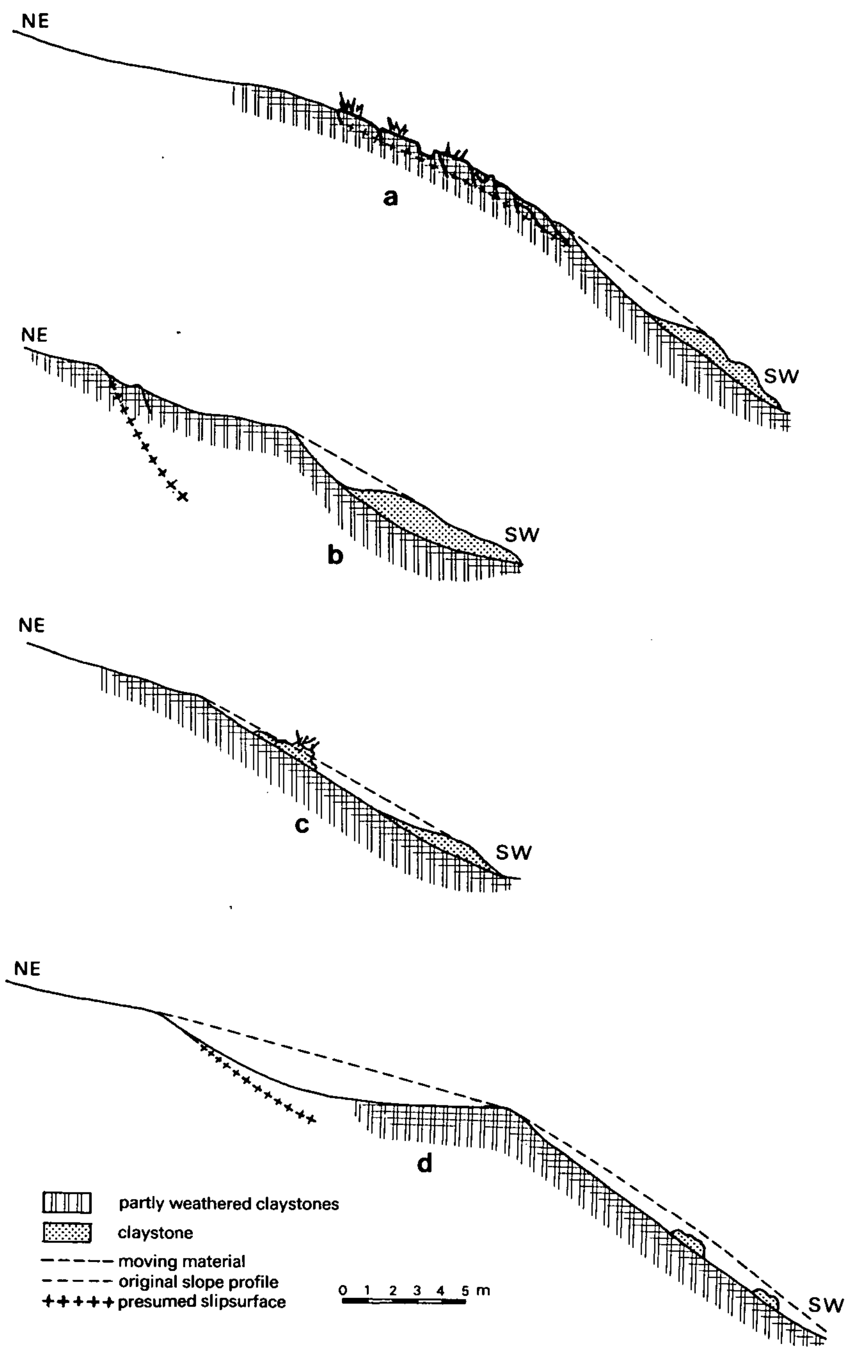


Figure 7.5 Shallow debris slides in the Irroiti valley.

has reached a height of ± 48 cm above the slip surface, which is ± 32 cm below the surface of the slope. Equation (15) (in Chapter 6) has also showed that a higher rise of the groundwater might have lead to a lower depth of the slip surface and thus of the amount of mass failure, assuming the regolith is homogeneous. The minimum depth of the slip surface is reached when the regolith is fully saturated and in our case (according to equation (13) would be ± 52 cm, which is still below the root zone. We have to keep in mind that the regolith in the upper zones might have greater strength due to the binding effect of the roots. If we assume a mean thickness for the cohesive regolith on claystone of 80 cm we can make the following remarks for this type of landslide:

- The critical angle at which failure can take place for this type of debris slide is according to equation (13) ± 42° for dry regolith (without groundwater) and ± 28° if there is a subsurface flow through the regolith parallel to the slope surface, while the water table reaches the slope surface.
- If at a certain slope angle the point of failure can be reached the maximum amount of mass which is involved in sliding is determined by the thickness of the regolith cover and the minimum amount of mass is determined by the thickness of the stronger upper root horizon or the minimum depth of the slip surface, which is developed when the regolith is fully saturated with flowing groundwater. The real amount of mass, which is set into motion lies between these two limits and is determined by the height of the groundwater in the regolith at catastrophic circumstances. The maximum length of the slide is determined by the total slope length, but the real length will be determined by the height, the groundwater reaches in the regolith along the slope.

Shallow debris slides also developed in the tributary valley of the Fiume Oliva (Valle del Signore, Valle Arpa and Vallone Spinoza) in sandstones and metamorphic rocks in the lower course of the Valle Collonci and the valley head of the Torrente Calcato in metamorphic rocks. Good examples were also found in the river basin of the Fiume Grande along the steepened slopes. Here the slopes averages 40° at the foot. Characteristic for the area with these shallow slides is the fact that due to the disappearance of the vegetation from a large area, these steep slopes became exposed to intensive gully erosion, which in an ultimate state leads to the formation of badlands (type no. 12).

Figure 7.6 and Plate 8 show an example of an area in the Vallone della Fabrica, where soil slipping has taken place at the steep foot of the slope (40°) and intensive gully erosion has completely cleared away the regolith layer and partly affected the fresh metamorphic rocks (A). The less steeper part slope-upwards (30-35°) (B) has become unstable and show the character of shallow slumping (type no. 8 see below). A recent example of a shallow debris slide on metamorphic rocks could be studied in the Vallone della Fabrica on the south wall, west of Molino Longo (see map Appendix A7 and Plate 9). The "soil slip" was about one month old when a more detailed study was done. The slipped valley walls were covered by a fairly dense shrub vegetation. The landslide extends as far as the foot of the slope where a river meander has undercut the slope. The

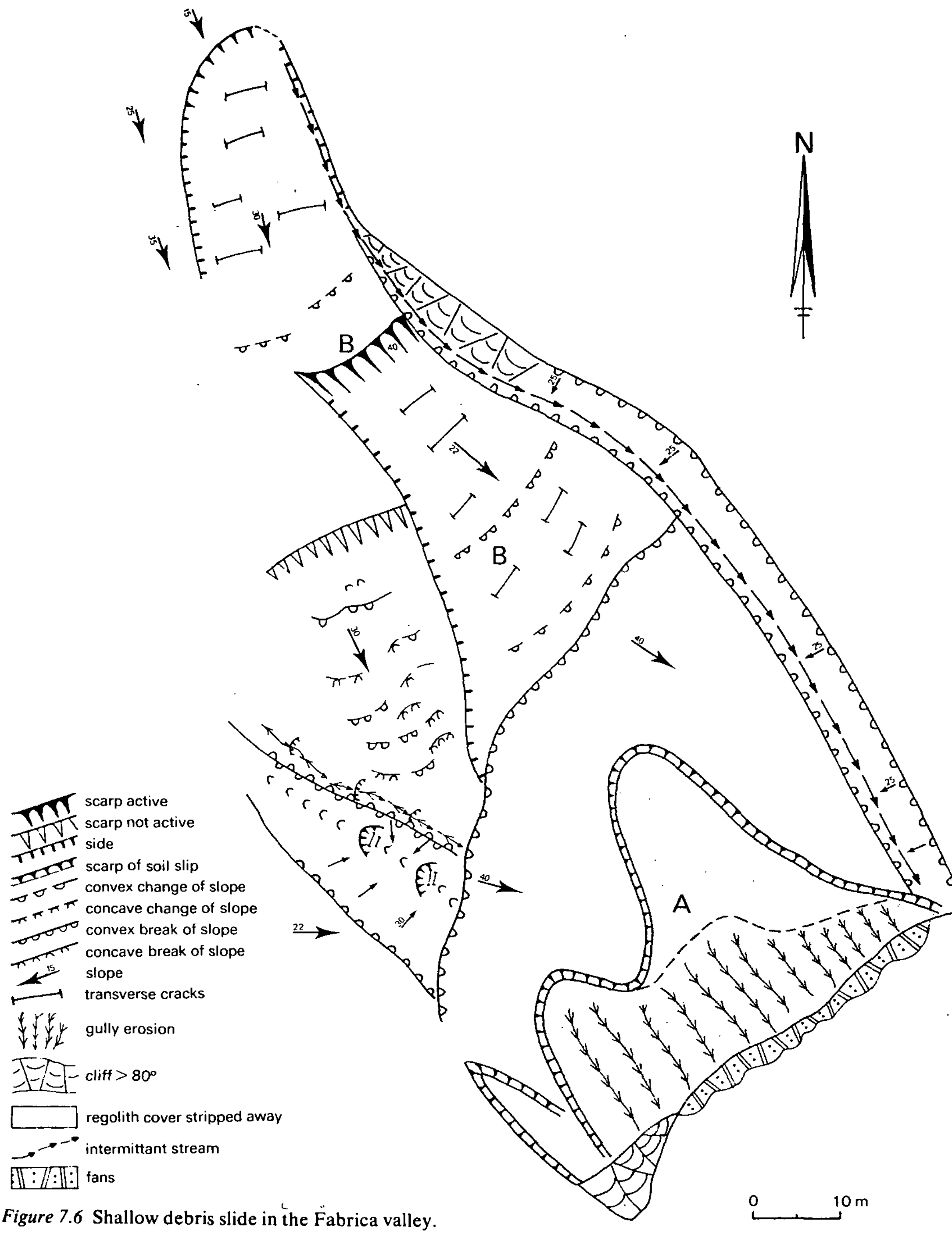


Figure 7.6 Shallow debris slide in the Fabrica valley.

total length of the slide was 50 meters, the width 13 meters. The average thickness of the slipped layer was 85 cm. The slipsurface undulates highly and the cross section shows a light concave form. Eighty percent of the debris has slipped away from the sliding area and was accumulated at the foot of the slope. A few pieces of regolith with shrub vegetation were present as remains in this flat "gutter". The detailed study revealed that the slipsurface lies within the regolith and the rock. The regolith can be subdivided in three zones: An upper horizon with dense roots of about 60 cm thickness, with angular rock fragments (1-3 cm, 15%) and a sandyloam matrix (bulk density, 1.54); a middle horizon (60-90 cm) with angular rock fragments (1-3 cm, 15%) and a sandy loam matrix (bulk density 1.62); a lowest horizon (90-120 cm) with a large rock fragment content (20-50%, size 2-5 cm) and the highest bulk density (± 1.83). The slipplane has developed in the middle zone. In this zone samples were taken in order to measure the strength values of the regolith. There was no cohesion and the angle of internal friction (φ) had a mean value of 46°. The friction angle is somewhat higher than the slope angle, which for this slide was 42°.
As was stated in Chapter 6 the depth of the slide in a cohesionless homogeneous regolith is determined by the total thickness of the regolith. For a layered regolith as in this case, the position of the slipsurface is determined by the horizon with the lowest angle of internal friction.
Therefore the upper horizon must have had higher strength values, probably due to the binding effect of the roots, and also the lowest zone had higher strength values, which must be due to the higher bulk density and to the fabric of large angular rock fragments which have been filled up by a finer matrix (Chapter 6).
Since the angle of internal friction of probably the weakest middle horizon is somewhat higher than the critical slope angle, the positive pore pressure of the groundwater must have played a part in initiating failure. If we assume for the zone above the slipplane a mean dry bulk density of 1.58 and a mean wet bulk density of 1.73 we can estimate, according to equation (13) (Chapter 6) that the water has to rise ± 18 cm above the slipplane (which is ± 66 cm below the slope surface). The critical slope angle for this cohesionless regolith is not determined by the depth of the regolith as is the case with cohesive clay material (see above and equation (15) Chapter 6). Equation (14a) and (14b) (Chapter 6) show that the critical slope angle for these debris slides in metamorphic rocks varies between ± 24° for fully saturated regolith with groundwater running parallel to the surface and ± 46° for dry circumstances. We have stated that in this cohesionless material the depth of the slide and therefore the amount of mass is determined by the depth of the weakest zone within the regolith.

With regard to the shallow debris slides (type no.7) we were able to quantify for two types of material, the boundary conditions for failure and the effect of certain variables on the amount of mass production. In the cohesive claymaterial the critical slope angle for failure depends a.o. on the thickness of the regolith. For regoliths with a thickness of 80 cm (which is assumed to be the normal thickness), the critical slope angle for dry conditions is ± 42°, and ± 28° for regoliths fully saturated with groundwater. In these fairly homogeneous regoliths the slipsurface developed at a maximum depth; we might

conclude that the thickness of the regolith determines the amount of mass production at failure.
The critical slope angles for the cohesionless regolith cover in metamorphic rocks is ± 46° for dry conditions and ± 24° for fully saturated regolith. In these cohesionless regolith failure took place in the weakest zone which lies on a depth between 60-90 cm in the regolith.

7.3 The influence of landscape variables on the development of rotational slides

In Chapter 6 we have stated that in cohesive material, with a certain critical slope angle and height, rotational slides occur. As we have stated, the amount of sliding mass involved, depends on the strength of the material, the positive pore pressure developed by the groundwater and the slope angle.
In Table 7.1 we have distinguished three types of rotational slides, viz:

- type no. 8: Shallow rotational soil slides mainly developed in metamorphic rocks.
- type no. 9: Rotational slides developed at relative steep slope angles in weathered claystone and sandstone, and with relative large displacement out of the source area.
- type no. 10: Deep seated rotational slides developed mainly in weathered claystone, but also deep weathered metamorphic rocks on relative lower slope angles with relative few displacement.

At first we will give attention to a type of circular slides which have developed in regolith and colluvial or solifluction material on metamorphic rocks. In general the depth of the slumps are rather shallow in relation to the length (± 1:10) and therefore the slipsurface is rather flat. The sides are diverging downslope. In general they belong to the type of "slope failure", for which an outcrop of fresh rocks functions as the base of the slump (see Figure 6.7). This type of massmovement can be considered as a transition from real slumps to the shallow debris slides described above which occur on steeper slopes in shallower regolith cover with flatter slipsurface (type no. 7). The slides are found on the south-eastern valley wall of the lower Savuto and the Fiume Grande. In general on these slopes there are not many distinct traces of recent active landsliding. The building of the Autostrada along these valley sides, showed, however, that these areas are far from stable and that landsliding can occur by the slightest interference. The landslide at the valley wall of the lower Savuto near "Nicoli" (see map Appendix A7) is a good example of this landslide type (no. 8). In Figure 7.7 a scarp wall (AB) is shown, having an average height of 5 meters and an average slope angle of 55° to 60°. This recent scarpwall is connected to an older, vegetated scarpwall (EF), under which lies a densely vegetated area with an irregular surface. The sides (AC) and (BD) have a height of 2 meters upslope which gradually diminishes to 0 meters about halfway down the complex (see plan). The foot of the complex has been excavated (see profiles 1-4). In the scarp (AB) at (G), two slip surfaces were partly exposed in the wall (see profile 1) (height 2.20 meters). The most important slipplane had a slope angle of 50° at the top of the wall and downslope the angle was 45°. There was a secondary slipplane

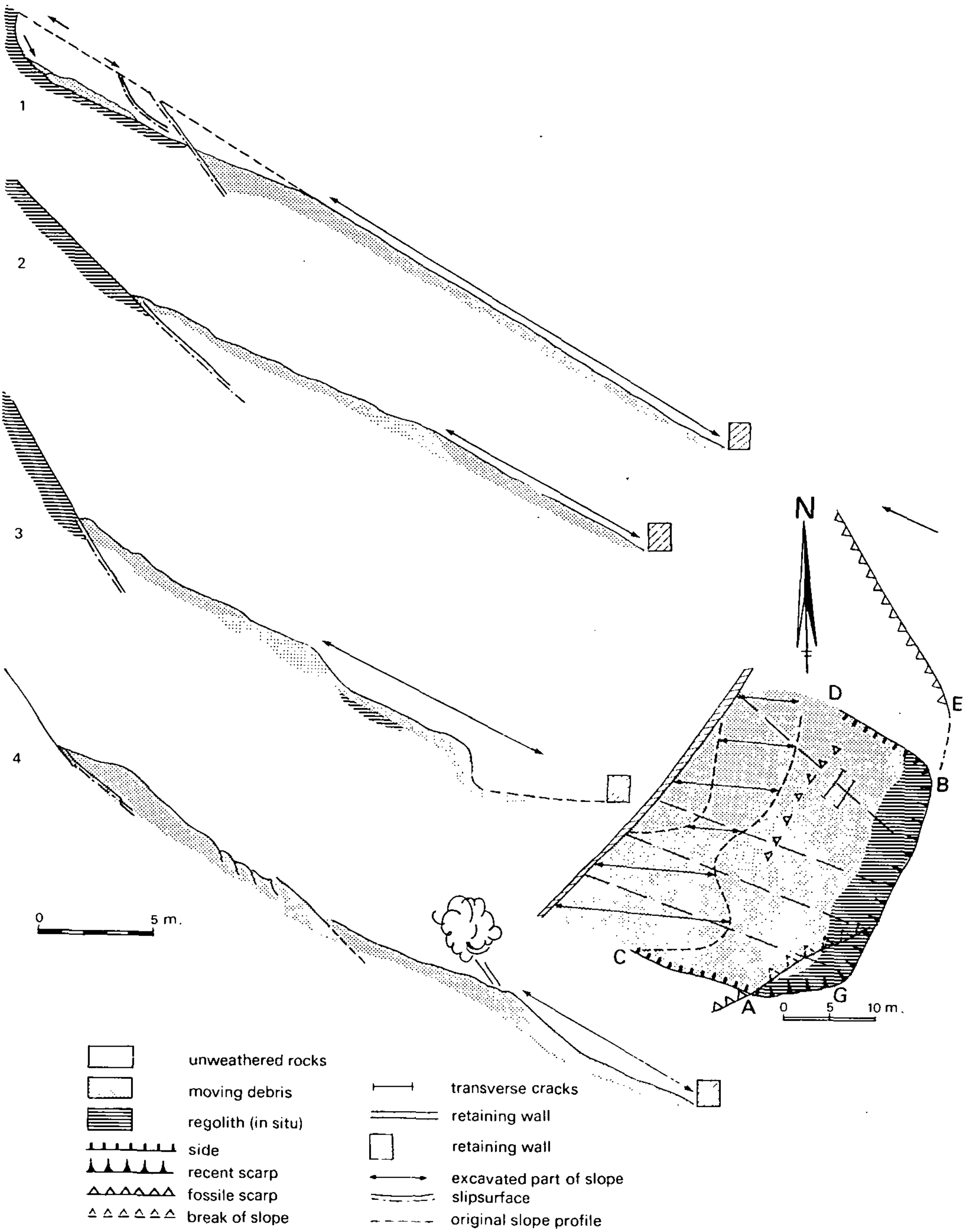


Figure 7.7 Shallow rotational slide in the Savuto valley (Nicoli).

which had a gradient varying from 60° to 20°. Along the main slipplane the solifluction material was completely changed to a "gneiss-like" structure. This was less clear along the secondary slipplane. Possible traces (for instance in the form of scarps) of the movement along these circles could not be found at the surface near the actual slide. The traces (of this movement) on the surface are suspected to have been wiped away completely by ploughing and water erosion. Profile 2 and 3 show that the hard rock just crops out the surface as a cliff. This is not the case in other profiles. Profile 4 shows how secondary scarps have developed.

The landslide at Nicoli developed on a slope of around 32°. The reconstruction we made of the slipplane by constructing a circle going from the scarp to the toe of the slope revealed that the landslide had the character of a rotational shallow slide, with a depth length ratio of about 1:10. The rotating movement (and hence the displacement of the material connected to it) has not been extensive (see Figure 7.7). It was observed that the greatest part of the slipplane has developed in the lowest zone of the regolith just above the fresh metamorphic rocks. The impermeable schists could have ponded the groundwater so that the groundwater could rise to a relative high level in the regolith (see below).

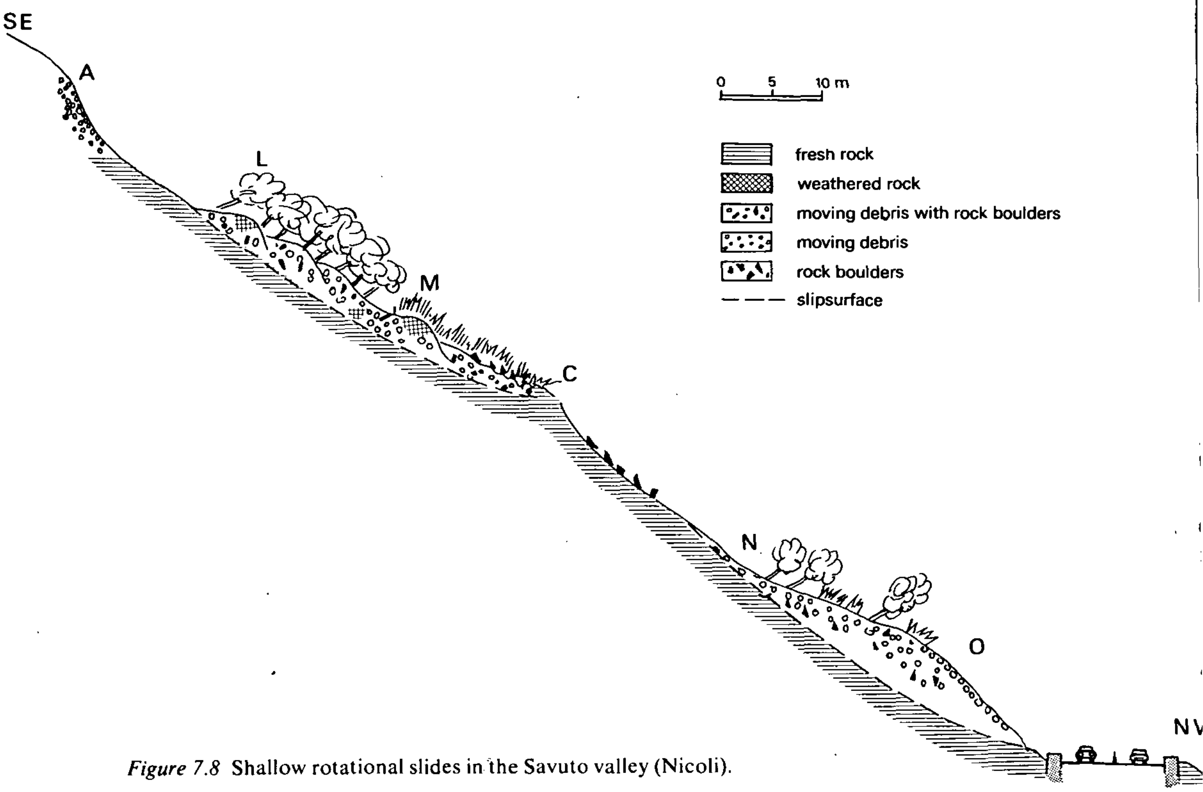


Figure 7.8 Shallow rotational slides in the Savuto valley (Nicoli).

The recent complex forms a part of an older complex to which the old scarpwall (EF) belongs (see Figure 7.7a). At the side at (G) a part of the slipcircle of the old landslide complex was exposed. Due to excavation at the toe area (see Figure 7.7b) for the construction of the Autostrada, probably a part of the old landslide has slid further downwards. The question arises whether sufficient material has been excavated at the foot and whether the block has sufficiently slided in order to create a new stable situation, especially when there occurs a large accumulation of groundwater in the slided mass. Precautions were taken to protect the landslide from an excess of runoff water, which can flow from the slope above into the complex. To this purpose a ditch was constructed around the scarpwall. This ditch was destroyed by further retreat of the scarp. This technique of protecting the landslide against a concentration of surface water has been often used along the Autostrada. It is obvious, that only a part of the water, which comes from the slope surface will be chanelled away by the ditch. A large part of the water still enters the landslide complex via subsurface flow through the mainscarp at the head (see Figure 7.7b).

A second typical landslide complex of type no. 8 lies 300 meters downstream on the same valleyside along the Autostrade.

Plate 10 shows that the slope has become unstable over a distance of 500 meters. A number of scarpwalls which has been indicated on this photograph shows that a complex of different landslides is involved. In the central part lies a landslide of which the outlines are easily recognized. This part of the valleywall must have recently, i.e. during the construction of the Autostrada, started to move. This can be ascertained among other by the presence of the recent rounded scarpwall (A), which goes over into two downhill diverging sides (B). The form is characteristic for surficial slides on metamorphic rock. Halfway down this landslide lies a second scarp (C) in the hard rock (see also Figure 7.8). Upstream from the complex at (D) a fossilized scarpwall can be observed. Residuals can also be distinguished ad (E) (see Plate 10). The material below the scarp (D) has been excavated. Downstream from the most central complex lies a less obvious, but recently formed scarpwall (G). Under this more or less recent scarpwall lies a likewise recently slided block, probably due to excavations at the foot (see photograph). The scarp lies partly in hard rock and is 4 meters high and ± 30 meters wide. The slope angle is 70°. The slided mass consists for the greatest part of loose material except at the top where a few blocks of hard rock have slided along with the rest. The thickness of the whole slided layer is not more than 2 meters. The sliding plane down to the excavation (edge H) is flatly curved. Just above the recent scarpwall (G) there are traces of a fossible scarp (I). The scarp (C) continues as a slipsurface in the scarpwall (A) at point (K).
A profile study has been made along the central complex in order to obtain more insight into the structure of these landslides (see Figure 7.8). The rounded scarpwall (A) is 6 to 8 meters high and has a slope angle of 50°. This wall passes into a slipsurface comprising of hard rock with an slope angle of 36°. Furtheron there is a part of the slided rock (L) on which the trees of an old forest vegetation chiefly lean forwards or sidewards. In this forest complex decayed rock was enclosed in a steep wall (height 3 meters, slope angle 45°). At (M) ons leaves the forest complex (see also Plate 10). In a steep wall rotten gneiss has been found again. The scarpwall (C) is reached via a slope with steps on which blocks lie scattered around. The scarpwall has a slope angle of 55° which passes over into a slipplane with a slope angle of 30°. The slope consists completely of hard rock. To the northeast of the profile-line the slided mass has for the greater part been excavated below (F) (see Plate 10). It must furthermore be noted that the hard rock there lies somewhat deeper. In the section between (C) and (N) the slipsurface is ex-

posed. At (N) a slided block can be seen again, and the original tree and shrub vegetation has also been retained. At (O) the slided block has been excavated. The slope consists completely of loose material. At the tracé of the Autostrada hard rock is exposed in situ.

Research carried out in the field and the maps and photographs presented here clearly showed that, due to the excavations of a fossile landslide complex for the construction of the Autostrada, various parts have sagged further down. Vague indications towards a landslide complex are to be found on the aerial photographs from 1955. The fossile scarpwall (D) and the less distinct scarpwall (I) probably belong to this old complex (see Plate 10). The results of the excavation activities during the construction of the Autostrada can best be studied in the central part of the complex beneath the scarpwall (A). An attempt has been made to reconstruct the two consecutive slipplanes in the profile (Figure 7.8).

By the reconstruction of the upper slipplane the exposed part of the slipplane beneath the scarps was used and the point (C) in which hard rock has also been found. Although it is assumed that the landslide follows a circular curve (and this was the starting point by the reconstruction, see Figure 7.8); even then the curve is fairly flat. An even better picture can be obtained of the form of the lower slipplane. Here, a greater part of the slipplane (C-N) is exposed. This section is fairly straight. Since the slip circle must emerge above the Autostrada (the hard rock has been found near the Autostrada) the slipplane has to make a slight curve in the lower part. At other spots along the Autostrada where the slipplane was completely exposed due to the excavations, the same curve can be found: an upper section which is very slightly concave to nearly straight which passes downwards into a section with a stronger concavity. The conclusion must be drawn from the study of the slipplanes that we are principally dealing with slumping. The concavity of the planes is, however, very slight and the slided blocks must have therefore rotated very little, but have had for the greatest part a "translative" movement parallel to the slope. This can be deduced also from the many forward leaning trees of block (L). Most of the trees would lean backwards in the event of a distinct rotation. It can further be concluded that the depth of which the mass moves in relation to the length of the landslide is small.

The slipped mass consists for the greater part of solifluction material and the slipsurface of hard rock.

It must be concluded that impermeable schists therefore have functioned as slipplanes for the solifluction layer on top. This has also been confirmed in other complexes.

The upper landslide A-C (Figure 7.8) has probably been formed after the development of the lower landslide C-O. The lower landslide C-O probably belongs to the scarpcomplex indicated by F, C and G in Plate 10. The strong excavation of this complex stream upward of the profile A-O may also have initiated landslide A-C. The rounded scarpwall (A) has developed on a somewhat less steeper slope.

For this type of shallow rotational slide (no. 8) of which we have given some examples above, the threshold conditions for failure could be quantified. For a number of slides the soil mechanical characteristics could be measured and the slipsurface reconstructed.

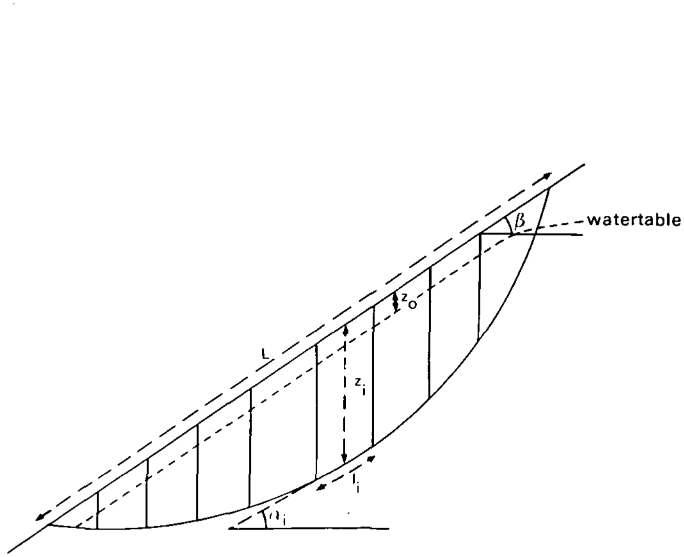


Figure 7.9 The stability of a slump. The method of slices (after Fellenius).

Using the equilibrium equation developed by Fellenius (see Lambe & Whitman 1969 and Chapter 6) the height of the groundwater, which was necessary to create failure can be estimated. Also we will analyse the influence of different parameters on the amount of failure.

In Figure 7.9 a slump with a circular slipsurface and groundwater running parallel to the surface is depicted.

At limited equilibrium conditions (F=1) we can write, according to Fellinius' equation (see Chapter 6 equation (12) and Figure 7.9).

$$\sum_{i=1}^{i=n} W_i \sin \alpha_i = cL + \left\{ \sum_{i=1}^{i=n} W_i \cos \alpha_i - \sum_{i=1}^{i=n} U_i \right\} \tan \varphi$$

in which (see Figure 7.9) n = the number of slices, W_i = the weight of slice (i) kg, α_1 = the slope angle of the slipsurface of slice i, c = the cohesion (kg/m^2), L = the length of the slipsurface (m), U_i = the pore pressure developed on the slipsurface of slice i (kg). If we assume that the groundwater is running parallel to the slope at a depth of z_0 below the surface (see Figure 7.9) we can write for the total pore pressure developed along the slipcircle (see Lambe & Whiteman 1969, p. 354).

$$\sum_{i=1}^{i=n} U_i = \cos^2\beta\ \sigma_w \sum_{i=1}^{i=n} (z_i - z_o)\, l_i = \cos^2\beta \sum_{i=1}^{i=n} (z_i\, l_i - z_o l_i)$$

in which (see Figure 7.9) β = the slope angle of the groundwater table, σ_w = bulk unit weight of water (kg/dm^3), z_i= the height of slice i (m), z_o= the depth of the groundwater table below the surface (m) and l_i the length of the slipsurface or slice i (m). In equation (1) and (2) which can be set up for each slide all parameters are known except for the depth of the groundwater table z_0. From each slide two samples were taken for the determination of the bulk density and the c and φ values. The wet bulk density varied between 1.72 and 1.85 kg/dm^3 for the slides. The cohesion between 0.10 and 0.15 x 10^3 kg/m^2 and the φ values between 41.2° and 48.1°. With the aid of the bulk density W_i could be calculated. By substituting equation (2) in equation (1) z_0 can be determined. The calculated value of z_0 (see Figure 7.9) is given in Table 7.3 column 5. In this Table the Length (L) of the slide has also been given, the maximum depth z, and the slope angle β.

Table 7.3 Calculated groundwater depths for six rotational slides (type number 8) in weathered metamorphic rocks

Landslide n°	L	β_{crit}	z_{max}	z_o	MW
1	58	33°	6.0	1.53	183
2	58	35°	5.0	0	94
3	18	34°	4.4	0.15	105
4	15	33°	4.0	0.69	72
5	135	33°	13.0	2.71	824
6	12	36°	2.4	0.39	15

L: length of slide in m, β_{crit}: critical slope angle, z_{max}: depth of slipcircle in m, z_o: depth of grounwater below surface in m, MW: volume of water in m³ involved at mass failure per 1 m slope width.

The Table shows that for these slides relative large concentrations of water are necessary before failure could take place. The groundwater has to rise to ± 90% of the maximum depth of the slip circle.

We now come to the question, which landscape parameters are important for the determination of the amount of mass failure for these shallow rotational slides (type no. 8), for which the slides given in Table 7.3 are assumed to be representative. According to Figure 6.8 Chapter 6 there exists an inverse correlation between the critical height (or length) of the slope and the slope angle β, assuming all other values are constant. This relation could not be established for these small range of slope angle values given in Table 7.3. Theoretically there also exists a positive correlation between the c and φ values and the amount of mass at failure (Chapter 6). We could not establish such a relationship for the investigated slides in Table 7.3 which developed in the same material. Probably the range in strength values is too small and the deviation of the mean value is caused by measuring faults and local variation of the material. Figure 7.10, however, shows a positive relationship between the depth and the length of the slide. Observations in the field have also shown that the maximum depth of the slipsurface has been reached within the regolith just above the transition zone with the fresh rock. The slipcircle therefore has developed at a maximum depth within the regolith. We can conclude that

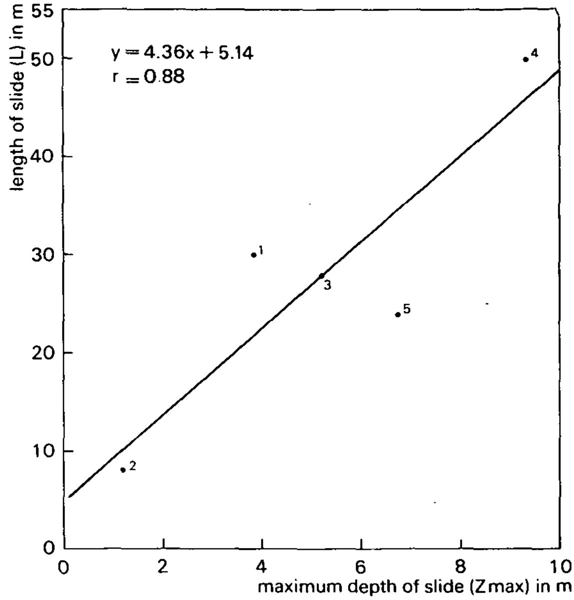


Figure 7.10 Relation between length and maximum depth of shallow rotational slides developed in weathered material on metamorphic rocks.

the thickness of the regolith functions as a threshold and determines the length of the slide and the amount of mass at failure. Above we have shown that for actual failure the groundwater has to rise at a proportional high level above the slipcircle or, in other words, within the regolith before failure can take place.

It is obvious that slopes covered with thicker regoliths also need an absolute larger amount of water for failure. These absolute masses of water per unit width of slopes are given in column 6 Table 7.2.

We will now discuss a type of rotational slide (no. 9), which in general has a higher depth length ratio (1:5) compared with the flat rotational slides of type no. 8. This type has been developed on relative steep slopes in claystone but also in weak cemented weathered sandstone (Mars). The fairly steep slope angle and therefore the steepness of the slip surface in general, has lead to a relative large displacement of the rotated blocks. This is at variance with the more deepseated rotational slides developed on relative less steeper slopes (type no. 10), which we will discuss below. Typical examples of the steep rotational slides (type no. 9) were found in claystone along the lower course of the Fiume Torbido.

The following characteristics could be mentioned:

- A relative steep concave slipplane, which is mostly visible due to:
- A relative large displacement of the sliding material and the formation of a lobate flow tongue at the foot of the slope.

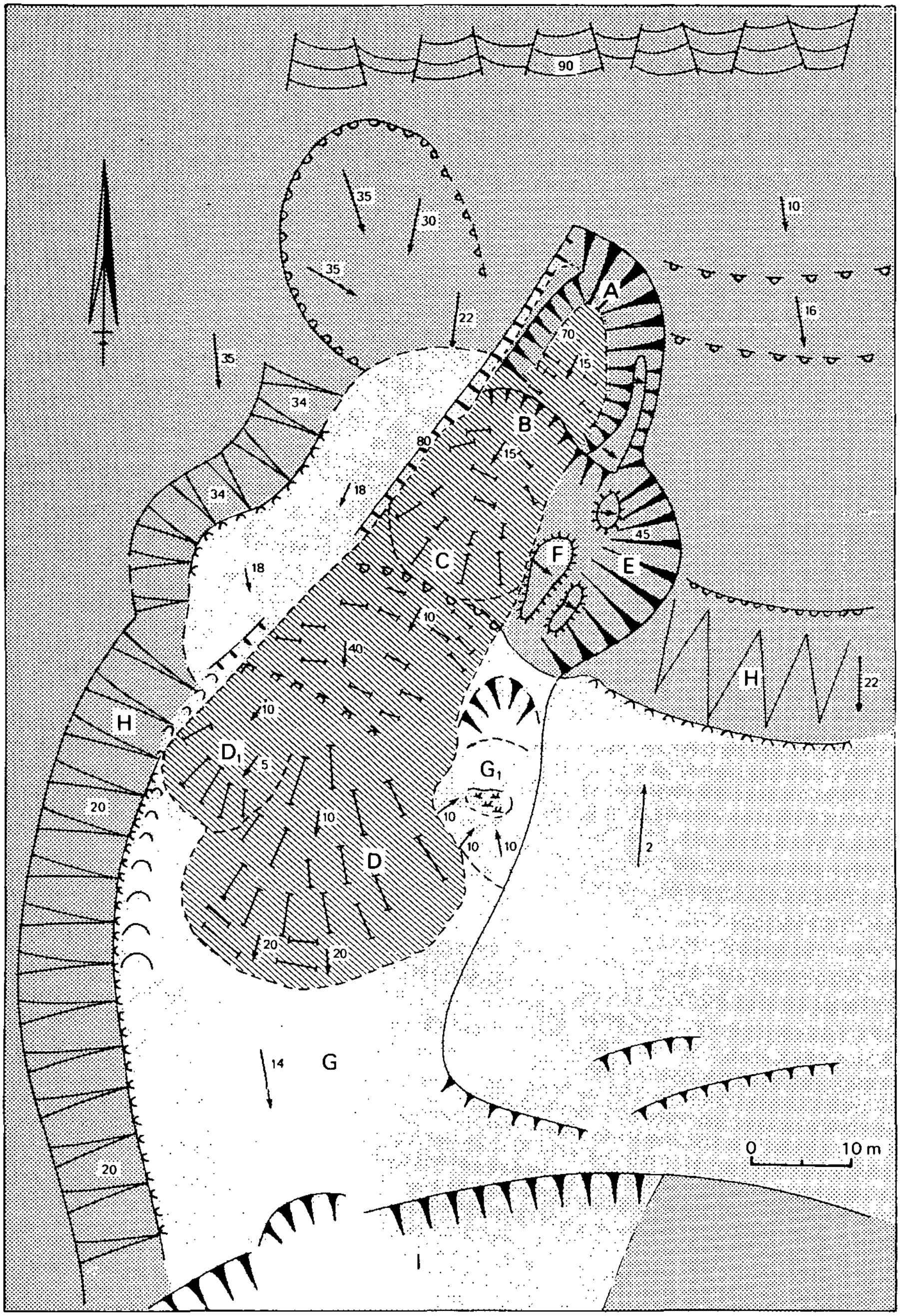
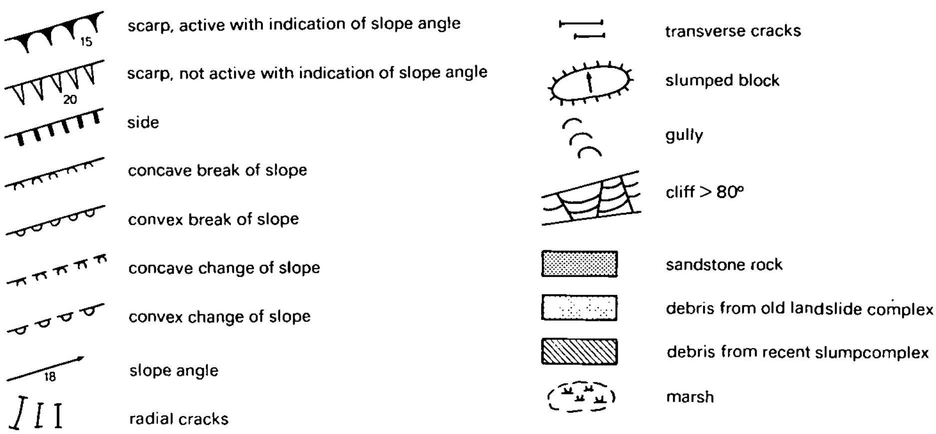


Figure 7.11 Rotational slides in weathered Mars-sandstone in the valley of the Fiume Ste. Maria.

– Most slides developed as a "slope failure" (see Chapter 6, Figure 6.7); the base of the slide in most cases has been formed by impermeable metamorphic rocks which crop out at the foot of the slope.
– The landslides developed in relatively steep slopes, which are related to the concave bank of the meander.
– Local faults can also have lead to weaker zones with landsliding.

This type of rotational slide has also been found in the weak cohesive sandstones (Mars), especially on the steep slopes of the Fiume Sante Maria (see map Appendix A7 and Plate 11). A large instable complex has been found downstreams of the area of "Casa Vino". The foot of the slope of this complex consists of an originally stabilized badland complex (a, Plate 11) (slope angle 35°), which has again become active partly via soilslips and gully-formation (b). Above this steepened foot a lateral concave slope averaging 30° can be distinguished (c). The slope is covered with a debris mass coming from upslope. The vegetation had disappeared and the debris mass has been affected by gullying and shallow mudflows. Further upslope the unstable complex was extended by a distinct rotation slide (d) which was most active during the research period of 1971-1974. By taking pictures (see Plate 12) and by fieldmapping the development of this complex could be kept up for a long period. Measurements were taken in June 1971, February 1972 and 1973 and June 1974. In June 1974 a detailed survey was carried out. Figure 7.11 shows the results of this mapping. A pronounced scarp with an angle of inclination of 55° can be distinguished (A). In 1971 this scarpwall lies a number of meters downstream: the complex has extended itself in a backward direction by slumping (see Plate 12). At the westside this extension correspondended to a joint plane with a dominant strike of 30° which can be followed along the whole complex as a side. The material in the slumping zone has disappeared in 1974 for the greater part. At (B),



in 1974, lies a second scarp which must have developed after 1973. The height is 4 meters and the angle of slope is 50°. About twenty meters furtheron a tongue area (C) with radial cracks was mapped. This tongue area is connected to the slump area under scarp (B). At (E) a secondary slump area, with a backwall of 8 meters length and an angle of 45° could be distinguished in the side of the main complex. The slumped block has, with exception of a few remains (F), completely disappeared. Further downstreams lies a second tongue area (D) with radial cracks and transverse cracks. These tongues lie on the older flowcomplex (G) which has, for the greatest part, been stabilized for years, as evidenced by the electricity pole which must be at least ten years old. Cross-sections of the old flow complex show a convex profile.
The rotational slide with a distinct flow tongue forms the further extension of an old unstable area, which already could be observed on aerial photographs of 1955. The scarps at (H) and the irregular topography at (G) (Figure 7.11) are the outer limits of this older landslide complex. Downslope (I) the area has become unstable again. The vegetation cover has disappeared and mudflows and gullying have strongly affected the debris (see c. Plate 12). In 1971 a pronounced rotational slump complex, with a distinct lobate toe area had developed (Figure 7.11). The rotated character of the slide indicates that the material before failure had a cohesive component (see Chapter 6), and therefore we assume that initial failure took place in partly weathered weakly cohesive sandstone. This is also indicated by the fact that the western side of the slide (see Figure 7.11) is very straight and tied to a marked joint strike direction. The material rapidly desintegrated after failure and due to wetting at the toe a lobate flow tongue could develop. In 1972 the material has been transported further downwards. The tongue area (D) had undergone a pronounced push. This could be observed, among others by the damages on the fields which have been cultivated on the tongue (Plate 12) and the fact that markers set out between (C) and (B) in 1971 (see Figure 7.11) could not be found. In 1973 the slump area had extended itself further upwards from the valley. The scarp walls became clearly visible because the material had sagged further downwards. Thus a second tongue (D) developed. The detailed mapping of 1974 (Figure 7.11) revealed the following developments:

- rapid discharge of material from the head region below the main scarp (A); only remnants of the old slump area of 1973 are still preserved here.
- the development of a new scarp (B) in the old debris material with a tongue area (C) connected to it. Consequently this is a local reactivation of the debris via a new (slump) flow movement, inside the older slump complex.
- the development of new slumps in the side scarp at (E) and the old flow material at (G).

It can be established how, particularly between 1973 and 1974, the activity of this complex has strongly increased. The continuous propulsion of the debris results in the instability of the flanks, so that the complex can extend itself further. The general picture we got from this slope is the development of an unstable area, which started via surfical debris slides at the foot of the slope, and extended further upwards via slump and flow processes which developed especially along various joint planes (see Plate 12).

Another example of this form of "retrogressive" landsliding can be found at a small distance further upstream. On Plate 7, a large more or less stabilized landslide complex. can be distinguished at the foot of the slope. Traces of recent activities can be observed only at the top of this complex (a). Investigations in the field revealed that a number of slump-flow complexes has developed along a fault plane (f). The top complex has affected the road to San Pietro. Under the complex (a) the metamorphic rocks crop out (m). The contactzones between the two types of rock generally form unstable areas. This particularly applies to the contact zone between sandstone and metamorphic rocks since these can pond the groundwater, which causes massmovements in the sandstone. The scarp (f) forms a fault plane which can easily be followed upslope and which can be seen as a slightly gaping crack in the wall along the road to San Pietro. A pronounced knick (k) in the white excavated wall on the photo shows, that the sandstone has moved along this plane. The road to San Pietro had already been affected by a slump movement at the top of the complex before 1971. The road had sagged down and therefore a new road had been constructed, which has resulted in an excavation of the slope at (g). Before 1971 two "walls" had been placed in order to support the old road. This had no effect at all, because the heavy walls were constructed in the head of the slumping area, and therefore functioned as an extra loading on this slumping block. In 1972 the slumping block moved further and the area extended even backwards. The desintegrated sandstones rapidly flowed away downslope via mudflows.
Summarizing we can state that on steeper slopes rotational slides develop. The material of these slides will be transported relatively rapidly out of the sliding areas. This is due to the steeper slipsurface but also to the wetting of the desintegrated material, especially in the case of sandstone debris, which causes the material to move as a mudflow along the steepened slope. Metamorphic rocks at the base and the ponding of groundwater by these rocks lead to instability of the claystone and sandstone. Especially in sandstone we observed that there occurs retrogressive slumping slope upwards along well-developed joint planes.
We now come to a type of rotational slide (type no. 10 Table 7.1), which is connected with relative lower slope angles compared with the types described above. As we have shown in the previous Chapter the lower slope angle, in general, leads to a greater length of the slide and greater depth of the slipcircle. Characteristics for this type of slides is the relative small displacement of the material out of the sliding area. Stabilized slides were found showing a main scarp, which forms only a very limited part of the sliding surface, while further transport by flow processes occurred in a very limited way. This type of slide was found on weathered material of claystone on slopes varying from 5-15°, and metamorphic rocks on slopes varying from 20-25°. Good examples of this type of slide developed in claystone in the "Valle degli Angeli" and the valley of the Fiume Torbido. In the "Valle degli Angeli", along a new constructed road, a typical slump of this type developed in a basin-shaped depression (lateral concavity) of a slope with an angle averaging 18°. The slope has been cut at the foot in view of the construction of the new road. The height of the main scarp of this slide (see Figure 7.12) is not more than 90 cm. A slight camber in the road talus points to recent movements of the slide just before mapping. The movements probably have taken place intermittently, during pe-

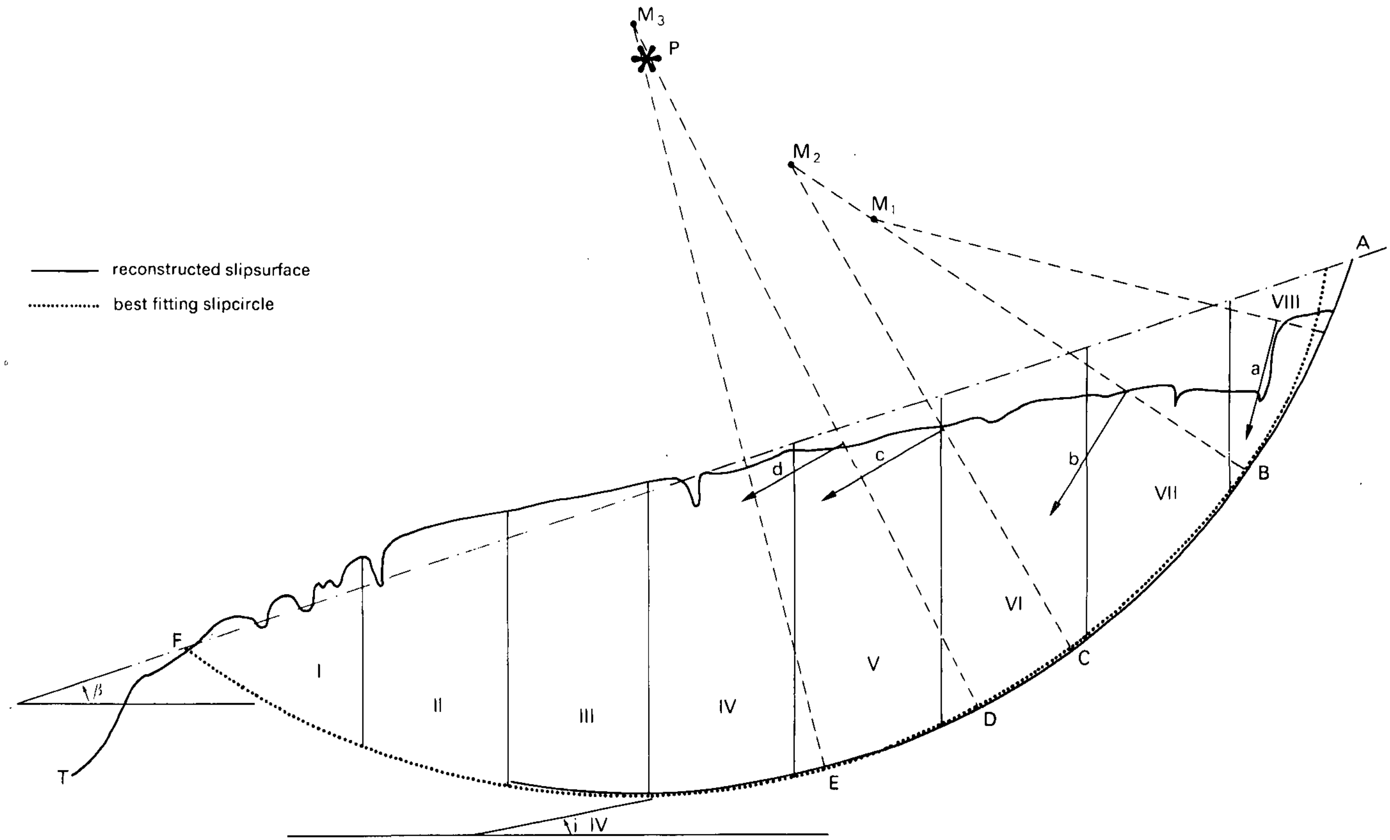
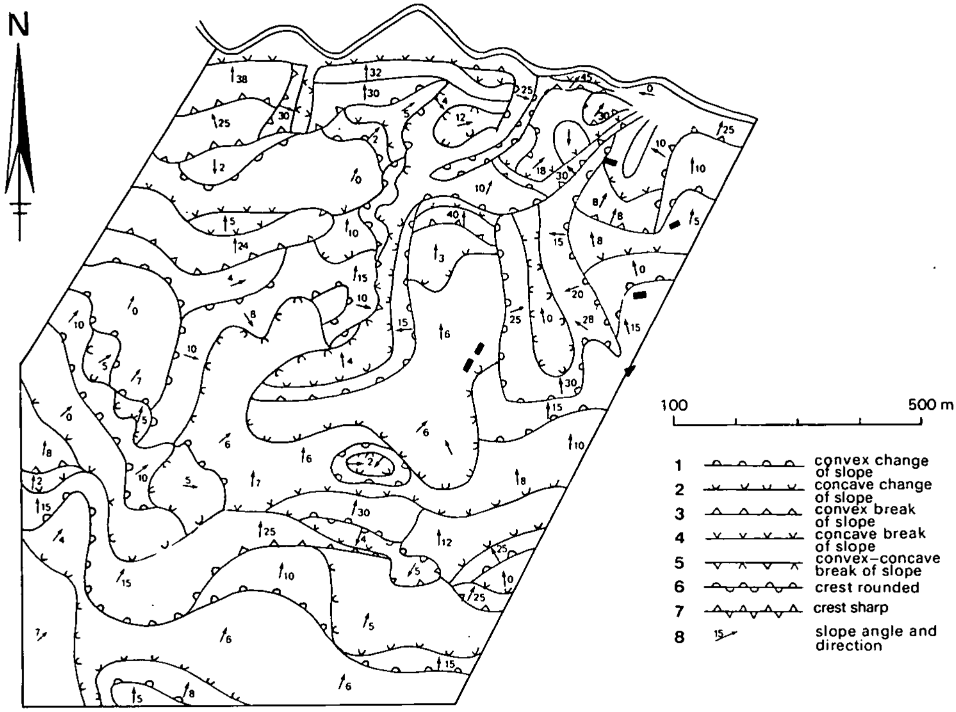


Figure 7.12 Reconstruction of a slipsurface in a slump developed in Ma-claystone; a, b, c, and d: dip of striage lines in side; I-VIII: slices; M1, M2, M3: centre of circle with respectively arc AB, BC and CD; P centre of best fitting slipcircle.

riods of heavy rainfall. Since the displacement of the material of this type of slide is limited, it is difficult to get an idea of the depth and form of the slipsurface which is important for the determination of equilibrium conditions (see below). However, especially in the claystone types we found striation lines in the vertical wall of the sides of the slides which make it possible to reconstruct a part of the slipsurface. The direction of the striation lines, indicates the direction of movement of the slumped block. For this slide the direction of these striation lines which were found along the side are given in Figure 7.12 by the arrows a, b, c and d. With the aid of these directions the real slipsurface (AE) (continuous line) could be reconstructed. The slipsurface begins at the scarp (point A). Assuming that the slipsurface has a more or less circular form, the circle part (AB) can be found by constructing the centre (M). This centre has been formed by the point of intersection of the two lines, which are drawn normally to (a) and (b). The centre (M2) and the circle part (BC) have been found in the same way. Since (c) and (d) are nearly parallel, no centre should be constructed for this part of the slip curve, which means that (CD) is a practically straight line. The circle part (ED) has (M3) as a centre. Given the curve A t/m E the best fitted circle (dotted line) was constructed through this curve, which is assumed to be the ideal slipsurface of the slump. The possibility exists that, in reality, the slipsurface becomes flatter at the toe and may pass through the foot of the slope at (T). We could not, however, detect the position of the slipsurface at the toe. Before we will set up the equilibrium conditions for this slide complex according to the model of Fellenius' we will describe some other examples of this type of rotational slide.

Further upstream in the head region of the Valle Irroiti a second example was found, for which the slipsurface could be reconstructed in the same way. Between two successive fieldwork periods an intermittent sagging of the slumpzone was observed: In 1973 the height of the scarp was 70 cm. No movement could be detected in this field period (of 3 months). In 1974 the scarp has increased to a height of 2 meters. Compared with the foregoing described type of slumps the displacement through time of these slides is relatively small. Therefore these types of slide are difficult to trace in the field, because the initial scarp may easily disappear by ploughing activity on these clayslopes. Detailed investigation on the valley walls of the Fiume Torbido revealed a number of unstable areas (see map Appendix A7, type 10) where this type of slow slumping could be detected. Instability especially occurs in parts of the slope with a profile- and contour-concavity and therefore a maximum concentration of groundwater. The main scarps which were found in these unstable areas are not high (20-50 cm) and such traces disappear quickly by ploughing. However, the crooked olive trees and the irregular topography are indications towards the fact that these areas have been unstable for a long time. On the aerial photographs these areas can be recognized by denser planted olive-trees and darker tints of the soil (concentration of groundwater). From interviews with the inhabitants it became clear that displacement of the material is not large, but through time movements frequently occurred. Retaining walls, which must protect the partly burried houses against the soil mass, which frequently pushes forwards, must constantly be repaired. The most prominant unstable parts of the slope are indicated on the map. But the many irregular slope profiles show that the most important parts



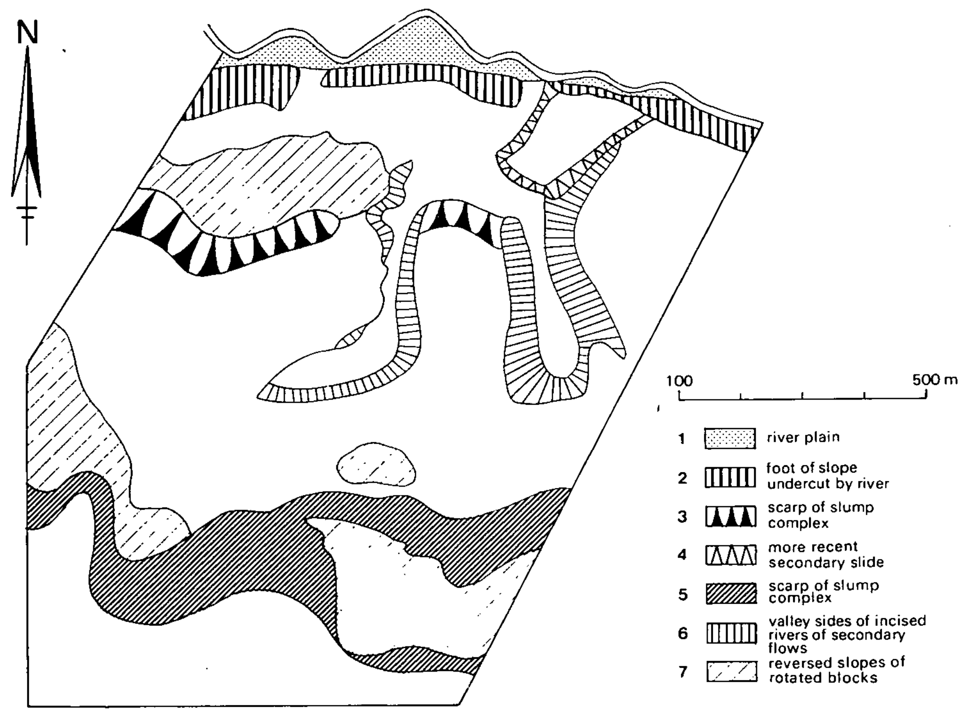


Figure 7.13 Morphometric map of a fossile slump area in the valley of the Fiume Torbido.

of the denudation of these slopes have taken place by massmovements. Water erosion and surface creep have, on the geological time scale, contributed in a much smaller way in the transport of the slope material. A stabilized example of this type of slide (10) was found in the upper valley and of the Valle Irroiti. At this point, the river shows a narrow incision of ± 10 mtr. The material of the landslide consists of heavily weathered claystone. No traces of fresh rock in situ could be observed in the scarp walls and in the incision of the river at the toe. A number of outcrops in the neighbourhood shows sandy layers which are practically horizontal. Scarps have developed in a slope of about 5° (except at the toe). The depth of the landslide is not known but the profile of the slide suggests, that in the underground the slipsurface must partially follow the hard substratum, since the mean thickness of the regolith is much lesser as the maximal depth of the reconstructed slipcircle would suggest. Also we may think of two retrogressive slumps developed in weathered clay, with the slipcircle resting on the base of fresh claystone, which lies nearly horizontal in this area.

A much older landslide complex of probably this type is found in the south eastern slope further downstream in the valley of the Fiume Torbido at Marina Savuto. It can be seen on the map that the expansion of this complex has been extensive.

The incision of the Fiume Torbido had steepened the foot of the slope of this complex. The clay beds gently dip in the direction of the slope. The complex is characterized by a slope with a softly undulating topography and closed depressions. The area is completely stable and is now under cultivation. In the area we performed a detailed morphometric mapping following Savigear's method and applied by Brunsden (1976) for detecting the characteristics of "fossile slides" (see Figure 7.13a).

The detailed morphometric survey revealed a scarp complex at the top (5) (see Figure 7.13b) and a secondary scarp halfway down (3). Before these scarps traces of backward rotated blocks with nearly horizontal or reversed slopes (7) could be distinguished.

The landslide complex has been affected in the lower part by broad valleys (6) and (4), which might be traces of secondary flows, having further transported a part of the slumped material to the river Torbido. The landslide complex can be considered as a complex of at least two large retrogressive slumps. The slipsurface may be partly determined by dipping clay siltstone layers towards the river.

Also in the area of metamorphic rocks, on slopes with a relative thick solifluction cover, and especially on parts of the slope with a profile and contour concavity, unstable areas with slow slumping movements can be found. Compared with the unstable areas developed in claystone, described above, the slope angle in this area is steeper (20-25°) (see Table 7.1). More pronounced slides show clearly the character of a slump, with a round crown at the head and a somewhat bulged toe area. In general the displacement is relatively small and therefore pronounced scarps are not always visible and in most cases are ploughed away. Indications toward these unstable areas are: a) locally denser olive planting and leaning trees, b) irregular topography, c) frequent sagging of roads, which necessitates constant reparation, d) the hydromorphic character of the lateral concave slope facets and many springs.

In one case we could find evidence for the depth of the slipcircle, which gave a depth-length ratio of the slide of 1:5. This ratio is larger than the depth/length ratio of the

shallow slides developed on the steeper slopes of the metamorphic rocks. We therefore assume that a lower slope angle and a thicker solifluction cover lead, at sufficient high water tables, to more deep seated slides (see below).
The above given description showed that in the claystone area two types of rotational slides can be found (type no. 9 and no. 10, see Table 7.1) which differ in morphometrical properties and also in degree of displacement out of the source area. For five of these recently developed slumps, developed in weathered material of Ma-clay siltstone, we were able to measure, in a more or less accurate way, the slipsurface. On the steepest slopes in which type no. 9 developed (see Table 7.1), the relative large displacement of the rotating blocks exposed most part of the curved slipsurface. On less steeper slopes, type no. 10 developed (see Table 7.1). The displacement of the rotating block of this type was relatively small, but it was possible to reconstruct the slipsurface with the aid of striage stripes (see above). For each slide two samples were taken, which gave a mean cohesion of the material of 0.097×10^3 kg/m^2 and a friction angle of 32°. The wet bulk density averaged 2.15×10^3 kg/m^3. By using the equations (1) and (2) the critical

Table 7.4 Calculated groundwater depths for five rotational slides (type number 9 and 10) in weathered claystone.

Landslide n°	L	β_{crit}	z_{max}	z_o	MW
1	30	25°	3.8	0.35	46
2	8	30°	1.2	0.20	5
3	28	21°	5.2	0.17	96
4	50	21°	9.3	0.69	302
5	24	17°	6.7	0	111

L: length of slide in m, β_{crit}: critical slope angle, z_{max}: depth of slipcircle in m, z_o: depth of groundwater below surface in m, MW: volume of water in m^3 per 1 m slope width

height z_0 of the groundwater below the slope surface could be calculated, assuming that the groundwater is running parallel to the slope at a constant depth.
This critical depth, together with other parameters of the slides, are given in Table 7.4. Given the fact that the soil mechanical properties of these slides do not differ much, we can wonder which other values determined the amount of sliding material. In Chapter 6 it was stated that a decrease in slope angle β must lead to an increase in length of the slide. Figure 7.14a, b. shows this trend for the 4 investigated slides. The weak correlation of the Figure indicates, that other variables also have influenced the amount of mass failure, for example the depth and length of the slide.
Above we mentioned that the depth of the regolith may also be a variable determining the amount of sliding material. Figure 7.14c shows a positive correlation between the depth and the length of the slide. In two cases we could establish that the slipcircle rested on the fresh claystone, while in the three other cases the slipcircle was not exposed far enough. However, we might conclude, that as in the case of type no. 8 dis-

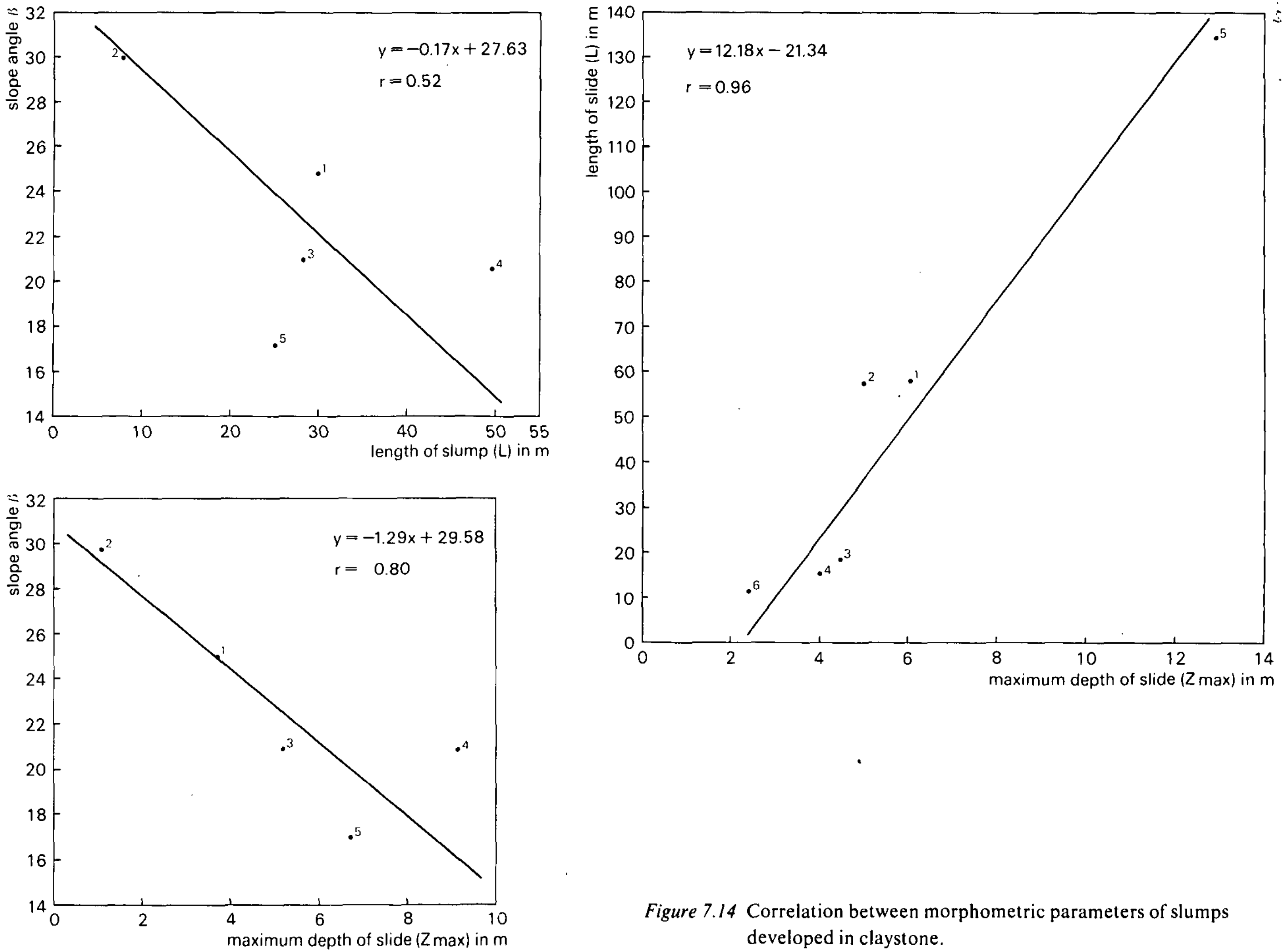


Figure 7.14 Correlation between morphometric parameters of slumps developed in claystone.

cussed above, the depth of regolith determines the amount of mass failure and that in shallower regoliths failure is only possible in steeper slope angels. In all cases the groundwater level has to rise to 9/10 of the depth of the regolith (see Table 7.4 column 6).

7.4 The influence of landscape variables on landslides with a dominant mudflow character

In this paragraph we will deal with landslides in which the material, after failure, has been further transported by slow mudflows (type no. 11) (Table 7.1). Movements are more or less continuous in the periods with high rainfall, which in the study area especially occur in the winter period (Chapter 2). The first examples given here are related to unstable areas in claystone with deep seated slumping (compare type no. 10) and large concentrations of water due to profile and contour concavity. In distinction with the unstable areas, described in the foregoing Paragraph (type no. 10), the displacement of the material is more rapid, due to the fact that the unstable area is captured by a steep valley which enables the material to "drain" via an elongated mudflow further downwards.

Examples of this type of landslide are found in the Timpa Caruso area (in the river basin of the Fiume Oliva, see map Appendix A7). In this area claystone crops out with sandstone (Mar) and metamorphic rocks underneath. In the lower course a steep valley has developed in the metamorphic rocks and in the sandstone. This valley branches in the upper part in the claystone area and in the extension of these branches large slumping areas have developed, which are partly still active. At some places, the material moved downwards through the valleys in the form of slow elongated mudflows. A similar complex developed in the river basin of the Torrente Collonci in the area of the Pianotorre (see map Appendix A7).

This area is a gently sloping depression consisting of claystone. Around this area metamorphic rocks and sandstone crop out. The tributary, the Torrente Zecco, which has a very straight course, incises into this claystone area. The whole clay area betrays the traces of instability. Large portions of the area are used for agriculture. In the wet winterperiod certain areas are inaccessible because of the oversaturation of water. The clay reaches a completely fluid phase. The most recent and active movements have taken place during the last few years in the headwater region of the Torrente Secco. Here fresh scarps have developed.

Further to the east at the same height is also a beginning of scarp formation. It appears from interviews from inhabitants that the complex is still expanding further backwards and forms a real threat to the surrounding farms. The most active area in the upper course of the Torrente Secco expands according to a pattern, which corresponds to the branching (of the river) or the supplying veins of water of this river in the headwater region (Plate 13).

In Figure 7.15 a prominent "supplying area" with a mainly slump character can be distinguished, which passes out into a long elongated tongue which moves downstream in the flat valley of the Torrente Secco. This long flow track forms evidence for the good "flowing" properties of the material (see Appendix A5).

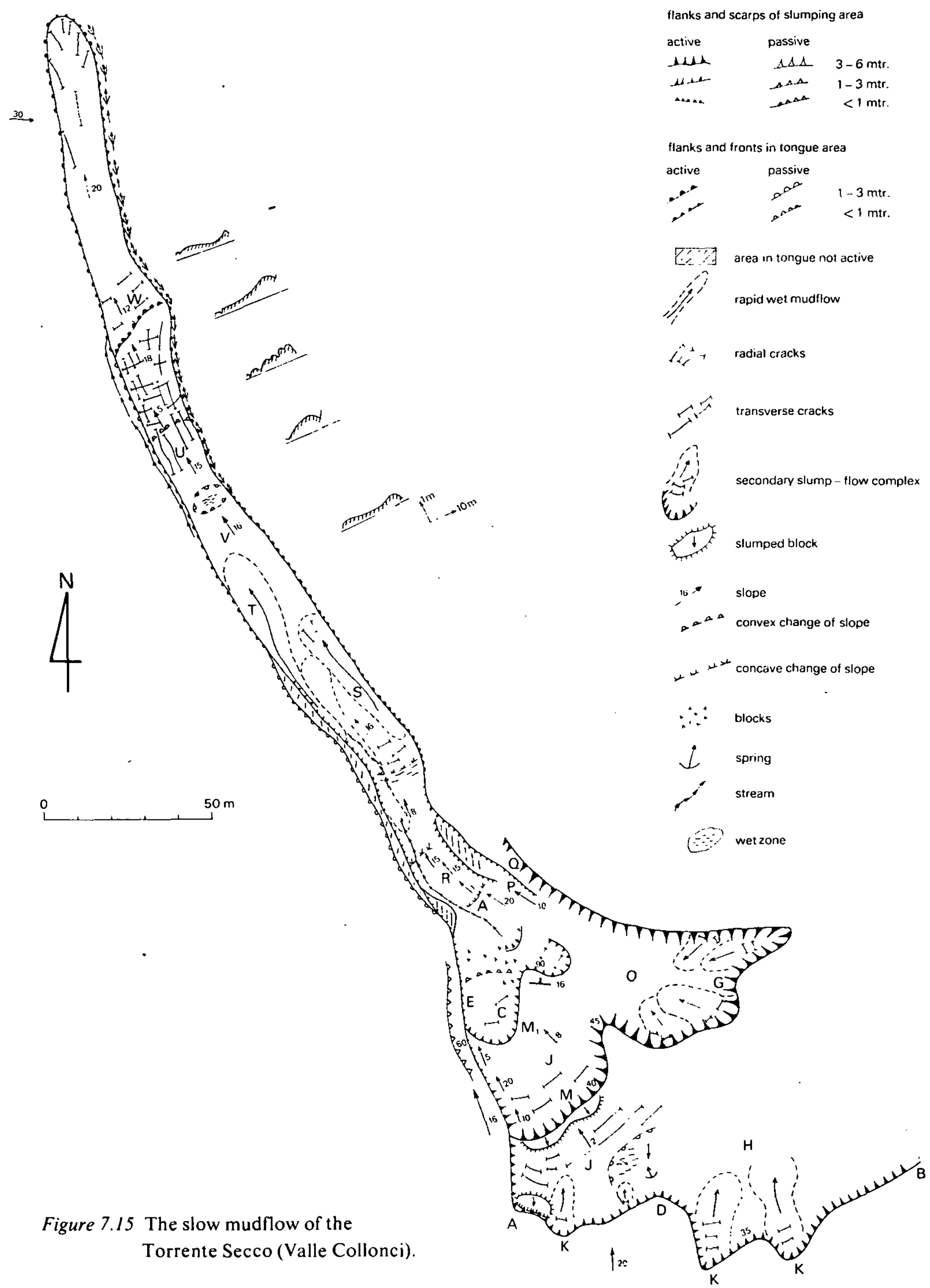


Figure 7.15 The slow mudflow of the Torrente Secco (Valle Collonci).

The slump area is limited above by an irregular scarp (A-B). It could be ascertained on this scarpwall that from 1973 to 1974 the surface of the complex has sagged down an average of 2 metres along the edge. This scarpwall was affected by a number of separate slumpflow complexes. The most recent (K) dated from 1973. At (H) there was a lower depression which could have developed due to a greater discharge of material. At (J) an area with principally a slump character could be recognized. The secundary smaller scarps with a few reversed slopes of rotating blocks in between them pointed to this. Slightly downstream a prominent second scarp (M) with a height of 5 metres and a slope angle of 40° has developed. The very recent wall (E) of 6 metres height had freed itself after 1973 due to the sagging down of slumpcomplex (C) at the height of this wall.

In the side (E) striations, which lay parallel to the surface of the original topographical slope, could be seen. The scarpwall (M1) with fresh striations with an angle of 45° and also with reversed slopes indicates that the whole complex has recently (after 1973) undergone slumpmovements. coupled with a sagging of the surface by which the wall (E) became free.
At (O) lay a second expansion of the complex which was bound to a small tributary of the river system. This part was scoured out fairly deeply by rapid flow movements of the material and by the transport of flowing water. It can also be established here that from 1973 to 1974 the scarpwalls have gained in height (at (G) from 3 metres to 8 metres). Due to this strong increase in height the scarpwall was damaged at many spots by secondary slump movements.
New scarps with a height of 5 metres also developed off (P) after 1973. The presence of striations showed that slump movements with an upper slipsurface of 40° have taken place. The hard rock also partly moved with it. The striations in this scarpwall were in 1973 and in 1974 parallel to the slope and measured 15°. At the height of (A) the material could escape out of the supply area into the shallow valley of the Torrente Secco via a slope of 20-25°. At (R), at both sides of the flow, a higher level of the tongue from 1973 could be recognized. The central part of the tongue moved on more rapidly and the surface lay 2 metres lower than the more rigid sides. The originally swollen tongue mass had sagged down. The elongated flow track curved along with the original gradient of the valley, causing transverse cracks due to rapid slope changes. In the relatively less moveable sides of the tongue, striations can be observed running parallel to the surface with a angle of 10-12° (see Plate 14).
At (S) and (T) two flow complexes clearly began to discern themselves from the surroundings. The material has (taking the microtopography at the surface into account) been very fluidal and must have moved onwards more rapidly than the rest of the tongue. These local movements can be considered as flow "rapids" in the total onward moving complex. At (T) the cross section of the tongue showed a convex profile. Here the tongue lays on a wide round valley floor. At (V) it can be seen in the cross section how the convex surface of the tongue sagged in again due to the discharge of material below, and a delayed supply from above. Some ten meters downstream there was a closed depression, with a small lake.
At the level of (U) lay an area with large longitudinal cracks of 60 cm to 1 meter wide. Further downstream transverse cracks joined to these longitudinal cracks, so that the material was dissected into a number of more or less rigid clay blocks separated by cracks of 1 meter deep and upto 1 meter width. In the walls of the cracks the striation showed a pattern such as given schematically in Figure 7.16.
Two directions of movement can be seen from the pattern: a movement parallel to the surface caused by a "flowing" in the underground, and a movement by which the more or less rigid blocks sag irregular with respect to each other, interrupted by phases in which the blocks moved onwards in the general flowing direction once more. The observed movements indicate to a flowing tongue, which at some places passed steep thresholds in the underground causing more or less vertical movements and transverse cracks. Furthermore, it must be concluded that flow movements have taken place in the underground while the top of the tongue material behaves here as a more or less rigid broken mass.
A scarp had developed at level (W). Below this scarp the material was wet upto the top and

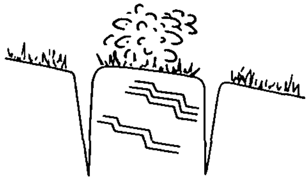


Figure 7.16 Striage lines in rigid clay-blocks on top of a slow mudflow.

downstream had the character of a wet flow. The debris had, contrary to the part above the scarp (U) moved onwards as a relatively wet and probably rapid flow. The tongue ends at a flat part of the rivervalley and had a swollen up character with a steep front of 30°.

The landslide complex, described above in detail, can be considered as a reactivation of a stabilized landslide complex that extends over a much greater area. A few steeper walls near Casa St. Elia and further to the north in the direction of Casa Pino form the old scarps of this complex. The irregular topography of the terrain also points to an earlier movement of the ground.

One of the main causes for the instability of this area is the great overload of water. On one hand there is a large supply of water from the sandstone complex lying above; the many springs at the boundary between sandstone and the clay point to this. On the other hand the metamorphic rock in the underground will pond the groundwater. At the western side the unstable complex is affected by a rapidly incising valley system. In the valley head of this small river where much groundwater from the surroundings is gathered together, the most recent massmovements develop. Outside the area studied in detail, landslides in the form of complex slump-flow movements also occur, through which the surrounding farms are seriously threatened (Plate 13).

In the area mapped in detail (Figure 7.15) a strong movement has taken place particularly after 1973. The scarps along the top of the slump area increased 30-50% in height in one year and a number of new scarps were formed by the rapid discharge of material. The detailed description made above shows that the movements are not homogeneous and that furthermore the mechanisms of the movements differ in time and in place. In each sector of the complex it could be ascertained that the supply and discharge were not balanced to each other. This could be seen most clearly in the tongue area. In certain sectors accelerated movements took place locally via mudflows. This accelerated discharge out of a certain sector caused slumping in the sector above it. The upstream part of the tongue had sagged strongly during the mapping period. Apparently a disequilibrium in the supply and discharge had developed here, caused principally by the fact that the movements in the supply area had dropped sharply. The various mechanisms of movement, which were observed within the complex must be related to the percentage of moisture in the clay. In Figure 6.1 (Chapter 6) the stress-strain curves of a characteristic sample were given in relation to the moisture content and Atterberg limits of the sample. For the flowing tongue the Atterberg limits

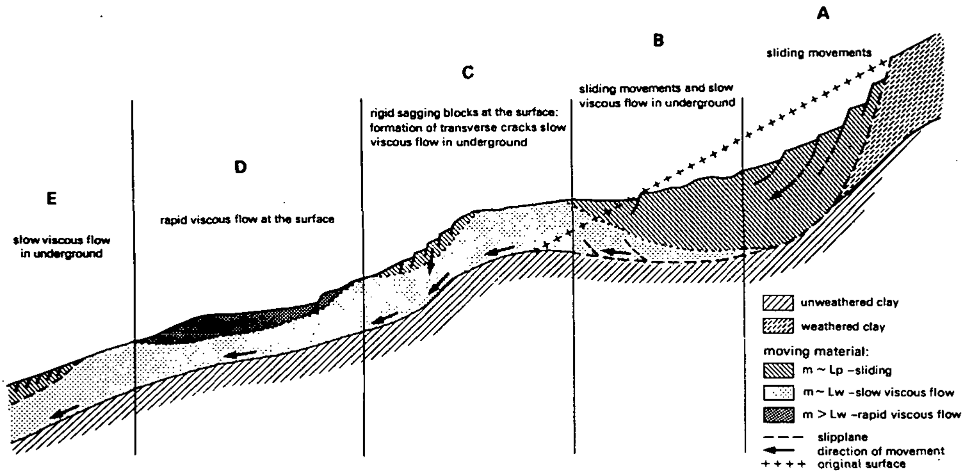


Figure 7.17 Schematic picture of the types of movements in the slow mudflow of the Torrente Secco.

were: L_p 25, L_w 47.6, PI 22.6 (see Appendix A5). The detailed description given above showed that probably three types of movement can be distinguished in the landslide complex (Figure 7.17).

Sliding movements along a well defined slipplane. These movements take place in the form of slumping in the supply area (section A and B Figure 7.17). The moisture content of the material must lie in the neighbourhood of the L_p-index. The material has a definite strength value, determined by cohesion and angle of internal friction and fails at a certain shear stress value τ_o along a slipsurface, without internal shearing within the moving mass (see Chapter 6, Figure 6.1).
In the tongue area (section C t/m E, Figure 7.17) movements in the subsurface can be explained by the mechanism of slow flow movements or continuous creep (Terzaghi & Peck 1967) or by the mechanism of sliding (a.o. Hutchinson 1970).
When movements take place by continuous creep, the moisture content of the clay must have reached the vicinity of the L_w-limit which gives the material a viscous component with a relative low yielding point (see Figure 6.1, Chapter 6). If the thickness of the tongue and the slope angle surpasses a critical value, the yielding point of the material is reached and continuous creep can take place. Unfortunately no data could be assembled of the maximum moisture contents within the flow and the related stress-strain characteristics of the material. However, we can make a rough estimation about the possibility of sliding of this tongue. If we take the soil mechanical values given in 7.2 as representative for the weathered claystone, and if we assume that the mean thickness of the tongue is 3 meters, the critical slope angle at which sliding takes place, in case the tongue is fully saturated with water is, according to equation (6.11) (Chapter 6) about 19.5°.

This critical angle is higher than the mean slope angle of the tongue (10-12°). We must conclude that, when the material is in a more plastic state, the slope angle is too flat to cause failure via sliding. Probably the material in the subsurface is in a more viscous state, due to a high moisture content, which enables the material to flow at lower slope angles. At the surface of this flow we observed rigid blocks of clay (see detailed description) with striage at the sides. It may be assumed that these blocks float as rigid masses on the flowing material in the subsurface (see Figure 7.17, section C).

– The detailed description given above showed also that flowing can take place at the surface. Elongated tracks of mud with a high liquidity has been observed (see Figure 7.18, section D). The material must have had a water content above the L_W-limit and started to move at low slope angles, superficially, which is due to the fact that the yielding point is very low to practically zero.

South and West of "Cozzo Ravo" in the neighbourhood of San Pietro (see map Appendix A7) extensive complexes of massmovements can be found. A special type with a dominant flow character (type no. 11) had developed in the head of the tributary valleys of the Fiume Catacastro. The lower course of the river profile has a steep gradient and the valley walls are very steep. These steep walls are partly sagged down by rockfall, particularly at the concave bend of the river along joint planes (type no. 2). Upstream the river profile shows a prominent "knick". Furtherup the valley branches. Here the river profile has a smaller angle and the valley walls are less steep. This section of the valley presumably dates from an earlier incision phase: it forms a relict of an older less steep dissected relief to which the flatter part of San Pietro may also belong. They are especially parts of this elder valley systems which have become unstable.

In 1974 a detail-mapping (see Figure 7.18) has been carried out along a longitudinal section taken through the Southwest branch. The Southwest branch of the landslide complex is limited at the top by a rockfall. The cliff of this rockfall has a strike of 260° and 330°. The wall has a gradient of 75° and is 26 meters long. The wall is unvegetated, as well as the side, which has a strike of 180°, which corresponds to a dominant direction of strike of joint planes measured in the neighboorhood (see joint plane frequently diagram Figure 7.2). This unvegetated side is not visible on the aerial photograph. It is assumed that the scarp has retreated some forty meters since the aerial photograph was taken. It could be ascertained during the mapping that the wall is still being affected by small falls. In front of the wall lay a block field with an maximum angle of 35°. At (A) a prominent scarp was present which means that the landslide complex is still extending further backwards. At the level of (B) a densely vegetated more or less stable tongue was found. At the level of (C) the profile became somewhat steeper. A number of scarps of of 1-3 meters and transverse cracks of 20-60 cm wide were found here and were active during the mapping. At (D) a reversed scarp is visible which points to a locally backwards slumping of material in an unslope direction (Ritchie 1958, Zaruba & Meckl 1969). The scarps and reversed scarps between (C) and (D) indicate that in this zone a complex of slumps have developed. This slumping area continues downslope untill the lake which was dammed by a reversed scarp with a slope angle of 40° (E). The lake itself is lying in a so-called "graben" (see Ritchie 1959). Downstream of the lake old valley system passed over into the younger valley stream with a steeper gradient. Here we found an active zone with prominent transverse cracks and steps with a height of 50 cm. The main scarp found here had a slope angle of 40° and a height of 8 meters. At (F) further downstreams the debris mass showed a convex longitudinal profile. The surface was for the greatest part incised by transverse and longitudinal cracks. The surface material of the landslide at this spot contained much water. This part of the complex can be considered as a tongue area which can be connected with the active slump area lying above. Due to the large amount of water which accumulated in this lower part the material took on the character of a liquid mud. Flowing is also easily initiated here by a steeper slope angle of 25°. The debris at the level of (G) had only a thickness of 4 meters. Discharge of debris took place due to the flowing water in the gullies, which extended rapidly upstream via the longitudinal cracks.

In the head of the less sharply incised older valley system of the Monte Cozzo Ravo, also a landslide system could be observed, showing a slow mudflow, which is feeded by a supply area with probably deep seated slumps. The southwest branch of the landslide complex is limited at the top by a rockfall, which is related to the development of joint planes (see detailed description) and dated after the period the aerial photographs were taken (1955). The head of the valley system, consisting of two major branches, is characterized by a complex of sliding (mainly slumping) masses. The detailed mapping showed that the flat slope of the valley are more or less stable, but that especially the broad valley floor itself has begun to move. We might think of a serie of retrogressive

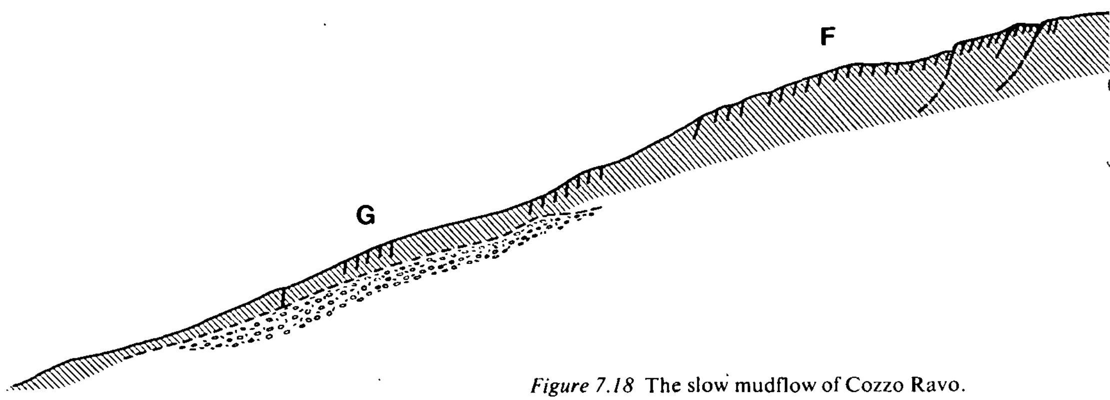
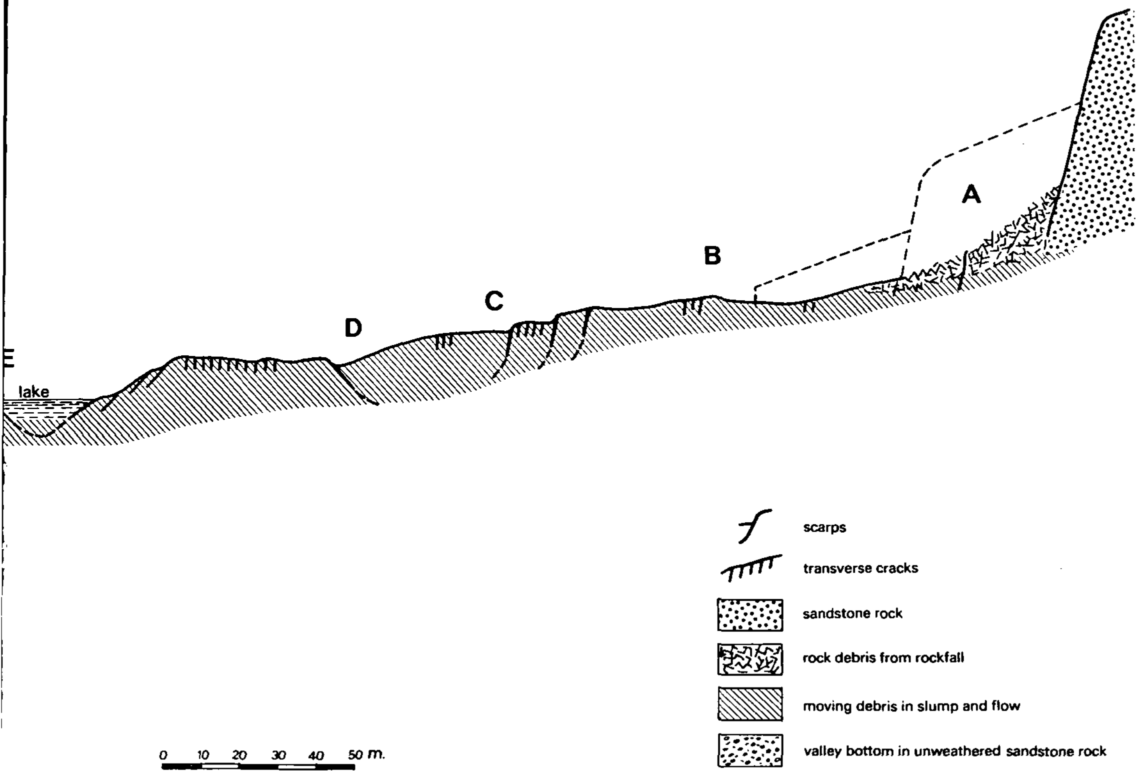


Figure 7.18 The slow mudflow of Cozzo Ravo.

slumps in the valley floor. The "graben" with lake (E) and rotated blocks up hill (D) (Figure 7.18) indicates, according to Ritchie (1959) that the slipsurface of these slumps are not quite circular but have a marked decrease in curvature downslope. This probably is due to the fact that the slipsurface is partly tied to bedding or fault planes in the sandstone. It can be ascertained that the system extends further continuously due to losses of mass in the southwestern branch. In this manner a shallow basin at the north-side of the complex at the height of (F) has begun to move fairly recently and a "tongue" which belongs to this basin can clearly be observed on the main stream as a "riding" glacier. Downstream of the lake at (E) the valley passes into a younger valley system with a steeper gradient and further downward steep and high valley slopes. The landslide complex passes here into a slow mudflow or mudslide. It could not be established, whether the movement was caused by flowing or sliding (see slump-flow complex of the Torrente Secco area). Observations in the field showed that especially in the wet winter period, this part of the landslide complex is fully saturated with water. At the level of (G) it could be established in a deep gully that the debris was "flowing" with a thickness of 4 meters over the original valley floor. The position of the extremity of this tongue is determined by the dynamic equilibrium, which is established between



the supply of debris from above and the discharge of debris by means of gully erosion and water erosion or secundary rapid mudflows to the water. The toe of the tongue has moved downward since 1955 due to a greater supply from above, which may be connected to the extension of total landslide complex. Apart from the effect of the lithological characteristics of the partly weathered rock, other factors also play a part:

- The strong retrogressive erosion of the lower river part, through which the upper valley system has become unstable.
- Concentration of water in the old flat valley system, causing development of a systems in which massmovements and intensive gully erosion operate at the same time.

The complexes described under type no. 12 (see Table 7.1) are complex erosion systems in which massmovements and intensive gully erosion operate at the same time. These so-called "badland" complexes are completely devoid of vegetation and have developed on steep slopes ($> 35^\circ$). They are characterized by a gully system which is determined by the lithological characteristics and the age of the system (Plate 15). Since the complexes were found on the steepest slopes in the study area, we have concluded that in most cases these badlands have developed in areas where shallow debris slides (type no. 7) rapidly have slipped large parts of the slopes of soil and vegetation. On these steep slopes it was impossible that the vegetation could regenerate because weathered material immediately is carried away by intensive gully erosion and mudflow processes (Plate 15). The badlands have developed in many places of the study area (see map Appendix A7) especially in the riverbasin of the Fiume Oliva. Extensive badlands are found in the upper basin of the Valle del Signore and the Valle Spinoza in metamorphic rocks and weakly cemented sandstones and in the Valle Grecci (in granites). Also in the lower course of the Valle Callonci and in the valley head of the Torrente Calcato active badland complexes with deep gully systems were found. In the river basin of the Fiume Grande we found that at the steepest foot of the slope gully systems have developed in areas which are recently affected by soil slips.

The installation of pegs in a number of gullies, varying in depth from 0.5-2 meters and in width from 1-4 meters, revealed that two processes are important in these gully systems:

- Surface water erosion at the interfluves (0-1 cm) after one year.
- Slump and flow processes on parts of the interfluves and at the gully bottom, which locally reaches depths of ± 1 meter.

The slided material is rapidly carried away via mudflow processes in the gullies downstream. River basin with extensive badland complexes, as e.g. the Valle del Signore, delivers in rainy periods relative large masses of sediment of the rivers. Measurements of sediment concentration after heavy rain period show concentrations which are 10-100 x higher in comparison with rivers which have no badland complexes in their drainage brain.

In the Vallone della Fabrica (Fiume Grande drainage basin) we have described debris slides (7.2) which are already affected by gullying (see Figure 7.6 and Plate 8). The gullied soilslip complexes have developed on slope angles of 40° about 50 years ago (oral communication from the inhabitants). The greatest part of the regolith layer has been cleared away. The complex consists of a lightly branched gully system. The gullies are on an average 50 cm deep and 2 meters wide, with a maximum depth of 3 meters and a maximum width of 7 meters. The slopes have a slightly concave profile and on some waterdivides between the gullies are still some remains of the regolith cover. From the geometry of the gullies it can be estimated that ± 800 m^3 material has been carried away in the estimated 50 years period, which means a mean thickness of net erosion over the surface of ± 1 cm per year in these metamorphic rocks.

7.5 Summary and conclusions

In the foregoing we have discussed the development of different types of landslide in relation to landscape and process variables. Attention was given to the amount of production of moving material and the transport characteristics of the landslides (see Table 7.1).

In the sandstone regions the rapid incision of the river has led to the development of a large number of rockslides, which generally produce large amounts of debris material. Special landscape and process variables which initiate motion in these sandstone region are a.o. the undercutting by rivers of the slope, weakening of the rock by faulting and development of joint planes dipping toward the free slope face and ponding of water in impermeable layers. However, the strength characteristics of the weakly cemented and cemented sandstone are such that steep and high slopes are needed before the point of instability is reached. The rockslide of type no. 1 (see Table 7.1) forms a good example of this system. It was shown that due to a relative high cohesive strength of the sandstone rocks, high cliffs could develop, which at the point of instability produced large quantities of rockmass. Relative high strength values must exist also along the bedding planes and joint planes of the sandstone rock, producing on places with a high relief energy large amount of rockmasses (see type no. 2, 3 and 5). High shear stresses were also induced in the past by earthquakes, which also led to large rockslides in areas, which nowadays are stable (type 1, 3 and 4).

As regard to the transport characteristics of the rockslides we found that for type no. 1 and 3 the debris must have rapidly come to rest, even on steeper slope angles. The limited travelling distance may be explained by two facts: a) failure in wellcemented Mar-sandstone rock leads to a disintegration in large blocks, with a limited amount of finer matrix, which prevents a high fluidity of the flow under wet conditions; b) failure is not induced for this type of slides by a high pore pressure of the groundwater but by a rapid rise in shear stresses due to earthquakes. This means that failure may have taken place under relative dry conditions. In variance with this is the type of transport described under type no. 5. This recent rockslide occured after heavy rain periods. The weakly cemented sandstone (Mars) rapidly desintegrated after failure in large quantities of mud, which is continuously set into motion via flows during wet periods.

Steep slope angles, especially at the foot of the slope, has led on places undercut by rivers to instability of the relative shallow regolith cover (type no. 7). In the claystone area instability occured on slopes between 32° and 36° while on slopes in metamorphic rocks shallow slides occured on slopes around 42°. Given the strength characteristics of the regolith, we concluded that positive pore pressure of groundwater was needed to initiate failure and the groundwater table has to rise to 2/3 (claystone) or halfway (metamorphic rocks) of the depth of the regolith above the shear plane. In the cohesive claystone regolith material the slipsurface developed at a maximum depth in the regolith just above the fresh rock which needed a minimum amount of pore pressure. Therefore, apart from the length of the slope over which sliding can take place, the depth of the regolith cover determines the amount of moving material. In the cohesionless regolith cover of the metamorphic rocks case-studies show that the slipsurface developed in the horizons with the weakest strength which was lying about in the middle of the regolith profile. It is the position of this zone which determines the amount of mass moving at failure.

On metamorphic rocks, with a thick regolith and solifluction cover (upto 10 meters) "flat" rotational slides developed on slopes varying from 30-35°, with a depth-length ratio of 1:10. These slides were especially activated by mass during the construction of the Autostrada. We established a positive correlation between the length and depth of these rotational slides and we estimated that for a number of these slides the point of failure was reached in case the groundwater table has risen to 80-90% of the maximum depth of the slip in the regolith profile. We concluded that this was the minimum depth the groundwater has to rise in the profile, because we found that the slipcircle developed at a maximum depth in the regolith profile just above the fresh rock. Therefore, the maximum depth of the regolith for these cases determines at last the amount of mass which can be taken into motion. We have to keep in mind, however, that a thicker regolith cover means a greater potential amount of sliding mass, but it needs also a larger water concentration before the point of disequilibrium is reached. On less steeper slopes (< 30°) rotational slides have developed (type no. 8 and 9) which generally had a lower depth-length ratio (1:5) than type no. 7. The slides developed in weathered claystone, sandstone and metamorphic rocks, especially on places where water assembles in the head-region of the streams. The study of these rotational slumps on varying slope angles reveals that in general the size of the slides increases with decreasing slope angle, while at steeper slopes the degree of displacement of the rotating block out of the area is larger than on less steeper slopes. This general trend could be established by the detailed study of a number of rotational slides in weathered claystone. Apart from the effect of slope angle on the amount of sliding mass, it was also the local thickness of the weathered regolith, which determines the potential maximum amount of sliding material. At the head of the river valleys in areas with deepseated rotational slides, the material can be further transported via relative slow mudflows which move into the valleys downstream (type no. 11). Movements take place especially in the wet season when large amounts of groundwater are available. The mechanism of movement may be either by sliding along the slipsurface or by internal shear (flowing) due to the high viscosity of the flow.

8

LANDUNITS IN RELATION TO THE OUTPUT OF THE MASSMOVEMENT CASCADING SYSTEM

8.1 The definition of landunits

In this Chapter we will discuss the output of the massmovement cascading system in relation to different landunits, which are distinguished on the base of different mapping characteristics.

As regard to the output between different landunits we will compare the number of slides within a landunit, the total surface which is affected by sliding and a rough estimation of the total volume of mass of the slides per landunit. The number of slides within a certain landunit depends on the degree of stability (which can be expressed by the F-value) at any place within the landunit. We have showed in the previous Chapters that increasing slope angle and depth of the material leads to a decrease in stability. Also decreasing c- and φ-values of the material lowers the degree of stability and therefore increases the chance that sliding occur within a certain landunit. A rise in groundwater functions as a trigger for landsliding and therefore the number of slides per landunit increases on places with accumulation of groundwater.

The total surface affected by massmovements and the total volume of mass involved at failure within a certain landunit is determined by the number of slides and the individual size of the slide. By studying the equilibrium equations for different types of slide we concluded in Chapter 6 that increasing c- and φ-values increase the size of the individual slides at failure, while increasing slope angle and pore pressure conditions decrease the size of the slide (see Chapter 6). In Figure 8.1 we have depicted how the above mentioned variables influence in an opposite manner the total production of moving material within a certain landunit.

Therefore a subdivision of the landscape into units according to mapping characteris-

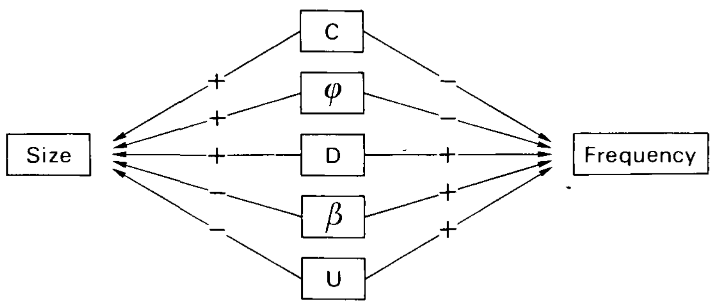


Figure 8.1 The influence of landslide variables on the number of slides per landunit (frequency) and the size of the landslides. c: cohesion of material; φ: internal friction of material; D: thickness of rock or soilmass; β: slope angle; U: pore pressure of groundwater.

tics based on these variables does not necessarily give significant differences in total volume of mass production between these units. We will test whether this statement, which is based on the theoretical considerations given above, is valid for the study area. Therefore the study area is subdivided into landunits according to some simple mapping characteristics which are related to the variables depicted in Figure 8.1. The landunits are distinguished on the base of one mapping characteristic. A further subdivision according to two or more characteristics, leads to smaller total areas per landunit in which the frequency of sliding is too limited to make liable comparisons in output.
A first possibility is to subdivide the landscape into units according to mapping characteristics, which are related with the strength properties (c and φ) of the material. For this purpose we can distinguish landunits with different rock and "soil" types. In Chapter 6 and 7 it was shown that not the strength of the intact rock is of importance but especially the tectonic structure of the rock: frequency of joints, faults, strength along bedding planes and dip of these discontinuities in relation to slope. It is difficult to distinguish within one rock type differences in tectonic structure, e.g. the density of joints. Further: differences in structure may be very locally, e.g. faulting zones, contact zones with other rocks, dip of joint – and bedding planes towards the free slope. Map I (Appendix A7) shows a distinction according to lithological units. Within these units, as far as possible, information is given about local conditions of the tectonic structure of the rock.
The "soil" (weathered regolith in situ or displaced deposits from Pleistocene and Holocene periods) is in the study area related to the lithological units. Therefore a subdivision on the base of the lithological characteristics also give a spatial differentiation of the related weathered material. As we have shown in the previous Chapters it might be of importance to differentiate landunits according to the available depth of especially the weaker weathered material, because the depth of the regolith cover forming a threshold influences the frequency and size of the landslides in the same manner. Unfortunately it is very difficult and often impossible without special techniques to make a primary subdivision of the landscape according to the depth of weathered material. The study of the landslides in weathered material reveals some general outlines as regard to the depth of the weathered material. The many steep slopes in sandstone and limestone (see Chapter 2) have only a thin to very thin regolith cover, with a maximum thickness of 1 meter. Locally the weakly cemented Mars-sandstone may have a thicker weathered regolith cover especially in the more flatter valley heads. In claystone areas on relative flatter slopes (see Chapter 2) weathering must have gone also to a greater depth, while the slope may be covered by deposits of clay material of previous landslides. In the area of metamorphic rocks, especially in the southern part of the study area (Savuto valley) the slopes are locally covered by thick packages of colluvial (solifluction) material, which can reach a thickness of more than 20 meters.
The next parameter which may be of importance as a differentiating factor in output between landunits in the slope angle (see Figure 8.1). Therefore in map II Appendix A7 the landslides are depicted in relation to landunits with different slope classes. We have distinguished four slope classes: 5-10°, 10-20°, 20-30° and > 30°.
These classes are more or less based on the range of slope angle values in which different

types of landslide have developed (see Table 7.1). The last importance variable determining the frequency of sliding and the size (see Figure 8.1) is the amount of pore pressure which is built up in a certain area. It is difficult to find a mapping criteria which enables us to distinguish landunits with differences in maximum pore pressure conditions. These differences in groundwater conditions are related to soil- and rock variables, vegetation- and topographical variables and the hydrographic network. Differences as regard to the maximum pore pressure conditions may be very locally, due to ponding of groundwater by impermeable layers, local slope curvatures, concentration of water at the foot of the slope. More generally groundwater concentration is tied to the structure of the hydrological network. It can be stated that accumulation of groundwater occur especially in the source area at the head of the stream. Therefore we have drawn the hydrographic network in the maps in order to show the relation between the spatial distribution of the slides and the stream network.

Differentiation in maximum pore pressure conditions between landunits might be due to differentiations in vegetation structure. Differences in vegetation structure lead to differences in evaporation and perception of rainwater and hence in groundwater level variations (Chapter 6). Also the infiltration capacity of the soils might be related to the vegetation structure and landuse (see Chapter 5) which also leads to differences in groundwater conditions.

Apart from this the rootsystems of vegetation influence the strength of the soil (Chapter 6). Tichy (1962) made a deforestation map of Basilicata (north-east Calabria) and compared this map with a landslide map by Kayser (1958). It appears that massmovements often take place in areas which have been deforested especially after 1879. Unfortunately such comparisons are not possible in the study area because the total area was deforested in the past and the vegetation structure consists mainly of more or less dense shrub and tree vegetation (see Chapter 5) alternated with areas under recent crop cultivation.

In map III (Appendix A7) the study area is distinguished in three types of landunit based on the vegetation structure c.q. landuse. We have distinguished arbitrary 1. densely vegetated areas (> 60%), 2. scarcely vegetated areas (0-60%) and 3. areas with recent crop cultivation.

8.2 The differences in output of the massmovement cascade in relation to landunits

On the base of the above mentioned three landunit maps we will discuss the output between the distinguished landunits. In the Tabels 8.1 - 8.3 a survey is given of the output of different types of landslide per landunit. As output we have considered for different types of slide the number (frequency) of slides per unit (column 3). The total surface (in m^2) affected by sliding (column 4) and the estimated total volume of the slides (m^3) (column 6). The last was the most difficult to estimate, because especially for the deep seated slides the slip circle could not always been reconstructed. As far as possible extrapolation has been made from landslides of the same type and size order, from which the depth of sliding was known.

Table 8.1 The output of the massmovement cascade in different lithological landunits

Lithological landunit	Type of slide[a]	n	A x 10³	a x 10³	V x 10³	v x 10³
Metamorphic rocks (sf)	*3*	1	530	530	5510	5510
	6	3	80	27	510	170
	7	8	90	11	70	9
	8	11	120	11	480	44
40 % [d]	*9*	9	145	16	510	57
	10	4	40	10	300	75
	12	9	250	28	805	89
total		45	1265		8185	
total mean				28		182
Silt-claystone (Ma)	*4*	2	415	207	4000	2000
	6	2	70	35	430	215
	7	4	5	1	5	1
	9	8	5	1	20	3
	10[b]	23	815	35	9690	421
15 % [d]	*10*[c]	12	120	10	880	73
	11	5	455	91	5595	1119
total		56	1885		20620	
total mean				34		368
Sandstone (Mars)	*2*	11	95	9	290	26
	5	2	20	10	70	35
	7	2	5	2	1	1
	9	5	20	4	40	8
	10[b]	4	75	19	1105	276
10 % [d]	*11*	2	30	15	455	227
	12	6	175	29	550	92
total		32	420		2511	
total mean				13		209
Sandstone (Mar)	*1*	14	560	40	3000	214
	3	4	270	68	1295	324
10 % [d]						
total		18	830		4295	
total mean				46		239
Granite (γ)	*7*	2	5	2	5	2
	12	1	40	40	115	115
0.5 % [d]						
total		3	45		120	
total mean				15		40

A: total area affected by landsliding in m², a: mean area per landslide in m², V: estimated total volume of sliding mass in m³, v: estimated mean volume per landslide in m³.

a See table 7.1; b complex slumping area; c separate slumps; d percentage of total area occupied by landunit.

To get an impression of the mean area and volume which is involved in failure for a given landslide, we divided resp. the total area and volume per landslide type by the number of landslides (resp. column 5 and 7).

Map I and Table 8.1 show the differences in output in relation to different lithological units. We will first compare the number of slides for different types per landunit. The Table shows that compared with the total percentage of area, occupied by this unit (15%), the silt claystone region produced the highest number (frequency) of landslides (column 3). A dominant number of slides show type no. 9, 10 and 11 which developed in thick weathered claystone covers. The reason for this relative high frequency might be the relative thick weathered regolith cover (see Figure 8.1). The material also have relative the lowest strength values, but this might be compensated by the relative lower slope angles in the claystone area (see Chapter 2).

It can be mentioned further that the infiltration capacity of the clay soils can become very high after desseccation due to the formation of cracks (see Chapter 5). This may lead to a relatively high rise of the groundwater table after heavy rainstorms.

A relative high number of slides per landunit is also found in the area with weakly cemented sandstone (Mars) (column 3). In these Mars landunits a dominant number of slides developed as well on the fresh sandstone rock (type no. 2) as in the weathered rock (type no. 9, 10, 12) (Table 8.1, column 3). The landslides are concentrated in the north-western part of the sandstone area in the neighbourhood of Amantea (map I). Explanations for this concentration might be: 1. The rocks in this area are stronger affected by tectonic activity, which leads to higher concentration of joint and fault systems, 2. A stronger erosive activity of the main rivers and their tributaries downstreams. The landslides in landunits of metamorphic rocks are concentrated in the southern part of the study area (Savuto and Fiume Grande region). The reason might be that these southern region is covered with thicker regolith mantles than in the north eastern region. A relative high number of slides which are related to the thicker weathered layers in metamorphic rocks belong to type no. 8, 9 and 10 (see Table 8.1 column 3). Also surficial slides (type no. 8) and the related badlands (type no. 2) are frequent in this region. The map I shows that unstable areas in this metamorphic landunits are especially concentrated along the main rivers at the foot of the slope and at the head of tributary rivers with very steep slopes. A relative low frequency of sliding occurs in the landunits with cemented sandstone (Mar) with mainly type no. 1. A glance on the map shows that the slides are concentrated at the boundary of these units in the steep high sandstone cliffs (type no. 1, see Chapter 7). All these slides dated from the past periods and are probably trigged by earthquakes. The slopes in these sandstones with a thin cover (or no cover) can be considered as stable at present times. The granite and limestone units cover a very small part of the total area, which hampers a comparison as regard to the output. In the granite area a number of landslides were observed in weathered material (a.o. type no. 7 and 12). As regard to the total mass production per landunit Table 8.1, column 4 t/m 7 shows that in the claystone region the largest area is affected by landsliding and these units produced together the largest volume of sliding material. This is explained by the high frequency of sliding (see above) and the fact that in this deep weathered material with relative low strength values a large number of deep seated

rotational slides (type no. 10 and 11) developed on relative flat slopes which means a high production of mass per landslide (see Table 8.1).
It is interesting to note the high mean mass-production per landslide of the fossilized complexes in different lithologial units (see Table 8.1, type no. 1, 3, 4 column 5 and 7). An explanation was already given in the previous Chapters. We will mention here that:

- The rocks, in which these fossilized slides (type no. 1, 3 and 4) have developed, have higher strength values (especially cohesion) than the weathered material, which means a potential higher production of mass if failure takes place (Figure 8.1).
- Instability in these rocks occurred due to the development of high shear stresses which were induced by earhquakes in the past. This means that places with strong material are brought to the point of disequilibrium, which also leads to a high production of mass.

We can conclude that a subdivision of the landscape according to lithology and related weathered material shows in the study area a differentiation as regard to the number of slides and landslide types. We also could observe from the map that the distribution within the landunits is far from homogeneous, due to the fact that strong local deviation of variables have created unstable situations (see below). Differentiations as regard to the total volume and (or) area are less clear per lithological unit. We may distinguish three groups: 1. high production in silt claystone and Mar-sandstone (the latter having only "fossile" complexes concentrated at the boundary of the units), 2. a medium production of the Mars-sandstone regions and the metamorphic rock regions and 3. a low production in the granite and limestone regions.

Table 8.2 and map II (Appendix A7) show the frequency and output of different types of landslides in relation to landunits, which are subdivided according to different slope angle classes. From the Table we can infer that generally there is an increase in frequency of slides with increasing slope angle values. The following explanations are given:

- At increasing slope angle values an increasing number of types of material with various strength values reaches the point of failure.
- At higher slope angles smaller amounts of groundwater are needed to cause instability (see Chapter 6).
- At higher slope angles the depth of sliding is lower which means that sliding is also possible in shallower regolith material (see Chapter 6).

The Table shows a differentiation in landslide types with different slope classes. In the lower slope classes (5-20°) predominately deep seated rotational slides in weathered material (especially clay) have developed (type no. 10 and 11). Also in these slope classes "fossilized" rockslides could develop (type no. 3 and 4), but we stated already that earthquakes must have induced the necessarily high shear stresses in this stronger rock material. In the slope class 20-30°, more shallow rotational slides (type no. 8 and 9) have developed, which confirms the thoughts given in the previous Chapter. In the slope class > 30° also surficial debris slides have developed (type no. 7) and the badlands (type no. 12) related to this type of slides. Based on the different equilibrium models, given in Chapter 6, it was stated that given certain strength values of the material the size of the slides decreases with increasing slope angle (see also Figure 8.1). This is in

Table 8.2 The output of the massmovement cascade in landunits with different slope angle.

Slope angle class	Type of slide[a]	n	A x 10³	a x 10³	V x 10³	v x 10³
5 ° - 10°	*4*	2	515	257	3590	1795
	10b	11	295	27	3515	320
(15%)d	*10c*	4	5	1	35	9
	11	4	365	91	4270	1067
total		21	1180		11410	
total mean				56		543
10° – 20°	*3*	1	195	195	1500	1500
	5	1	10	10	40	40
	6	2	70	35	430	215
	8	2	80	40	330	115
(15%)d	*9*	6	5	1	10	2
	10b	15	550	37	6455	430
	10c	6	1	1	25	5
	11	2	125	62	980	490
total		35	1036		9770	
total mean				30		279
20° – 30°	*3*	2	60	30	335	170
	5	2	10	5	45	25
	6	1	15	15	90	90
	7	2	5	2	5	2
(15%)d	*8*	4	20	5	10	2
	9	10	50	5	15	2
	10b	3	40	13	45	15
	10c	3	5	2	25	10
	12	2	20	10	50	25
total		29	225		620	
total mean				8		22
> 30°	*1*	12	460	38	2100	175
	2	11	95	9	235	21
	3	1	70	70	660	660
(25%) d	*6*	2	90	45	485	242
	7	16	90	6	70	4
	8	5	20	4	60	12
	9	6	70	12	240	40
	11	1	5	5	75	75
	12	13	360	28	1165	90
total		67	1260		5090	
total mean				19		76

A: total area affected by landsliding in m², a: mean area per landslide in m², V: estimated total volume of sliding mass in m³, v: estimated mean volume per landslide in m³

a See table 7.1; b complex slumping area; c separate slumps; d percentage of total area occupied by landunit.

partially accordance with the results found in the study area because for most landslide types the mean output (area or volume) decreases in the first three slope classes (column 5 and 7). The Table also shows that the total production per landslide type (column 4 and 6) which is determined by the number of slides and the mass per individual slide decreases in the first three slope classes. Increasing slope angle class values show generally an increasing number of landslide per landunit, but a decreasing mean volume per landslide which results in a decrease in the total production per landunit. The slope angle class $> 30^\circ$ shows again an increase in the total massproduction which must be related to the rapid increase in the number of slides per landunit.
Concluding we can state that a subdivision of the landscape according to different slope angle value classes results in a differentiation as regard to the frequency and type of landslides between these units. As regard to the differentiation in total volume and surface affected by sliding we found a decrease in output in the first three classes and again a rise in output in the last class with the highest slope angle values.
Table 8.3 and map III (Appendix A7) show the relation between landslides and landunits distinguished according to vegetation structure and landuse.
The Table shows a relative high frequency of slides in the areas with open vegetation compared with the agricultural areas and the areas with a closed vegetation structure. The agricultural areas show the highest amount of mass production (column 6) in relation to the other areas. The more densely vegetated areas seem to be more stable than the areas with open vegetation. The following possible explanations can be given:

- The areas with open vegetation are lying in more steeper slope classes, while the agricultural areas are in regions with more flatter slopes. This explains the higher number of landslides in the open areas (see above). On the other hand on these flatter slopes more deep seated slides can develop which obviously results in a greater total mass production.
- The greater total mass production in the agricultural areas might also be explained by the fact that the infiltration capacity in these areas is higher than in areas with open vegetation (see Chapter 7), which can result at a given rain input in a higher rise of the groundwater table and thus a higher frequency of failure.
- Areas in open vegetation are less stable than areas with closed vegetation due to a greater density of the roots which increases the strength of the soil (Eyles 1971) and a greater interception and evaporation of the biomass which reduces the maximum rise of the groundwater table. However, the depth of the roots most times is not sufficient enough to strengthen the total regolith even in the shallow slides (type no. 7). Further we established in Chapter 5 that the densely vegetated areas show higher infiltration capacities.

As a conclusion we can say that a subdivision according to the vegetation structure leads also to differentiation in output, but an explanation for this differentiation is rather difficult to give. Further there may exist an autocorrelation between slope angle at one side and vegetation structure and landuse on the other side.
In the above given analysis of the relation between landunits and landslides, we mentioned already occasionly the fact that the distribution of landslides within the landunits is

Table 8.3 The output of the massmovement cascade in landunits distinguished according to landuse and vegetation structure

Landunit	Type of slide[a]	n	A x 10³	a x 10³	V x 10³	v x 10³
Agricultural area	*1*	1	110	110	445?	445
	2	1	1	1	1	1
	3	1	50	50	200?	200
	4	2	475	237	2295?	1147
	5	1	10	10	40	40
	6	2	70	35	390	195
	7	1	1	1	1	1
60 % d	*8*	6	270	45	1355	226
	9	3	5	2	20	7
	10b	24	880	37	11165	465
	10c	2	1	1	10	5
	11	5	425	85	5140	1028
total		49		47	21062	
total mean			2298			430
Open vegetation	*1*	10	485	48	1760?	176
	2	10	85	8	255?	25
	3	1	65	65	380	380
	5	1	10	5	40	20
	6	2	55	27	225	112
	7	11	140	13	140	13
30 % d	*8*	2	5	2	10	5
	9	15	105	7	455	30
	10b	5	80	16	950	190
	10c	12	10	1	10	1
	11	2	30	15	305	152
	12	18	480	27	1645	91
total		90	1550		6175	
total mean				17		69
Closed vegetation	*1*	1	20	20	75	75
	6	1	40	7	170	28
	7	3	10	1	10	1
	8	4	1	1	1	1
10 % d	*9*	3	1	1	5	1
	10c	2	20	2	170	17
total		14	92		431	
total mean				7		31

A: total area affected by landsliding in m², a: mean area per landslide in m², V: estimated total volume of sliding mass in m⁻³, v: estimated mean volume per landslide in m⁻³.

a See table 7.1; b complex slumping area; c seperate slumps; d percentage of total area occupied by landunit.

not homogeneous. This is due to the fact that instability is also caused by local deviation of the value of variables within the landunit.
This local deviation of variables are related to:

- Local weakening of the strength of the rock, due to faults and on contact zones with other rocks.
- Local water concentration at the head of steams, at places with impermeable layers, and contact zones with other impermeable rocks.
- Local erosion activity of the river at the foot of the slope.
- Local instabilities caused by previous slides (retrogressive sliding).
- Local instabilities created by man due to the construction of roads or irrigation activities.

A glance at the map shows that a great number of landslides (45%) are concentrated at the head of the streams. Further 75% of the sliding are related to the active erosion of the river while 6% of the landslides were activated by man due to road construction and irrigation activities. We found that 35% of the slides developed along faults or strong developed fault systems, while 5% of the slides developed at the contact zone between 2 rocktypes. Further we could detect that in 10% of the cases water concentration was due to ponding of groundwater by local impermeable layers, while 5% of the cases retrogressive sliding must have taken place.

8.3 Summary and conclusions

In the discussion given above we have tried to analyse, whether the landscape can be subdivided into landunits according to certain criteria, which show differences in frequency and the total mass production of various types of landslides. Such a map may give an impression of the spatial differentiation in degree of stability of the landscape. We have shown that subdivision of the landscape for this purpose faces two problems:

- A number of variables influences in an opposite manner the frequency of sliding and the mass production per landslide. This means that a subdivision of the landscape based on the above given variables does not necessarily give significant differences as regard to the total produced mass of a landunit.
- The distribution of landslides within the landunit and therefore the possibility that failure should occur, is not homogeneous which is due to local deviation of certain variables.
- The depth of the overlying weaker material i.c. the regolith cover is a very important variable which determines both in a positive way the frequency of sliding and the amount of mass production per landslide. However, this parameter cannot always be determined in the ordinary practice of mapping.

In the study area a subdivision of the landscape according to the lithological characteristics of the rock and the related weathered material have shown a differentation regarding the number of slides per landunit and the landslide types. It was more difficult to discern a differentiation regarding the total volume: the highest total volume production was found in the silt-claystone region and in the Mar-sandstone region (with only fos-

silized slides), a medium production in the Mars-sandstone and metamorphic rocks, while granite and limestone regions showed the lowest production.
Also a dubdivision according to slope angle classes shows a differentiation regarding the frequency and type of sliding. As regard to the totally produced volume we could establish a decrease in output with slope angle in the first three slope classes, while in the class with slope angle values $> 30^\circ$ the amount of mass production increases. A subdivision of the landscape according to vegetation structure revealed that the units with open vegetation shows the highest frequency and total production of mass.
A landscape map which is based on the above described criteria must be completed, with a number of mapping criteria, which show the local influence of certain variables on the degree of stability and hence the possibility of sliding on particular localities within the landunit. Therefore local information has to be given about fault and joint systems, contact zones between lithological units, special areas with water concentration, local erosion activity of rivers, indication of activity of man.

9

SUMMARY

Various types of "pragmatic" landscape maps, in which the distinguished units are supposed to show differences in potentials with regard to a particular problem, have been produced for many purposes. However, the differences of these potentials are seldom measured. In this thesis a discussion has been made whether in a mediterranean landscape, landunits can be distinguished on the base of some general visible landscape characteristics, which show significant differences in output as regard to the sediment transport on slopes.
Two systems of sediment transport were chosen: the system of sediment transport by falling and running water (water erosion) and the system of sediment transport which takes place mainly under the influence of gravitational forces (landsliding or massmovement). In order to study the differences in output of these transport processes between the distinguished landunits, the following steps were taken:

- An analysis was made of the influence of landscape variables (or parameters) on the output of the sediment transport processes.
- A selection was carried out of visible mapping criteria, related to these variables, and the definition of landscape units based on these criteria.

An analysis of the differences in output of the transport processes between the landunits, was carried out.

The influence of landscape variables on the output of the sediment transport processes.
Two systems of the water erosion transport processes could be distinguished: the transport by splash erosion and the transport by overlandflow erosion. Measurements on the output were done by using a portable rainfall simulator and measuring plots. It appeared that the density of the herb vegetation, the aggregate stability and the stone cover pavement have a strong effect on the output of splash erosion and overlandflow erosion. Compared to the bare soil a slight density of the herb vegetation proved to be a very effective factor in the protection of the soil particularly against splash erosion. A stone pavement with gravel varying in size from 2-6 mm had a protective effect against water erosion on a horizontal surface, but on steeper slopes (20-30°) the gravel is transported even more easily than the finer fractions. It was established, that the bulkdensity which must be related to the mechanical strength of the soil showed a marked correlation to the output of the water erosion processes. Textural indices didn't show a marked relationship to the output: The clay mineral content seems to have on one hand a binding effect on the aggregates, while on the other hand the swelling clay minerals weaken the aggregates during wetting. The slope length seemed to have no effect on the output of overlandflow erosion and hence the total water erosion output, particularly on the more or less natural slopes. This is explained by two facts:

- A great part of the sediment is transported by splash erosion; on more or less natural slopes the transport rate of splash erosion was two to four times higher than the transport rate of overlandflow erosion.

– Transport of sediment by overlandflow erosion is local since no correlation could be established between slope length and overland flow on the more or less natural slopes.

Therefore we consider the water erosion on natural slopes in this area to be a "point to point transfer" of sediment.

The study of the input-output relationships of the overlandflow erosion process also reveals that particularly on the more or less natural slopes the transport rate by overlandflow erosion is controlled by the amount of material which is detached by splash impact shear and (or) by overlandflow shear, and not by transport capacity of the flow. Further more an important part of the transported sediments by overlandflow seemed to be supplied by splash erosion. Four main variables are important to the degree of stability of the slope against massmovements, the type of massmovement and amount of transport by massmovements. These are the mechanical characteristics of the material, the angle and height of the slope, the thickness of the rock- or soil material and the amount of groundwater in the material. In the study area twelve types of massmovement complexes were distinguished mainly on the base of the mechanism of initial failure, the mechanism and amount of transport, the morphometrical and material characteristics of the slides. Five types of rockslides have been distinguished which mainly developed in cemented – and weakly cemented sandstones. One type concerns the instability of steep cliffs developed in the cemented sandstone. The other four types showed failure along bedding and joint planes facing toward the free slope face.

A further subdivision of these rockslides was based mainly on the character and the transportability of the mass after failure. The great quantities of rock mass involved in these rockslides (especially the "fossilized" ones) point to the fact that the strength of the rock material is relatively high, and further more that the old landslides are induced by earthquakes which produce high shear stresses and hence high quantities of mass at failure.

Shallow translational slides developed on steep slopes (20°-40°) in relatively thin regolith covers (± 1 mtr) lying over different types of rock. The steepness of the critical slope varied with the strength of the regolith. Stability analyses revealed that the instability must have occurred under the influence of positive porewater pressure of the groundwater which must have risen up to approximately one third to one half of the depth of the regolith. The amount of material involved at failure depends on the thickness of the regolith or the depth of the weakest zone within the regolith. Flat rotational slides developed on less steeper slopes of metamorphic rocks, covered by a thicker regolith or solifluction mantle (up to 10 mtrs.). Stability analyses showed that the groundwater must have risen nearly to the soil surface in order to start failure. On less steeper slopes (< 30°) in all types of weathered rocks more deepseated rotational slides with a depth-length ratio of 1:5 developed. Most of these slides were found at the head of the streams, which showed a concentration of the groundwater. The study of these rotational slides showed that the size of these slides increase with a decreasing slope angle. The displacement of the rotating blocks seems to be larger on the steeper slopes. These deepseated slides may form complexes in the head of river valleys. The material may be transported further downstream via relatively slow mudflows.

Landunits related to the output of the sediment transport processes.

Five mapping criteria related to the variables influencing the output of water erosion were chosen, in order to subdivide the landscape into landunits. The following sequence of criteria seems to give the best differentiation in output on each classification level in the area: 1 the degree of agricultural activity of man, 2 the vegation structure, 3 soil and related parent material, 4. slope angle, 5. slope length.
Landunits under recent cultivation have much higher erosion outputs than the other landunits. Landunits with abandoned fields proved to be the most resistant against erosion, due to a denser herb growth, which also increases the infiltration rate of the soil. Furthermore the landunits with a decedeous forest cover without a shrub and herb cover appeared to be very sensitive to water erosion, due to a relatively high erodibility of the soil and a lower infiltration capacity compared to soils under a herb-cover. The sealing of the soil surface, particularly in soils derived from sandstone and metamorphic rocks, may locally produce high amounts of overlandflow and sediment. Satured overlandflow could occur locally in thin soils on metamorphic rocks which resulted in a very high production of sediment. On the contrary the production of overlandflow and sediment was locally very low in soils on claystone mainly due to the formation of dessication cracks.
Three mapping criteria were chosen to subdivide the landscape into landunits in order to compare the differences in output of the massmovement cascading system between these units: 1. the different rock and related "soil types", 2. the slope angle and 3. land use and vegetation structure. As output of the landunits we considered the number of slides per landunit and the total area and mass involved in sliding per landunit. In analysing the differences in output between the landunits we faced two problems:

- Theoretically it appeared that the landscape variables in the landslide equilibrium model influences in an opposite manner the degree of stability of the slope (and hence the frequency of sliding per landunit) and the mass production per landslide. This means that the total production per landunit, which is determined by the number of slides and the amount of mass per landslide does not necessarily differ between landunits of which the subdivision is based on one of these equilibrium parameters.
- The distribution of landslides within the landunit and therefore the possibility that failure should occur is far from homogeneous due to local strong deviation of certain equilibrium parameters. Therefore landscape maps showing differences in slope stability, and mass production of landslides between landunits must be completed by a number of mapping criteria, which show the influence of certain variables on the degree of stability on particular localities within the landunit.

In the study area a subdivision of the landscape according to the lithological characteristics of the rock and the related weathered material have shown a differentation as far as the frequency of sliding and type of sliding are concerned. It was more difficult to discern a differentiation regarding the total mass of slided material. The highest mass production was found in the silt-claystone region and in the Mar-sandstone region (with only fossilized slides) a medium production was found in the Mars-sandstone regions

and metamorphic rocks, while granite and limestone regions showed the lowest production.
A subdivision of the landscape according to slope angle also showed a differentiation in the types of landslide and number of slides per landunit. It appeared that with higher slope angle classes the number of slides per landunit increased but the mean mass per landslide decreased. This resulted in a net decrease of total mass production with increasing slope angles for the first three slope classes. A subdivision of the landscape according to the vegetation structure revealed that units with an open vegetation cover showed the highest number of landslides and total sliding mass.

10

SAMENVATTING

De "pragmatische" landschapskartering heeft o.a. als doel verschillen in potentieel aan te geven tussen de onderscheiden eenheden. Zelden worden deze verschillen tussen landschappelijke eenheden via metingen geanalyseerd. In deze studie wordt nagegaan of op basis van zichtbare en karteerbare kenmerken landschappelijke eenheden kunnen worden onderscheiden, die significante verschillen in transport van sediment op hellingen vertonen. Voor dit doel zijn twee processystemen gekozen: a) het transport van sediment door vallend en stromend water (water erosie) en b) het transport van materiaal, voornamelijk onder invloed van de zwaartekracht (massa beweging). De volgende problemen kregen in deze studie de aandacht:

- Een analyse van de invloed van verschillende landschaps-variabelen (-parameters op de hoeveelheid transport van sediment op hellingen.
- Een selectie van zichtbare karterings criteria, die in verband staan met deze landschaps-variabelen en de definiëring van bepaalde landschappelijke eenheden.
- Een analyse van de verschillen in hoeveelheid sediment transport tussen de onderscheiden landschappelijke eenheden.

De invloed van landschaps-variabelen op de transport hoeveelheid van sediment op hellingen.

Het water erosie proces werd onderverdeeld in twee proces systemen: het transport van sediment door spat erosie (splash erosie) en door stromend water over de helling (overlandflow erosie). Metingen werden verricht met een draagbare regenval simulator, en met behulp van proefvelden. Vastgesteld kon worden dat de dichtheid van de kruidenvegetatie, de aggregaat stabiliteit van de bodem en de grindbedekking aan het oppervlak van invloed zijn op de hoeveelheid transport door water erosie. Het bleek verder dat een geringe toename van de dichtheid van de vegetatie t.o.v. de onbedekte bodem een sterke daling van met name de hoeveelheid splash erosie liet zien. Een grindbedekking (korrelgrootte 2-6 mm) beschermt op een horizontaal oppervlak de bodem tegen erosie. Op steile hellingen daarentegen, bleek dit grind gemakkelijker transporteerbaar dan de fijnere bodemfracties. Ook de bulkdensity van de bodem, die mede bepalend is voor de schuifweerstand van de bodem, bleek van invloed op de hoeveelheid transport van sediment. De invloed van bepaalde textuur indices op de hoeveelheid water erosie was minder duidelijk. Geconcludeerd werd, dat de kleifractie in de bodem enerzijds een bindend effect heeft op de aggregaten, anderzijds wordt de stabiliteit van deze aggregaten verzwakt door de zwellende eigenschap van bepaalde typen kleimineralen bij bevochtiging van de grond.

De helling lengte bleek geen invloed te hebben op de hoeveelheid sediment transport met name op min of meer natuurlijke hellingen. Er werden twee verklaringen gegeven:

- Een groot gedeelte van het sediment bleek getransporteerd te worden door splash erosie. Dit proces geschiedt onafhankelijk van de helling lengte. Op de min of meer natuurlijke hellingen werd twee tot vier maal meer sediment vervoerd via splash erosie dan via overlandflow erosie.

– Het transport van sediment via overlandflow erosie is vermoedelijk lokaal omdat er geen positief verband gevonden kon worden tussen de helling lengte en de hoeveelheid overlandflow.

Het water erosie proces op min of meer natuurlijke hellingen in het studie gebied wordt daarom gezien als een locale verplaatsing van sediment van het ene punt naar het andere punt. ("point to point transfer").
Vastgesteld kon worden dat de hoeveelheid sediment die door overlandflow verplaatst wordt niet bepaald wordt door de maximale transport capaciteit van het stromend water (transport limited conditions), maar door de hoeveelheid sediment, die losgemaakt wordt door de impuls van vallende regendruppels en de schuifspanning van het stromend water (detachment limited conditions).
De mate van stabiliteit van de helling, het type massabeweging en de hoeveelheid materiaal dat wordt getransporteerd hangt af van een aantal variabelen: a) de mechanische eigenschappen van het materiaal, de hoeveelheid grondwater in het materiaal, de hoogte en hoek van de helling en de dikte van het materiaal. In het studie gebied werden twaalf typen van transport door massabeweging onderscheiden, voornamelijk op basis van het type beweging bij het punt van bezwijken, het type beweging tijdens het transport, en verder de morfometrische en materiaal eigenschappen van de aardverschuiving. In zandsteen konden vijf typen rockslide-complexen worden onderscheiden. Een verdere onderverdeling van deze rockslides geschiedde op basis van het karakter en de transporteerbaarheid van de massa na het bezwijken. De grote hoeveelheid materiaal die bij deze typen aardverschuiving in beweging wordt gezet, duidt op het feit dat de sterkte van het gesteente relatief hoog is. Instabiliteit in deze rotsmassa's kan worden veroorzaakt door de ontwikkeling van hoge schuifspanningen tijdens aardbevingen. Op steile hellingen (20°-40°) ontwikkelden zich ondiepe verschuivingen in regolithen van ongeveer een meter dikte met een min of meer recht schuifvlak evenwijdig aan de helling. De sterkte van de regolith was mede bepalend voor de kritische hellingshoek. Stabiliteitsanalysen brachten aan het licht, dat het grondwater tot ongeveer halve hoogte in de regolith moet stijgen alvorens beweging kan optreden. De hoeveelheid materiaal, die in beweging komt hangt af van de dikte van de regolith of de diepte van de zwakste zone in de regolith.

Ondiepe roterende aardverschuivingen werden aangetroffen in solifluctie pakketten op metamorfe gesteenten met een dikte tot 10 meter. Het grondwater moet in deze pakketten tot vlak onder het maaiveld stijgen alvorens beweging optreedt. Meer diepe roterende aardverschuivingen met een diepte -lengte van ongeveer een op vijf, komen voor op minder steile hellingen (< 30°) in diverse verweerde gesteenten.
De meeste van deze aardverschuivingen werden gevonden in de brongebieden van rivieren, waar concentratie van grondwater optreedt. Vastgesteld kon worden, dat de afmetingen van de aardverschuivingen toenemen met afnemende hellingshoek. De verplaatsing van de roterende blokken bleek in het algemeen groter op steilere hellingen. De

diepe roterende aardverschuivingen kunnen in de brongebieden van rivieren uitgebreide instabiele complexen vormen. Het bewegende materiaal kan over grote afstanden verder getransporteerd worden via langzame modder stromen.

Landschappelijke eenheden in relatie met de hoeveelheid sediment transport.
Vijf karterings criteria werden gekozen waarmee het landschap op verschillende klassificatie niveaus kan worden onderverdeeld. Deze criteria staan in relatie met belangrijke landschapsvariabelen, die van invloed zijn op de invloed transport door water erosie. Voor een indeling van bovenaf van het landschap, was de opeenvolging van criteria die op elk niveau een maximale differentiatie in output tussen de eenheden liet zien als volgt: 1. de mate van agrarische activiteit van de mens, 2. de vegetatie structuur, 3. de bodem in relatie met het moedergesteente , 4. de hellingshoek, 5. helling lengte. Landschappelijke eenheden waarin akkerbouw wordt bedreven, produceren in vergelijking met de andere eenheden een grote hoeveelheid sediment door water erosie. Landschappelijke eenheden met akkers die al meer dan 10 jaar zijn verlaten hebben daarentegen de laagste sediment productie, door de dichte kruiden vegetatie en relatief hogere infiltratie capaciteit van de bodem. Verslemping aan het bodem oppervlak, wat vooral werd waargenomen op bodems ontwikkeld in zandsteen en in metamorf gesteente – bleek lokaal aanleiding te geven tot veel overlandflow en sediment transport. „Saturated overlandflow" ontwikkelde zich in dunne regolith bodems op metamorfe gesteenten, hetgeen eveneens resulteerde in een grote sediment productie. Een zeer lage sedimentproductie kon voorkomen op kleibodems waarbij door de snelle infiltratie van water via krimpscheuren in de bodem de hoeveelheid afstromend water en sediment transport sterk vermindert.
De landschappelijke eenheden met loofbos bedekking zonder ondergroei bleken zeer gevoelig voor water erosie. Dit werd veroorzaakt door een hoge erodabiliteit van de bodem en een relatief lagere infiltratie capaciteit in vergelijking met bodems onder een kruiden vegetatie.
Drie karteringscriteria werden gekozen teneinde het landschap te verdelen in eenheden die eventueel verschillen in hoeveelheid massabeweging konden opleveren: a) de lithologie en het verweerde gesteente materiaal, b) de hellingshoek, c) vegetatie structuur en landgebruik. Geanalyseerd werden o.a. de verschillen in aantal aardverschuivingen tussen de landschappelijke eenheden, het totale oppervlak, aangetast door aardverschuivingen en het totale volume materiaal dat in beweging is gekomen. Bij een bestudering van deze verschillen kwamen twee problemen naar voren.

– Op theoretische gronden kon worden aangetoond, dat de parameters in het evenwichts model van een bepaald type aardverschuiving een tegengestelde invloed uitoefenen op enerzijds de mate van stabiliteit van de helling (en dus het aantal aardverschuivingen per landschappelijke eenheid) anderzijds het volume grond c.q. gesteente per landslide, dat bij bezwijking in beweging komt. Dit betekent, dat het totale volume materiaal dat per landschappelijke eenheid in beweging komt niet veel hoeft te verschillen met eenheden waarin de evenwichts parameters andere waarden hebben.
– De verspreiding van aardverschuivingen binnen een landschappelijk eenheid is niet homogeen. Dit hangt samen met locale sterke afwijkingen van de waarden van evenwichtsparameters binnen eenheden of op de grens tussen twee eenheden. Daarom

moeten landschapskaarten, die informatie verschaffen omtrent de mate van stabiliteit en materiaal productie tussen de eenheden, aangevuld worden met gegevens over locale afwijkingen van belangrijke parameterwaarden.

In het studie gebied geeft een indeling van het landschap op basis van lithologische criteria verschillen in aantallen aardverschuivingen per eenheid en type aardverschuiving. Verschillen in totale massa productie per eenheid waren minder duidelijk; vastgesteld kon worden dat de productie in de kleisteen gebieden en de Mar-zandsteen gebieden (met alleen fossile landslides) het hoogst was. De gebieden met metamorfe gesteenten en Mars-zandsteen vertoonden een middelmatige productie, terwijl de graniet en kalksteen gebieden de laagste materiaal productie opleverden.

Een onderverdeling van het landschap volgens de hellingshoek vertoonde eveneens een differentiatie in aantallen en typen aardverschuivingen. Het bleek dat in eenheden met een hogere hellingshoek klasse meer aardverschuivingen voorkomen, maar dat het gemiddelde volume per aardverschuiving afnam. Dit resulteerde in een netto afname van het totale volume per landschappelijke eenheid. Een onderverdeling van het landschap volgens de vegetatie structuur en het landgebruik, liet zien dat eenheden met open vegetatie het grootst aantal aardverschuivingen en totale massa productie opleverden.

APPENDIX A1

MEASUREMENT OF SPLASH DETACHMENT AND INFILTRATION RATE BY MEANS OF A PORTABLE RAINFALL SIMULATOR.

Splash detachment and infiltration characteristics were measured by use of a portable rainfall simulator designed by Adams et al. (1957) which was slightly modified (Plate A16). This rainfall simulator is very simple and can easily be used on every spot in the field and handled by one man. For a general description of the apparatus we refer to Figure A.1. The apparatus consists of a steel infiltration cylinder (1) sharpened at the lower

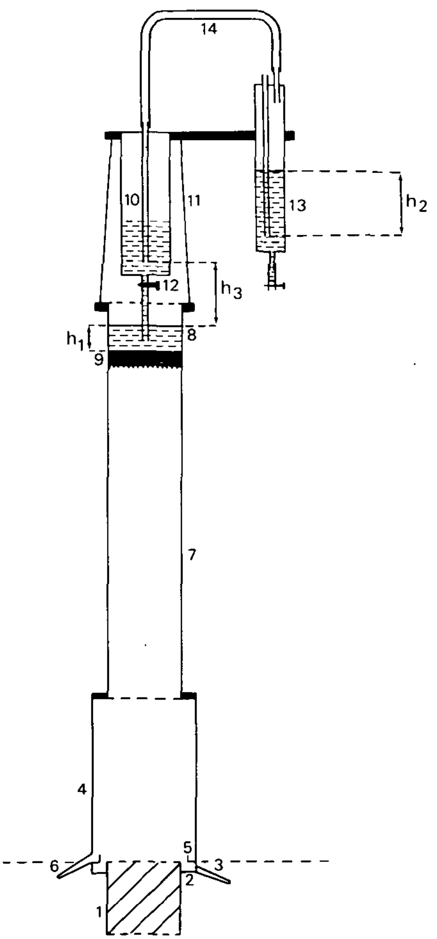


Figure A1 The portable rainfall simulator.

end which can be driven into the soil. The cylinder contains at the upper end a runoff trough (2) with a runoff spout (3). The cylinder is driven into the soil so that its top is at the same level as the soil surface. All other parts of the apparatus are made of plexiglass. A removable splash shield (4), 40 cm in height, rests vertically on the runoff trough (2). We constructed an extra trough (5) in this splash shield to catch the soil particles which are splashed up. The splashed water is drained through a "splash spout" (6). A removable cylindrical windshield (7), 60 cm in height, rests on the splash shield. The cylinder can be set in a vertical position by three adjustable screws and a levee. On top of the windshield rests coaxially a plexiglass supply-tank (8). The raindrop applicator (9) consists of 100 glass capillary tubes (1.6 mm diameter bore, 5 mm long) with 1.4 mm diameter chrome wire supported in each, to cause the formation of drops. The drops have a size of 5.3 mm. It is assumed to be constant for different constant heads. A 1 litre water reservoir (10) of plexiglass is held by a holder (11) with metal legs which can be screwed in the rim of the supplytank. The stopcock (12) at the base of the water reservoir is only used to release the water and not to control the delivery rate of water to the raindrop applicators. Control is achieved by a pressure head regulator (13) which controls through a plastic tube (14) the head of water in the supplytank. The pressure head regulator, water reservoir, connecting plastic tube and supplytank form a system in which water and air pressure can reach a dynamic equilibrium. Under these conditions waterdrops are falling at a steady rate under an equilibrium constant head (h1) in the supply tank. This constant head is maintained by a periodical supply of water from the waterreservoir. The constant head which is reached at equilibrium in the supplytank depends on the head of water (h2) in the pressure head regulator in such a way that h2 = h3. Measurements were done on the end velocity of the raindrops falling from a height of one metre. By using a measuring device with infra-red rays (Pot, oral communications) end velocities were measured with a mean of 4.80 m/sec. Based on this velocity the supply of energy to the soil surface per m^2 per mm rain is 23.04 Joule. According to the measurements of Wischmeier in the United States this energy supply is delivered by natural rainstorms with an intensity of ± 18 mm per hour.

The test procedure in the field was the following:

With the steel cylinder a sample was taken out of the ground and placed on a horizontal spot in the field. The slopes were too steep to let the cylinder in place on the ground. On top of the cylinder the splash shield and wind shield were placed and leveled. Then the rainfall simulator system was prepared. By regulating the height of the water in the pressure head regulator (13) the water level in the water supplytank was adjusted to the desired rainfall rate. When the system was raining at the desired rate, the supplytank with regulating system was placed on the windshield and the stopwatch was started. The head of the water in the water reservoir was noted. This was done again after the experiment was stopped. In this way the total amount of supplied water could be calculated to check the rainfall intensities.

Plastic bottles were placed under the runoff spout (3) and the splash spout (6). The amount of runoff was measured at two minute time intervals by changing and emptying the plastic bottle in a volume size cylinder. Time was noted when runoff started.

The experiment had to be stopped after 15 minutes, because by that time the front of the percolating water had reached the lower end of the cylinder in the most permeable soil samples. The splashed material in the splash trough and against the splash shield, and the material in the runoff trough was caught separately by rinsing with water. The sediment was filtered and weighed.
The total volume of water from the runoff was measured and the suspended sediment filtered and dried on a pre-weighed filter. The volume of splashed water measured also. The infiltration rate was then calculated by subtracting the mean amount of splash water per 2 minutes and the amount of runoff per 2 minutes from the amount of water supply every 2 minutes.
In this way an infiltration rate curve can be drawn. An example is given in Figure A2. For the purpose of this study the following results are used:

- The amount of splashed material derived from the splash trough (5) which is given in grams per 100 mm of supplied rain.
- The fc-value in mm/min, which is the ultimate constant infiltration rate (see Figure A2).

The samples were taken under dry conditions and the soil moisture is assumed to be constant. Rainfall intensities varied from 150-200 mm/hr.

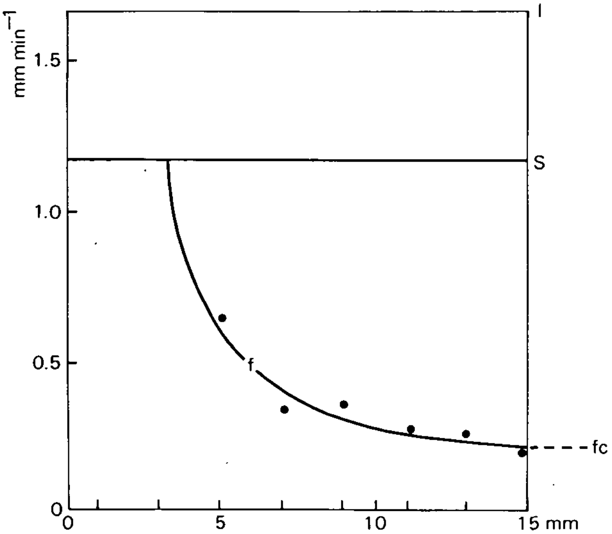


Figure A2 The infiltration rate of a soil developed in metamorphic rocks. I: rainfall intensity in mm min^{-1}; S: mean amount of water in mm min^{-1} splashed out of the test area; f: infiltration rate in mm min^{-1}; f_C: ultimate infiltration rate in mm min^{-1}.

APPENDIX A2

METHODS OF MEASURING SPLASH AND OVERLANDFLOW EROSION

For the measurement of the sediment transport by overlandflow and splash. two types of instrument were used: "Gerlach troughs" after Gerlach (1966) and the splash-boards after Ellison (1944) (Plate A16). The Gerlach troughs, 50 cm in length, were inserted in holes in the soil, with a lip on the upslope side, projecting 1 cm into the soil 1 cm below the soil surface (Figure A3).
A certain amount of the troughs were covered with a plate, which prevented the direct

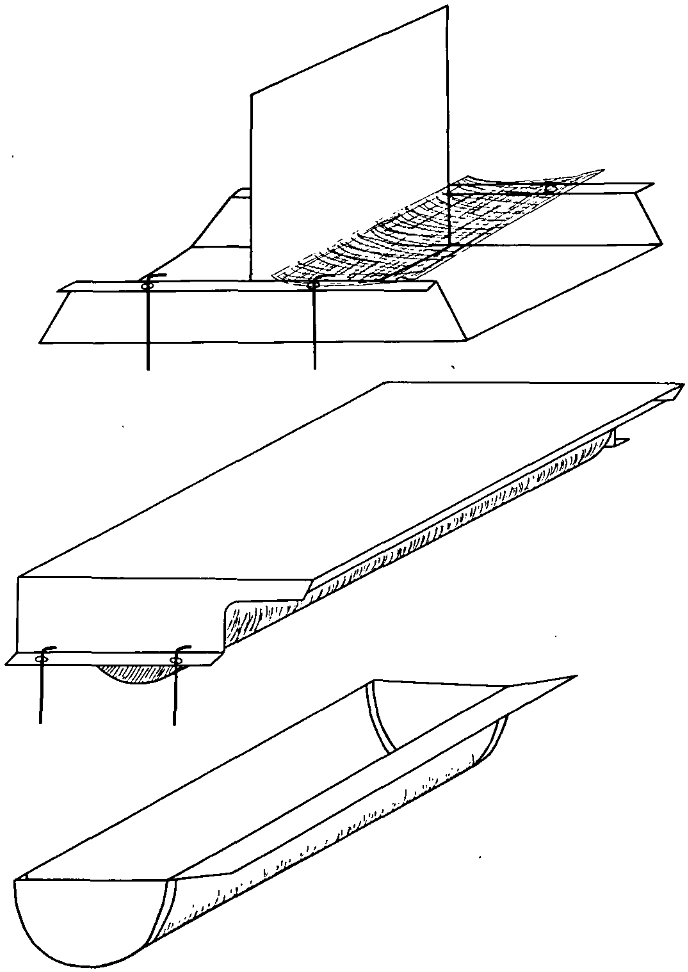


Figure A3 Splash shields and "Gerlach" throughs for measuring splasherosion and overland flow erosion.

input of rain (Figure A3). A provision was made for the overlandflow water to run from the trough in a plastic reservoir of 10 litres. With this equipment sediment transported by overlandflow and the amount of runoff could be measured. A number of troughs were not covered by a plate and with the equipment sediment transported by overland-flow and splash could be measured. Protections were made to prevent the sediment from splashing out of the troughs by using a canopy of gauze. To catch the material which is transported by splash erosion alone, a splashboard 50 cm in width was used with on both sides troughs (Figure A3). This allows material coming from upslope and downslope direction to be distinguished. A small canopy of gauze was placed over the troughs to prevent material splashing out again. The troughs were not sunk into the ground but were laid flat on the ground. A drain was made at the upper edge to prevent overlandflow sediment from coming into the troughs. The Gerlach troughs and splash troughs are relatively small in regard to the great variation in transport of sediments between certain spots on a slope. The material also has a tendency to wash in at an accelerated rate from the small vertical free faced exposed soil horizon especially in the first periods.

Measurements were done in the spring of 1972 and 1973 during the rainy season. In 1972 eight slopes were selected in landunits with a more or less natural character. On these slopes 4-6 Gerlach troughs were placed and 2-4 splash shields. In 1973 four slopes were selected in the agricultural area. On these slopes measuring plots were constructed 1 metre in width and 4 metres long. Rainfall data were assembled from the nearby stations and from rain gauges placed near the plots.

APPENDIX A3

DESCRIPTION OF MEASURING PLOTS

site	slope length	slope form	slope angle	exposition	elevation	parent material	% trees	% shrubs	% grasses	% stones
1	45 m	straight	25	N	65	Ma-claystone	-	-	80	3

physical and chemical data of A-horizon

horizon	depth	gravel	sand			silt	clay
A	10 cm	-	14.12	6.47	8.73	55.61	15.07

mineralogy of the clay fraction					
M/C	MM	Bn	SI	CNM	NM
-	x	x	x	x	tr
Be	M2M	M3T	I	G/C	BK
tr	x	xx	xx	xx	x

pH(H_2O)	pH(KCl)	C	N	C/N	Exchangeable cations (meq/100gr soil)						base sat. pct.	aggregate stab.(McCalla)
					Ca	Mg	K	Na	Sum	CEC		
7.78	7.09	4.15	0.15	27.6	62.0	1.99	0.47	0.14	64.8	15.4	100	105.1/0.1gr

SOIL DESCRIPTION

0 - 20 cm	A	2.5Y 4.5/2	Silty clay; moderate fine to coarse subangular blocky; sticky plastic when wet, very hard when dry; few fine pores; common fine roots; few gravel; diffuse boundary
20 - 60 cm	(B)	2.5Y 5/4	Sandy clay; moderate to coarse subangular blocky and fine granular; non sticky slightly plastic when wet, slightly hard when dry; common fine pores; few fine roots; few gravel and stones; gradual boundary
60 - 180 cm	C	7.5Y 4/3	Sandy clay; moderate to fine granular; non sticky; slightly plastic when wet, slightly hard when dry; common fine pores; few fine roots; many gravel and stones

Soil type: "sol brun calcaire vertique" (C.P.C.S.-system)

site	slope length	slope form	slope angle	exposition	elevation	parent material	% trees	% shrubs	% grasses	% stones
2	35 m	straight	25	NW	430	sf-metam. rocks	90	-	42	26

physical and chemical data of A-horizon

horizon	depth	gravel	sand			silt	clay	mineralogy of the clay fraction					
								M/C	MM	Bn	SI	CNM	NM
A1	10 cm	10.76	24.99	9.59	7.19	36.50	10.00	-	-	-	x	x	tr
								Be	M2M	M3T	I	G/C	BK
								tr	xxx	tr	xx	x	xx

pH(H_2O)	pH(KCl)	C	N	C/N	Exchangeable cations (meq/100gr soil)						base sat. pct.	aggregate stab.(McCalla)
					Ca	Mg	K	Na	Sum	CEC		
6.05	5.36	6.0	0.36	16.67	7.6	2.38	0.10	0.08	10.2	18.3	55.7	7.1/0.1gr

SOIL DESCRIPTION

1 - 4 cm A11 5 Y R 2/4 Sandy loam; very fine, fine subangular blocky, firm (moist), slighly hard (dry); many medium fine pores; common fine roots; many gravel; distinct boundary

60 cm A12 5 Y R 3/4 Sandy loam; weak very fine subangular blocky; soft dry; common fine pores; common fine roots; many gravel; abrupt boundary

80 cm (B_t) 5 Y R 2/3 Sandy loam; strong fine angular blocky; hard dry; common fine pores; very few fine roots; very much gravel; gradual boundary

100 cm C 5 Y R 4/3 Structureless; loose dry; many gravel and stones

Soil type: "sol brun faiblement lessivé" (C.P.C.S.-system)

site	slope length	slope form	slope angle	exposition	elevation	parent material	% trees	% shrubs	% grasses	% stones
3	60 m	straight	28^o	SE	615 m	sf-metam. rocks	-	-	20	25

physical and chemical data of A-horizon

horizon	depth	gravel	sand			silt	clay	mineralogy of the clay fraction					
								M/C	MM	Bn	SI	CNM	NM
A1	10 cm	4.64	30.66	17.81	11.36	24.88	10.56	-	-	-	x	x	x
								Be	M2M	M3T	I	G/C	BK
								tr	xxx	tr	xx	x	xx

pH(H_2O)	pH(KCl)	C	N	C/N	Exchangeable cations (meq/100gr soil)						base sat. pct.	aggregate stab.(McCalla)
					Ca	Mg	K	Na	Sum	CEC		
5.66	4.65	2.09	0.17	12.29	4.2	0.90	0.07	0.08	5.25	11.7	44.9	78.7/0.1gr

SOIL DESCRIPTION

0 - 2 cm A11 7.5 Y R 2/3 Sandy loam; weak fine subangular blocky; friable moist, soft dry; many fine proces; common fine roots; many gravel; abrupt boundary

2 - 20 cm A12 5 Y R 3/3 Sandy loam; weak medium subangular blocky; friable moist, soft dry, many medium and fine pores; common fine roots; many gravel; gradual boundary

20 - 40 cm (B) 5 Y R 3/4 Sandy loam; weak very fine subangular blocky; friable moist, soft dry; many medium and fine pores, few fine roots; many gravel; gradual boundary

C > 40 cm 5 Y R 3/4 Structureless; loose dry; very few fine roots, very much stones

Soil type: "sol brun modal" (C.P.C.S.-system)

site	slope length	slope form	slope angle	exposition	elevation	parent material	% trees	% shrubs	% grasses	% stones
4	25 m	straight	29	S	710 m	sf-metam. rocks	-	-	25	50

physical and chemical data of A-horizon

horizon	depth	gravel	sand			silt	clay	mineralogy of the clay fraction					
								M/C	MM	Bn	SI	CNM	NM
A1	10 cm	9.19	25.71	14.80	10.46	26.36	13.65	-	-	-	x	x	x
								Be	M2M	M3T	I	G/C	BK
								tr	xxx	tr	xx	x	xx

$pH(H_2O)$	pH(KCl)	C	N	C/N	Exchangeable cations (meq/100gr soil)						base sat. pct.	aggregate stab.(McCalla)
					Ca	Mg	K	Na	Sum	CEC		
5.42	4.81	3.54	0.26	13.6	5.6	1.76	0.12	0.08	7.6	17.8	42.7	20.2/0.1gr

SOIL DESCRIPTION

0 - 2 cm $A_{1.1}$ 7.5 Y R 3/3 Sandy loam; moderate very fine subangular blocky; slightly hard dry;many fine and medium pores; many fine and medium roots; clear boundary

2 - 20 cm $A_{1.2}$ 5 Y R 3/3 Sandy loam; moderate fine angular blocky; slightly hard dry; many fine and medium pores; common fine and medium roots; many gravel; gradual boundary

20 - 30 cm C Structureless; loose dry; very few very fine roots; very much stones

Soil type: "sol peu évolué d'apport colluvial modal" (C.P.C.S.-system)

site	slope length	slope form	slope angle	exposition	elevation	parent material	% trees	% shrubs	% grasses	% stones
5	10 m	straight	33^o	SE	Mar-s sandstone	-	-	-	80	15

physical and chemical data of A-horizon

horizon	depth	gravel	sand			silt	clay	mineralogy of the clay fraction					
								M/C	MM	Bn	SI	CNM	NM
A1	10 cm	0.99	23.67	28.87	21.86	19.39	5.11	-	-	x	x	x	-
								Be	M2M	M3T	I	G/C	BK
								x	tr	x	x	xxx	tr

$pH(H_2O)$	pH(KCl)	C	N	C/N	Exchangeable cations (meq/100gr soil)						base sat. pct.	aggregate stab.(McCalla)
					Ca	Mg	K	Na	Sum	CEC		
6.20	5.19	0.99	0.08	12.38	11.4	1.17	0.19	0.07	12.8	10.0	100	52.5/0.1gr

SOIL DESCRIPTION

0 - 10 cm A_1 10 Y R 4/4 Loamy sand; weak fine subangular blocky; very friable moist; soft dry; many fine random pores; many fine roots; very few gravel; diffuse boundary

10 - 20 cm AC 10 YR 6/4 Loamy sand; weak fine subangular blocky; very friable moist; soft dry; many fine random pores; common fine roots; very little gravel; diffuse boundary

20 - 60 cm C 10 Y R 6/6 Loamy sand; structureless; loose dry; many discontinuous random pores; few fine roots; very little gravel.

Soil type: "sol peu évolué d'apport colluvial modal" (C.P.C.S.-system)

site	slope length	slope form	slope angle	exposition	elevation	parent material	% trees	% shrubs	% grasses	% stones
6	15 m	straight	34°	NE	430		-	-	45	15

physical and chemical data of A-horizon

horizon	depth	gravel	sand			silt	clay
A1	6 cm	3.12	25.78	28.62	22.17	13.75	6.54

mineralogy of the clay fraction					
M/C	MM	Bn	SI	CNM	NM
-	-	x	x	x	-
Be	M2M	M3T	I	G/C	BK
x	tr	x	x	xxx	tr

pH(H_2O)	pH(KCl)	C	N	C/N	Exchangeable cations (meq/100gr soil) Ca	Mg	K	Na	Sum	CEC	base sat. pct.	aggregate stab.(McCalla)
8.00	7.70	1.55	0.11	14.09	36.5	1.28	0.31	0.04	38.1	9.7	100	37.3/0.1gr

SOIL DESCRIPTION

0 - 3 cm A_0 moder (local)

3 - 20 cm A_1 7.5 Y R 3/6 Loamy sand; weak fine subangular blocky; fine granular blocky; fine granular; soft dry; many fine and medium pores; many fine roots; few gravel; gradual boundary

20 - 40 cm (B) 5 Y R 4/3 Loamy sand; weak fine subangular blocky; fine granular; soft dry; many fine and medium pores; few fine roots; few gravel; gradual boundary

40 - 60 cm C 5 Y R 5/3 Loamy sand; structureless; loose dry; many discontinuous random pores; few fine roots; very little gravel

Soil type: "sol brun calcaire modal" (C.P.C.S.-system)

site	slope length	slope form	slope angle	exposition	elevation	parent material	% trees	% shrubs	% grasses	% stones
8	15 m	straight	32	NW	430	Mar-s sandstone	80	-	10	13

physical and chemical data of A-horizon

horizon	depth	gravel	sand			silt	clay
A1	5 cm	4.05	33.98	28.51	12.50	15.51	

mineralogy of the clay fraction					
M/C	MM	Bn	SI	CNM	NM
-	-	x	x	x	-
Be	M2M	M3T	I	G/C	BK
x	tr	x	x	xxx	tr

pH(H_2O)	pH(KCl)	C	N	C/N	Exchangeable cations (meq/100gr soil) Ca	Mg	K	Na	Sum	CEC	base sat. pct.	aggregate stab.(McCalla)
5.63	4.86	1.53	0.10	15.3	4.3	1.69	0.07	0.013	6.2	9.6	64.6	103.4/0.1gr

SOIL DESCRIPTION

0 - 0.5 cm A_{00} Litter

0.5 - 1 cm (A_0) Moder

1 - 3 cm $A_{1.1}$ 7.5 Y R 3/3 Loamy sand; weak very fine subangular blocky; soft dry; many medium fine pores; many fine roots; few gravel; distinct boundary

3 - 30 cm $A_{1.2}$ 10 Y R 4/4 Loamy sand; weak fine subangular blocky; soft dry; many medium fine pores; many fine roots; few gravel; gradual boundary

30 - 60 cm C 10 Y R 5/8 Weathered slope

Soil type: "sol peu évolué d'apport colluvial modal" (C.P.C.S.-system)

site	slope length	slope form	slope angle	exposition	elevation	parent material	% trees	% shrubs	% grasses	% stones
9	10 m	steps	30°	N	530	Mar-s sandstone	-	90	90	3

physical and chemical data of A-horizon

horizon	depth	gravel	sand			silt	clay
A1	4 cm	0.81	18.93	38.57	18.20	16.83	6.67

mineralogy of the clay fraction					
M/C	MM	Bn	SI	CNM	NM
Be	M2M	M3T	I	G/C	BK

pH(H_2O)	pH(KCl)	C	N	C/N	Exchangeable cations (meq/100gr soil)						base sat. pct.	aggregate stab.(McCalla)
					Ca	Mg	K	Na	Sum	CEC		
6.25	5.72	10	0.48	20.83	34.0	3.77	0.30	0.10	38.2	33.7	100	85.4/0.1gr

SOIL DESCRIPTION

0 - 1 cm	A_{00}		Litter
1 - 3 cm	A_0		Moder
3 - 12 cm	A_1	7.5 Y R 3/3	Loamy sand; weak fine subangular blocky; slightly hard dry; many fine and medium pores; common medium roots; very little gravel; abrupt boundary
12 - 30 cm	C	10 Y R 3/8	Loamy sand; structureless; loose dry; many discontinuous random pores; few fine roots; very little gravel
		Soil type:	"sol peu évolué d'apport colluvial modal" (C.P.C.S.-system)

site	slope length	slope form	slope angle	exposition	elevation	parent material	% trees	% shrubs	% grasses	% stones
10	4 m	straight	22.5°	NW		Mar-s sandstone	-	-	-	5

physical and chemical data of A-horizon

horizon	depth	gravel	sand			silt	clay
Ap	5 cm	-	18.52	36.24	21.93	19.50	3.81

mineralogy of the clay fraction					
M/C	MM	Bn	SI	CNM	NM
-	-	x	x	x	-
Be	M2M	M3T	I	G/C	BK
x	tr	x	x	xxx	tr

pH(H_2O)	pH(KCl)	C	N	C/N	Exchangeable cations (meq/100gr soil)						base sat. pct.	aggregate stab.(McCalla)
					Ca	Mg	K	Na	Sum	CEC		
6.22	5.20	0.73	0.03	22.81	17.4	0.93	0.14	0.06	18.0	5.9	100	15.2/0.2gr

SOIL DESCRIPTION

0 - 30 cm	A_p	10 Y R 4/4	Loamy sand; weak fine to moderate subangular blocky; very friable when moist, soft when dry; many fine to medium pores; few fine roots; very little gravel; gradual boundary
30 - 50 cm	AC	10 Y R 6/4	Loamy sand; weak fine granular; very friable when moist, soft when dry; many medium pores; very little gravel; diffuse boundary
50 - 70 cm	C	10 Y R 6/6	Loamy sand; weak fine granular; very friable when moist, soft when dry; many medium pores; very little gravel
		Soil type:	"sol peu évolué d'apport colluvial modal" (C.P.C.S.-system)

site	slope length	slope form	slope angle	exposition	elevation	parent material	% trees	% shrubs	% grasses	% stones
11	4 m	straight	18°	W	120	sf-metam. rocks	30	-	-	40

physical and chemical data of A-horizon

horizon	depth	gravel	sand			silt	clay	mineralogy of the clay fraction					
								M/C	MM	Bn	SI	CNM	NM
Ap	5 cm	-	1.60	24.19	20.33	44.51	9.27	-	-	x	-	x	tr
								Be	M2M	M3T	I	G/C	BK
								tr	xxx	tr	xx	x	xx

$pH(H_2O)$	pH(KCl)	C	N	C/N	Exchangeable cations (meq/100gr soil)						base sat. pct.	aggregate stab.(McCalla)
					Ca	Mg	K	Na	Sum	CEC		
6.3	5.5	1.4	0.11	12.73	5.90	1.81	0.60	0.12	6.50	16.4	39.6	6.8/0.1gr

SOIL DESCRIPTION

0 - 20 cm	A_p	7.5 Y R 2/3	Loam; moderate medium subangular blocky; common fine pores; few fine roots; many gravel; gradual boundary
20 - 60 cm	AC	5 Y R 3/3	Loam; moderate fine subangular blocky; slightly hard when dry; common fine pores; very few fine roots; many gravel; distinct boundary
60 - 170 cm	C	5 Y R 3/4	Stones, bedrock
		Soil type:	"sol peu évolué d'apport colluvial modal" (C.P.C.S.-system)

site	slope length	slope form	slope angle	exposition	elevation	parent material	% trees	% shrubs	% grasses	% stones
12	4 m	straight	21°	S	80 m	Ma-claystone	-	-	-	3

physical and chemical data of A-horizon

horizon	depth	gravel	sand			silt	clay	mineralogy of the clay fraction					
								M/C	MM	Bn	SI	CNM	NM
Ap	5 cm	-	7.20	32.61	13.88	34.25	12.05	-	x	x	x	x	tr
								Be	M2M	M3T	I	G/C	BK
								tr	tr	x	xx	xx	x

$pH(H_2O)$	pH(KCl)	C	N	C/N	Exchangeable cations (meq/100gr soil)						base sat. pct.	aggregate stab.(McCalla)
					Ca	Mg	K	Na	Sum	CEC		
7.71	7.01	3.48	0.16	21.75	24.0	0.91	0.61	0.15	25.7	16.5	100	64.6/0.1gr

SOIL DESCRIPTION

0 - 20 cm	A_p	7.5 Y R 2/3	Silty clay; moderate coarse subangular blocky; firm moist; common pores; common medium roots; many gravel; gradual boundary
20 - 35 cm	(B)	7.5 Y R 3/3	Silty clay; moderate medium angular blocky; firm moist; few pores; very much gravel; thin cutans; gradual boundary
35 - 50 cm	C	7.5 Y R 3/3	Silty clay; moderate medium angular blocky; firm moist; few pores; very much gravel
		Soil type:	"sol brun calcaire vertique" (C.P.C.S.-system)

APPENDIX A4 EROSION DATA OF MEASURING PLOTS

Measuring period	1 Total rainfall in mm.	2 Number of days with rain	3 Mean overland flow in ml mm^{-1} rain	4 Mean overland flow erosion in gr l^{-1}	5 Mean overland flow erosion in gr 10 mm^{-1} rain	6 Mean splash erosion in gr 10 mm^{-1} rain	7 Mean water erosion in gr 10 mm^{-1} rain
PLOT 1							
19/2-29/2	58	6	-	-	-	-	-
29/2- 7/3	35	2	34.9 (8.7)	2.6 (1.1)	92 (42)	43 (40)	50 (48)
7/3-16/4	65.5	8	-	-	-	-	-
16/4- 1/5	57.2	8	-	-	-	-	-
1/5- 8/5	89.8	4	47.4 (12.5)	0.3 (0.1)	13 (8)	7 (2)	6 (2)
PLOT 2							
21/2-13/3	150.9	10	1.0 (0.24)	7.6 (0.8)	78 (8)	320 (146)	437 (229)
13/3-17/4	38.5	10	1.4 (0.7)	109.4 (83.9)	150 (120)	812 (321)	881 (164)
17-4- 5/6	105.1	11	22.8 (9.1)	12.1 (4.0)	270 (80)	163 (64)	395 (257)
PLOT 3							
4/2-13/3	156.6	10	21.7 (2.0)	8.3 (0.9)	187 (25)	4 (2) 137 (50)	250 (88)
13/3-17/4	42.3	10	13.0 (2.1)	6.0 (2.1)	78 (25)	- - 19 (4)	146 (87)
17/4- 6/5	110.2	11	17.9 (1.8)	3.5 (0.6)	62 (20)	3 (1) 36 (29)	45 (9)
PLOT 4							
24/2-13/3	158.2	10	17.5 (8.5)	9.8 (3.2)	172 (62)	149 (53)	304 (192)
13/3-17/4	43.7	10	13.4 (4.7)	8.3 (3.3)	112 (51)	26 (11)	104 (49)
17/4- 6/5	112.8	11	18.8 (6.3)	2.5 (0.7)	47 (21)	33 (8)	40 (35)
PLOT 5							
25/2- 7/3	81.7	7	109.9 (33.3)	3.6 (1.0)	396 (170)	16 (14) 120 (20)	416 (63)
7/3-28/3	45.5	5	43.4 (12.3)	10.3 (2.4)	447 (57)	21 (9) 100 (38)	223 (14)
28/3-15/4	51.3	6	50.7 (21.2)	3.5 (1.6)	179 (62)	9 (3) 50 (30)	231 (152)
15/4- 1/5	63.2	10	55.4 (13.8)	3.9 (1.8)	214 (65)	12 (8) 70 (9)	50 (27)
1/5- 8/5	91.4	5	20.8 (7.4)	7.3 (2.4)	151 (24)	12 (10) 70 (12)	285 (37)
PLOT 6							
25/2- 8/3	62.5	4	2.0 (0.6)	7.7 (1.5)	157 (49)	9 (3) 286 (8)	353 (162)
8/3-28/3	36.3	3	6.2 (3.6)	8.0 (1.9)	46 (13)	15 (5) 156 (42)	151 (59)
28/3-15/4	39.2	5	8.0 (2.3)	0.9 (3.1)	68 (25)	39 (1) 295 (15)	311 (20)
15/4- 1/5	57.2	8	1.7 (0.5)	3.8 (1.2)	73 (20)	76 (69) 183 (12)	36 (17)
1/5- 8/5	89.8	4	2.4 (0.7)	0.1 (0.0)	2 (1)	15 (2) 122 (56)	57 (50)

Note: Figures in parenthesis are standard deviations

Measuring period	1 Total rainfall in mm.	2 Number of days with rain	3 Mean over-land flow in ml mm^{-1} rain	4 Mean over-land flow erosion in gr l^{-1}	5 Mean over-land flow erosion in gr 10 mm^{-1} rain	6 Mean splash erosion in gr 10 mm^{-1} rain	7 Mean water erosion in gr 10 mm^{-1} rain
PLOT 7							
4/3- 7/3	43.7	3	-	-	-	26 (10) 217 (39)	-
7/3-28/3	45.5	5	-	-	-	29 (12) 147 (4)	-
28/3-15/4	51.3	6	-	-	-	18 (4) 176 (51)	-
15/4- 1/5	63.3	10	-	-	-	9 (5) 1(?)39 (23)	-
1/5- 8/5	75.8	5	-	-	-	21 (18) 87 (45)	-
PLOT 8							
29/2-14/3	132.6	8	14.7 (4.3)	10.8 (6.2)	158 (72)	25 (7) 298 (106)	308 (38)
14/3-17/4	42.8	9	12.4 (3.1)	6.0 (2.1)	74 (31)	17 (3) 110 (29)	171 (49)
17/4- 6/5	67.8	13	12.2 (3.0)	0.1 (0.4)	114 (25)	55 (20) 286 (38)	153 (77)
PLOT 9							
25/2- 8/3	70.1	4	9.1 (5.1)	3.4 (1.5)	53 (21)	-	53 (25)
8/3-28/3	40.3	3	4.8 (2.0)	4.3 (3.0)	47 (25)	-	47 (9)
28/3-15/4	43.2	5	5.3 (2.8)	0.6 (0.2)	20 (11)	-	20 (8)
15/4- 1/5	60.5	8	4.7 (2.4)	5.5 (2.3)	52 (32)	-	52 (34)
1/5- 8/5	89.7	4	2.5 (1.0)	4.4 (1.5)	27 (10)	-	27 (10)

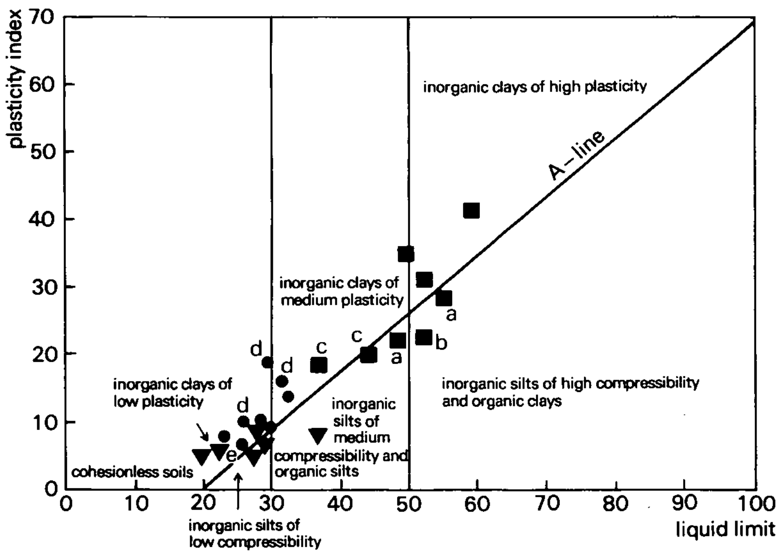
Measuring period	1 Total rainfall in mm.	2 Number of days with rain	3 Mean over-land flow in ml mm^{-1} rain	4 Mean over-land flow erosion in gr l^{-1}	5 Mean over-land flow erosion in gr 10 mm^{-1} rain	6 Mean splash erosion in gr 10 mm^{-1} rain	7 Mean water erosion in gr 10 mm^{-1} rain
PLOT 10							
-24/2	23.5	-	7.5	52.2	400	-	-
24/2-27/2	62.0	-	82.6	127.8	10557	186 971	-
27/2-11/3	38.5	-	27.9	21.5	601	128 543	-
11/3-19/3	49.7	-	95.8	29.5	2826	127 836	-
19/3- 1/4	44.8	-	23.3	6.9	161	93 284	-
1/4- 4/4	22.4	-	23.4	23.8	558	71 481	-
4/4-19/4	49.7	-	147.1	11.3	1662	147 930	-
PLOT 11							
20/2-25/2	51.0	-	220.5	30.2	6669	-	-
25/2-12/3	26.1	-	488.8	26.9	13141	289 487	-
12/3-19/3	44.6	-	252.0	34.4	8667	82 341	-
19/3- 2/4	36.2	-	262.3	6.5	1706	36 305	-
2/4- 4/4	14.9	-	804.3	52.2	41994	213 666	-
4/4-17/4	21.1	-	461.2	9.8	4535	182 672	-
17/4-21/4	21.4	-	440.4	15.2	6690	110 252	-
PLOT 12							
20/2-26/2	52.2	-	-	16.4	98	-	-
26/2-11/3	26.1	-	-	-	981	33 410	-
11/3-19/3	44.6	-	-	-	-	-	-
19/3- 1/4	36.2	-	39.2	14.8	2025	49 725	-
1/4- 4/4	14.9	-	48.7	6.8	322	24 653	-
4/4-15/4	21.1	-	-	-	•-	39 562	-
15/4-22/4	21.4	-	45.3	10.4	472	73 800	-

Note: see page 207

APPENDIX A5

SOME PHYSICAL AND MINERALOGICAL CHARACTERISTICS OF THE SLIDED MATERIAL

In Table A1 some physical and mineralogical characteristics of different types of landslide are given. In Figure A4 the Plasticity Index and Liquid Limit values[1] for different remoulded soils are plotted in a Plasticity Chart. From the Table (column 4-6) and Figure A4 we can infer that the clay soils have a high Plasticity Index and Liquid Limits compared with the sandstone and metamorphic rock soils. According to the Unified Soil Classification System made by the Bureau of Reclamation and the Corps of Engineers (Wagner, 1957) the claystone soils belong to the inorganic clays with medium to medium to-high plasticity, while the other soils can be classified as inorganic clays or silts with a low to medium plasticity. The relatively low Liquid Limits and PI-values of the sandstone soils and the soils derived from metamorphic rocks mean that a relative



● soils derived from claystone

■ soils derived from sandstones

▼ soils derived from metamorphic rocks

Figure A4 The relation between Liquid Limit and Plasticity Index for different soil materials of landslides.

Table A1: Physical and mineralogical characteristics of slided material.

Location	Landslide type	Lithology	Lp	Lw	PI	A	grainsizes 2000/420	420/150	150/50	50/2	< 2	Bases Mg	Ca	K	Na	S	T	Mixed Layer M/C	MM	B	SI	Smectites CNM	NM	B	Mica's M2M	M3T	I	G/C	Kandites BK
Cleto	4	Ma	28	52	24	0.89	3.38	4.49	13.49	51.66	27.08							tr	-	x	x	x	-	tr	tr	x	xx	tr	x
St. Pietro	5	Mars	20	26.8	6.8	2.13	5.28	36.25	36.8	18.4	3.2	1.71	26.4	0.23	0.09	28.40	8.30	-	x	x	x	x	tr	tr	tr	tr	x	-	x
			10	29.5	19.5	2.41	3.4	30.2	27.5	30.8	8.1																		
St. Antoni	6	Ma	18	36.6	18.6	0.54	0.32	1.25	20.6	43.2	34.6	3.08	58.9	0.25	0.07	62.30	7.40	-	-	x	x	x	-	tr	x	x	x	xx	x
							5.2	3.5	11.3	43.5	36.2							-	-	x	x	x	-	tr	tr à x	x	xx	tr	x
			22	43.5	21.5	0.52	2.59	5.32	20.58	29.96	41.55							x	x	x	x	x	x	x	tr	tr	xx	xxx	xx
Nocera	7	Sf	22	28.9	6.9	0.58	38.4	12.7	9.2	27.6	12.0	0.98	23.5	0.16	0.13	24.77	11.52	x	-	x	x	x	-	tr	xxx	x	x	-	xx
Nicoli	8	Sf	18	27.4	9.4																								
St. Pietro	9	Mars	21	34.5	13.5	1.16	0.37	9.53	44.7	33.8	11.6	0.72	23.2	0.20	0.08	24.2	12.2												
Campora	10	Ma	20	52.0	32	1.03	8.5	9.6	8.8	42.0	31.0	1.25	58.20	0.20	0.21	59.90	14.60	-	x	x	x	x	tr	tr	tr	x	x	xxx	tr à x
Nocera	10	Sf	29	37.5	8.5	0.76	21.7	11.6	10.0	45.4	11.2	1.05	18.50	0.19	0.17	19.90	22.40	-	-	x	-	x	tr	tr	xxx	tr	xx	x	xx
Cozze Finochio	11	Mars	21	29.4	8.4	0.60	24.5	20.2	19.3	21.8	14.0	1.64	36.60	0.37	0.18	38.80	2.60												
			19	27.4	8.4	1.79	5.0	22.8	46.9	20.5	4.7							-	-	tr	x	x à xx	-	tr	tr	x	xx	x	x
Valle Colonci	11	Ma	25	47.6	22.6	0.99	4.2	4.8	20.2	47.8	22.9	1.98	58.4	0.47	0.15	61.0	16.4	-	-	x	x	xxx	x	x	tr	x	xx	x	x à xx
Nocera	12	Sf	14	20.2	6.2	13.5	32.9	18.07	18.9	26.8	4.6																		

Lp = Plastic limit, Lw = Liquid limit, PI = Plasticity index.

A = Activity index, M/C = montmorillonite-chlorite, MM = Montmorillonite-mica 1:1, Bn = Bentonite, SI = "Swelling illite", CNM = Ca & Ca-Na Montmorillonite, NM = Na-Montmorillonite, Be = Beidellite, M2M = Muscovite 2 M, M3T = Muscovite 3 T, I = Illite, G/C = glauconite/celadonite, BK = badly cristallized kaolinite.

xxxx: dominant compound; xxx: large quantities (over 20%); xx: medium quantities (5-20%); x: small quantities (1-5%); tr: trace (less than 1%); -: absent.

small increase in water content between the Plastic Limit and the Liquid Limit, leads to a rapid decrease in strength. During high intensive rainstorms the Liquid Limit may be relatively easily reached and the material changes in a liquid mud, with very low to zero yield strength. In this case wet mud flows with a fairly high flow velocity may develop. The claystone soils need a higher water content to reach such a liquid state, but below this ultimate value there lies a larger range of moisture content values between the Liquid Limit and the Plastic Limit (IP index) in which the clay has a viscous component. If the yield strength (see Figure 6.1) of the clay is surpassed under these conditions the material is going to move as a relatively slow viscous flow. It is interesting to note in Figure A4 that the flow of Valle Collonci (a in Figure A4) (see page 166) shows a high Plasticity Index, which means that this flow has the capacity to move as a slow viscous flow at lower slope angles. The same can be said for the fossile flow near Cleto (b in Figure A4) (see page 135) and in a lesser way for the flow of St. Antonio (c) (see page 140) which is mapped as a more rapid debris flow, developing at a steeper slope angle. The flow developed after failure in the rockslide near S. Pietro (d) (see page 135) has relatively low Liquid Limits and therefore has the character of a rapid mud flow. It is interesting to note that the landslide complex of Cozze Finochio (e) (see page 170) developed in sandstone has also low Liquid Limits. Therefore it can be discussed whether in this slow moving sandy mass there exist slow viscous flows. Probably the mass in the upper end moves as a sliding mass while in the wet tongue area rapid mud flows are present. The PI-index is determined by the activity of the clay minerals which can be defined as the capacity to atttract a certain amount of water at their surface. This depends on the type of clayminerals and the type of cat-ions attracted to the surface. The activity of the clay in the soil can be expressed as the ratio between the PI-index and the percentage of clay fraction ($> 2\ \mu$) in the soil (see Table A1 column 7). According to Grimm (1962) Na^+ montmorillonites have activity values varying from 3-7.Ca^{2+} montmorillonites from 1.2 - 1.3. Illites from 0.3 - 0.6, kaolinite poorly christalised from 0.3 - 0.4 and kaolinite well christalized $>$ 0.1. The Table shows that the activity of the soils may reach above 1.2 which points to the presence of Ca-montmorillonite or Na-montmorillonite. The clay mineral analyses[2] show that Ca^{2+}-montmorillonites dominate in all samples over Na^+-montmorillonite. The Table also shows that a dominant content of illite and/or kaolinite lowers the activity of the clays below 1.

NOTES

1 For the determination of the Atterberg limits see Sowers (1965, pp. 391-399).

2 The current clay mineralogical identification method in the laboratory of the Department of Physical Geography of the University of Utrecht has been described by Romein (in prep.). An analysis of the clay content of the samples in given by Romein (1980).

APPENDIX A6

LABORATORY ANALYSIS

1 Particle size analysis

Determinations were performed on the fine earth of all samples by sieving and the pipette method. Air dry samples were gently crushed and sieved through a 2 mm sieve. The fine earth fraction has thereupon been treated with H_2O_2 to remove organic carbon. Aggregation by ferric oxides was broken up by boiling the samples with 1 N HCl. A sodium-pyrophosphate – sodium-carbonate mixture has been used as a peptizing agent.

2 pH-H_2O and pH-KCl

The soil is shaken with water or 1 N KCl during 2 hours. In the suspension the pH is measured with a glass electrode pH-meter.

3 Exchangeable bases and cation exchange capacity

The soil is mixed with purified sand, put into percolation tubes and subsequently treated as follows:

- Percolation with water/96% alcohol (1 : 1) to leach water-soluble salts.
- Percolation with 1 N NH_4-acetate/96% alcohol (1 : 1) pH 8.2, determination of Ca, K and Na in the percolate with the flame-photometer and Mg by atomic absorption. The results expressed as me/100 gram of oven-dry soil give the content of exchangeable Ca, Mg, K and Na respectively.
- Percolation with 1 N Na-acetate pH 8.2 to saturate the soil complex with sodium.
- Percolation with pure 96% alcohol to leach excess Na-acetate.
- Percolation with 1 N NH_4-acetate pH 8.2 to exchange the absorbed Na and determination of sodium with the flame-photometer.
  The results in me/100 gram of oven-dry soil give the total exchange capacity, or C.E.C.

4 %C (Walkley & Black)

The soil is oxidized with potassium-di-chromate and sulphuric acid without application of external heat. The amount of potassium-di-chromate used is determined by titration with ferrous sulphate.
According to Walkley & Black, working with American soils, only 77% of the carbon in the organic matter is oxidized. Therefore, in calculating the %C of the oven dry soil the 77% recovery factor is used. The %C gives the content of carbon present in the readily oxidizable organic matter, which is assumed to be well humified.

5 %N (Kjeldahl)

The soil is oxidized with concentrated sulphuric acid and a mixture of selenum and sulphates of copper and sodium as a catalyst. After steam destillation into boric acid, the NH_3 is determined by titration with 0.01 N HC1 and the results are presented as % N of oven-dry soil.

6 Clay-mineralogy

The fraction (> 50 μ) was selected by decanting of the suspension following Stokes law as an extension of the grainsize analysis. X-ray diffraction analysis of random powder specimens of the samples were mainly carried out with a Philips X-ray diffraction equipment. A few samples were (also) analysed with a Philips X-ray diffraction Camera (Debije-Scherrer powder camera, diameter 114.83 mm). In both cases Co-radiation and Fe-filters were used ($\lambda Co_{K\varphi}$ = 1.7902 Å).
The instrument used for differential thermal analysis was a Du Pont de Nemours model 990 thermal analyzer, consisting of a 1200°C DTA-cell with small platinum cups, and a honeywell-recorder. In the laboratory the constant heating rate for routine analysis was 10°C/minute. The thermal reactions of samples were measured from room temperature up to 1100°C against a reference standard of white powdered Al_2O_3. Each sample was measured for about one hour and the electric furnace of the DTA-cell was allowed to cool for another hour.

7 Aggregate stability

The stability of the aggregates was determined by the water-drop method of Mc. Calla (1944). A soil lump weighing approximately 0.15 g. was placed on a 1-mm sieve and drops of distilled water 2.4 mm in diameter, falling 30 cm from a burette were allowed to strike it. When a soil lump or aggregate was broken down and at the point of being washed through the screen, it was considered destroyed. For one aggregate stability value 10 individual determinations were made. The stability value is expressed as the number of raindrops which are necessary to destroy 0.1 g of aggregate material.

Plate 1 Lateral erosion of the Torrente Collonci.

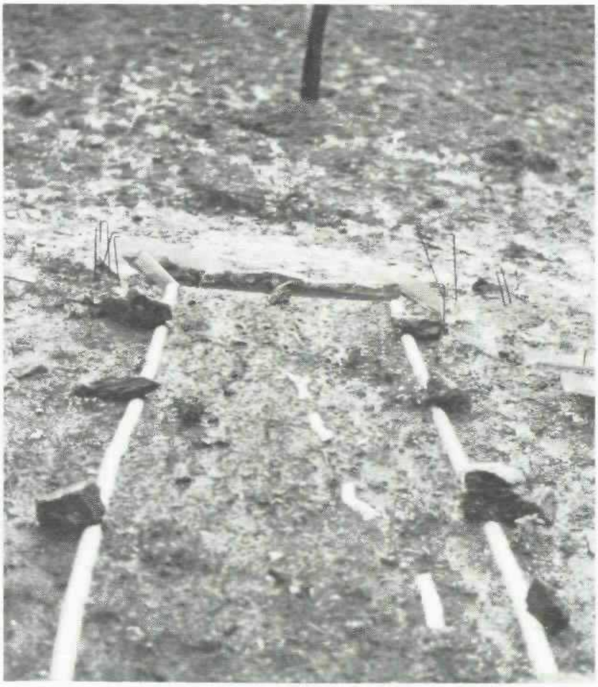


Plate 2 Satured overlandflow on measuring plot 11.

Plate 3 Surface sealing on a freshly ploughed sandstone soil (plot 10) after 3 months with rain.

Plate 4 The formation of a slab in a cliff of Mar-sandstone.

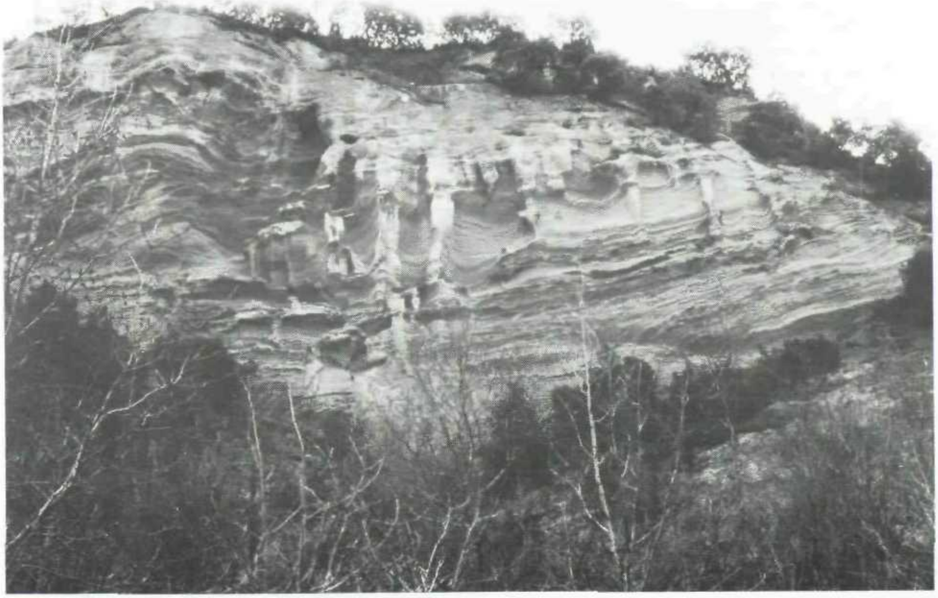


Plate 5 Granular desintegration of Mar-sandstone cliffs.

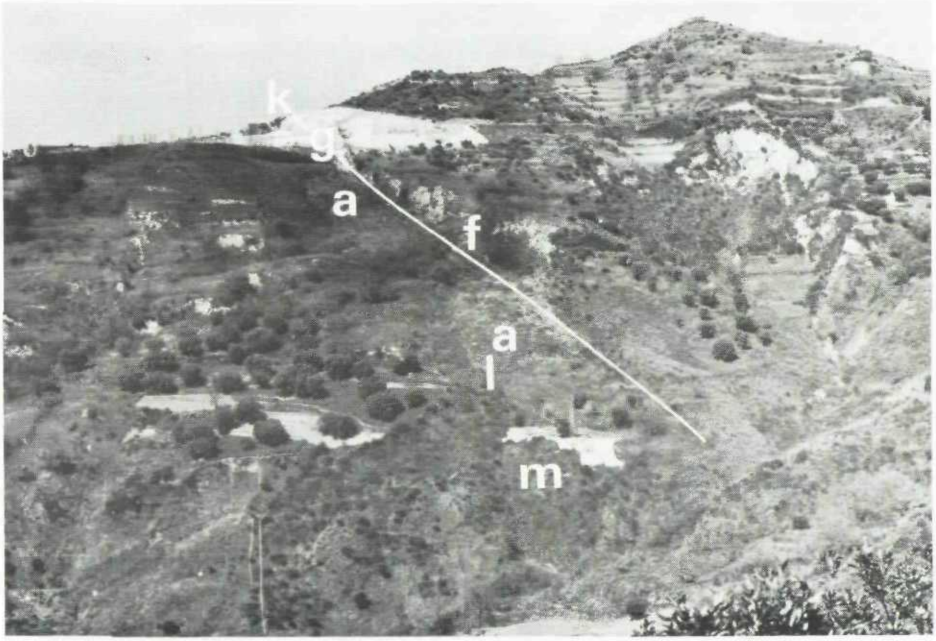


Plate 7 Retrogressive slumping along a fault in the Ste. Maria valley.

Plate 6 The head region of the block slide of San Pietro.

Plate 8 Shallow debris slides in regoliths on metamorphic rocks in the Fabrica valley.

Plate 9 Shallow debris slides in regoliths on metamorphic rocks near Molino Longo

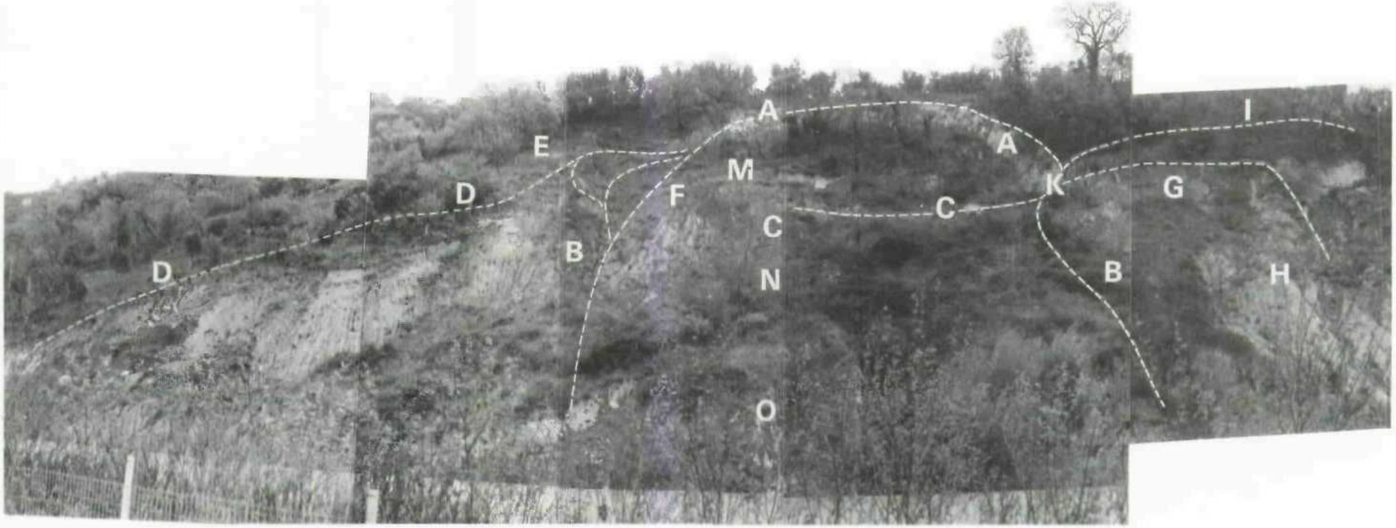


Plate 10 Shallow rotational slides in regoliths on metamorphic rocks in the Savuto valley.

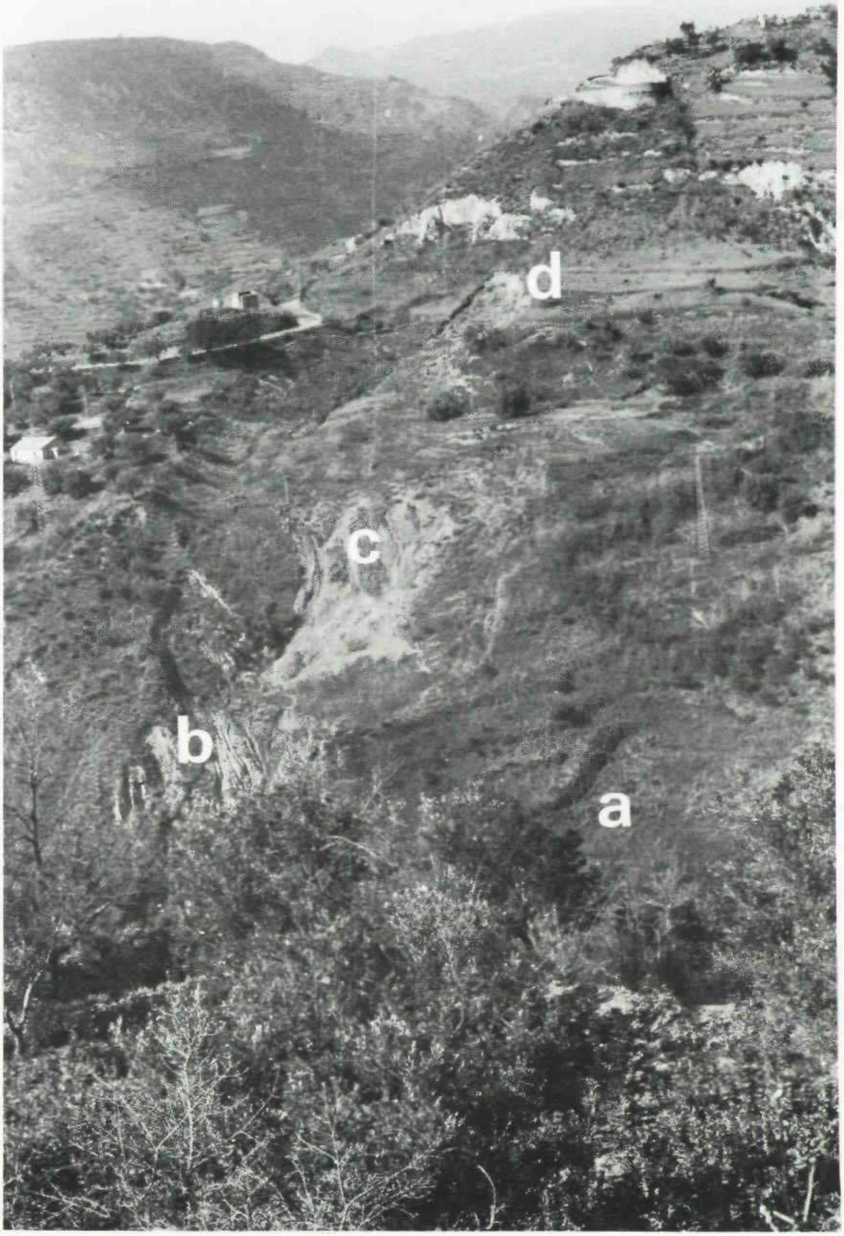


Plate 11 Different types of massmovements in the Ste. Maria valley.

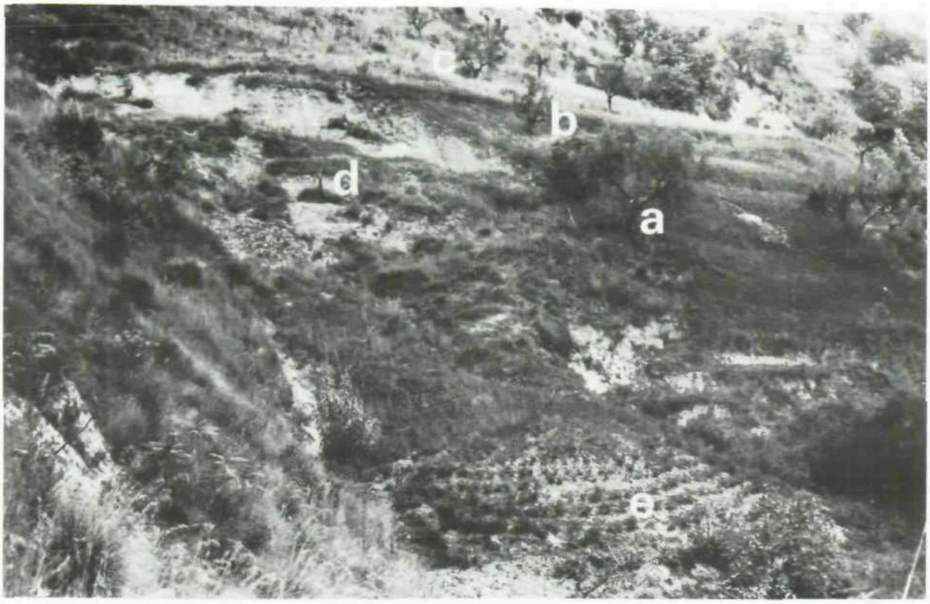


Plate 12 A slumping area in Mars weathered sandstone in the Ste. Maria valley. Pictures were taken in 1971 (12a) and 1974 (12b); a, b and c are corresponding points; the tree at d has disappeared; the small field at e is destroyed by pushing of the toe area.

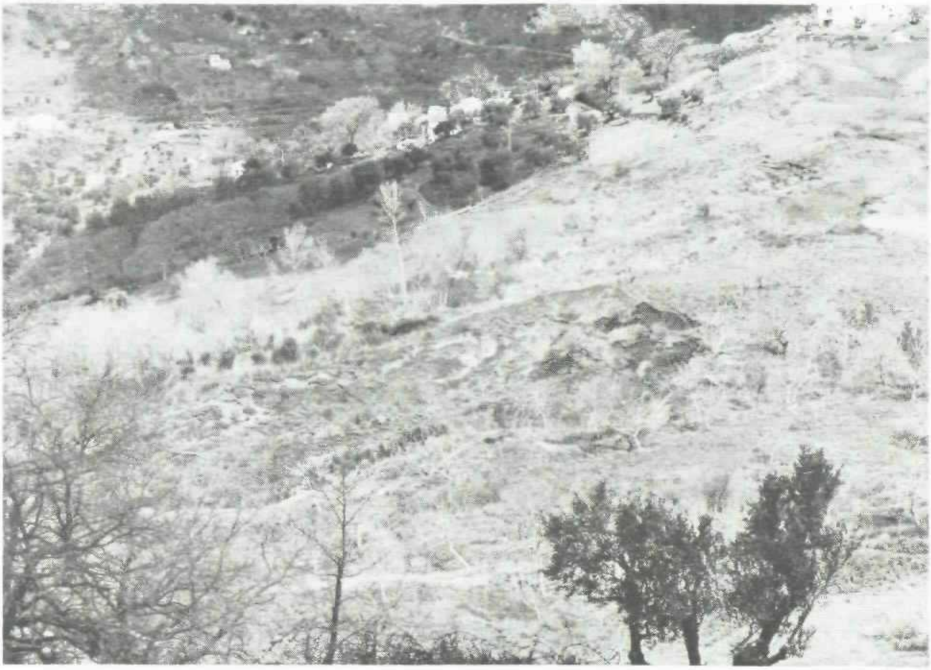


Plate 13 The supply area of a slow mudflow of the Torrente Secco (Valle Collonci).

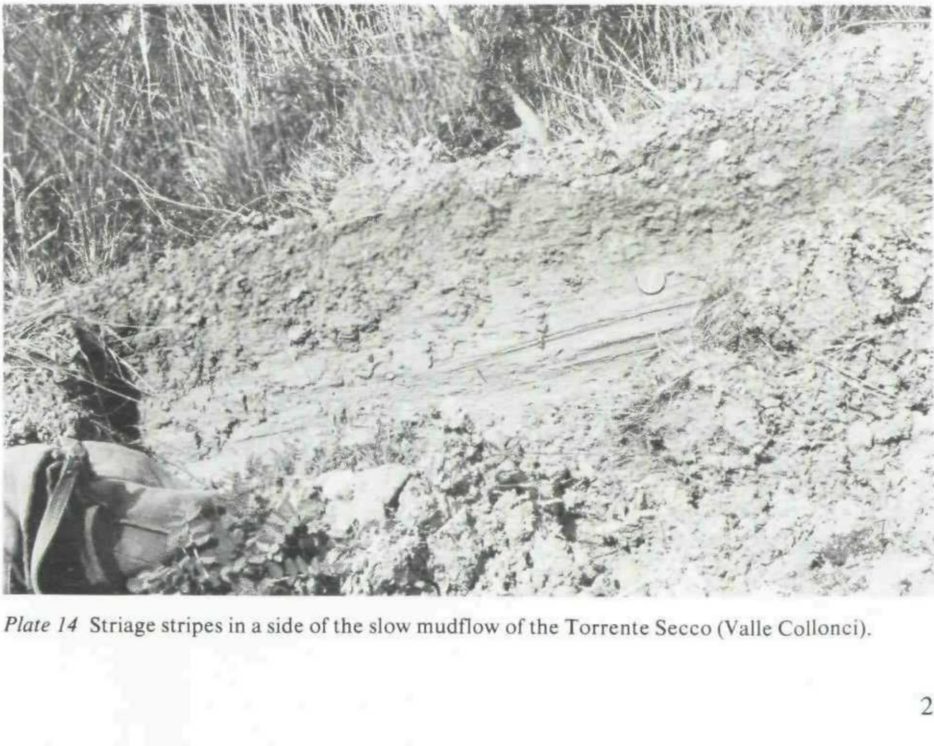


Plate 14 Striage stripes in a side of the slow mudflow of the Torrente Secco (Valle Collonci).

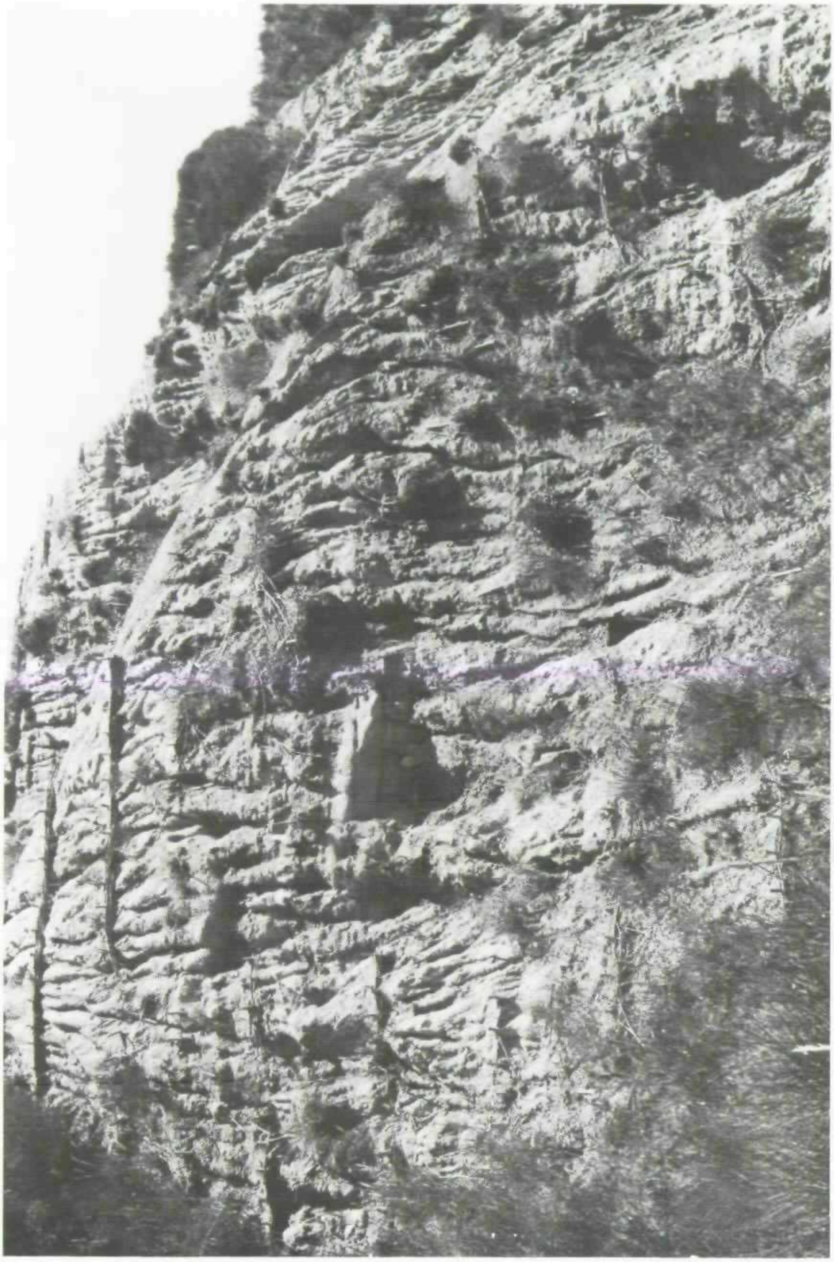


Plate 15 Badlands in metamorphic rocks near Terrati.

Plate 16 Field instrumentation on plot 11; a: the closed Gerlach throughs, measuring overland flow erosion; b: splash shields; c: portable rainfall simulator.

BIBLIOGRAPHY

ADAMS, J.E., D. KIRKHAM & D.R. NIELSEN (1957), A portable rainfall simulator -infiltrometer and physical measurements of the soil in place. Soil Science Society Proceedings 21, pp. 474-477

AHNERT, F. (1977), Some comments on the quantitative formulation of geomorphological processes in a theoretical model. Earth Surface Processes 2, pp. 191-201.

ALLISON, F.E. (1968), Soil aggregation – some facts and fallacies as seen by a microbiologist. Soil Science 106 (2), pp. 136-143.

ANDRE, J.E. & H.W. ANDERSON (1961), Variation of soil erodibility with geology, geographic zone, elevation and vegetation type in northern California wildlands. Journal of Geographical Research 66, pp. 3351-3358.

ASCH, TH.W.J. van & R.A. STEENBERGEN (1972), Een landschapskartering ten behoeve van het erosie-onderzoek. K.N.A.G. Geografisch Tijdschrift 6, pp. 454-460.

ASCH, TH.W.J. van & J.M. ROELS (1979), Een beginpoging tot het opstellen van een splash model en de resultaten van enkele metingen. Berichten Fysisch Geografische Afdeling 12, pp. 59-69.

BARNETT, A.P., J.S. ROGERS, J.H. HOLLADAY & A.E. DOOLEY (1965), Soil erodibility factors for selected soil in Georgia and South Carolina. Transactions of the American Society of Agricultural Engineering 8, pp. 393-396.

BAVER, L.D., W.H. GARDNER &W.R. GARDNER (1972), Soil Physics. New York; Wiley.

BENNET, R.J. & R.J. CHORLEY (1978), Environmental systems. Philosophy, analysis and control. London: Methuen & Co.

BEST, A.C. (1950), The size distribution of raindrops. Quaternly Journal of the Royal Meteorological Society 76, p. 16.

BISAL. F. (1960), The effect of raindrop size and impact velocity on sand splash. Canadian Journal of Soil Science 40, pp. 242-245.

BISHOP, A.W. (1973), The stability of tips and spoil heaps. Quaternly Journal of Engineering Geology 6, pp. 335-376.

BISHOP, A.W. & N.R. MORGENSTERN (1960), Stability coefficients for earth slopes, Geotechnique 10, pp. 29-150.

BJERRUM, L. & F. JØRSTAD (1968), Stability of rockslopes in Norway. Norwegian Geotechnical Institue 79, pp. 1-11.

BLONG, R.J. (1973), A numerical classification of selected landslides of the debris slide-avalanche flowtype. Engineering Geology 7, pp. 99-114.

BOUSQUET, J.C. & P. GUEREMY (1968), Quelques phénomènes de néotectonique dans l'Apennin Calabro-Lucanien et leurs consequences morphologiques. 1 - Bassin du Mercure et haute vallée du Sinni – Revue de Géographie Physique et de Géologie Dynamique 10, pp. 225-238.

BOUSQUET, J.C. & P. GUEREMY (1969), Quelques phénomènes de néotectonique dans l'Apennin Calabro–Lucanien et leurs conséquences morphologiques 2-l'Escarpement méridional du Pollino et son piedmont. Revue de Géographie Physique et de Géologie Dynamique 11, pp. 223 -236.

BOUYOUCOS, G.J. (1935), The clay ratio as a criterion of susceptibility of soils to erosion. Journal of the American Society of Agronomy 27, pp. 738-741.

BRUNSDEN, D. (1979), Massmovements. In: EMBLETON, C. & J. THORNES (1979), Process in Geomorphology, pp. 130-186. London: Edward Arnold.

BRYAN, R.B. (1968), The development, use and efficiency of indices of soil erodibility. Geoderma 2, pp. 5-26.

BRYAN, R.B. (1969), The relative erodibility of soils developed in the Peak District of Derbyshire. Geografiska Annaler 51-A, pp. 145-159.

BRYAN, R.B. (1974), Water erosion by splash and wash and the erodibility of Albertan soils. Geografiska Annaler 56-A, pp. 159-181.

BRYAN, R.B. (1976), Considerations on soil erodibility indices and sheet wash. Catena 3, pp. 99-111.

BURTON, A.N. (1964), Marine levels in South Italy. Nature 203, p. 1060.

BURTON, A.N. (1970), Note on the Alpine Orogeny in Calabria, Southern Italy. Quaternly Journal of the Geological Society London 126, pp. 369-381.

CARSON, M.A. (1971), The mechanics of erosion. London: Pion.

CARSON, M.A. & M.J. KIRKBY (1972), Hillslope form and process. Cambridge: The University Press.

CARSON, M.A. & D.J. PETLEY (1970), The existence of threshold hillslopes in the denudation of the landscape. Transactions of the Institute of British Geographers 49, pp. 71-95.

CARTA GEOLOGICA DELLA CALABRIA (1968), Foglio 236-III N.E., 236-III S.E. Cassa per opere straordinarie di pubblico interesse nell'Italia Meridionale.

CHANDLER, R.J. (1970), A shallow slab slide in the Lias clay near Uppingham, Rutland, Géotechnique 20, pp. 253-260.

CHANDLER, R.J. (1972), Periglacial mudslides in Vestspilzbergen and their bearing on the origin of fossil solifluction shears in low-angled clay slopes. Quaternly Journal of Engineering Geology 5, pp. 223-241.

CHANDLER, R.J. (1977), The application of soil mechanic methods to the study of slopes. In: HAILS, J.R. (1977), Applied Geomorphology. Amsterdam: Elzevier.

CHAPMAN, G. (1948), Size of raindrops and their striking force at the soil surface in a red pine plantation. Transaction of the American Geophysical Union 29(5), pp. 664-670.

CHESTERS, G., O.J. ATTOE & O.N. Allen (1957), Soil aggregation in relation to various soil constituents. Soil Science Society of America Proceedings 21, pp. 272-277.

CHILDS, E.C. (1969), An introduction to the physical basis of soil water phenomena. New York: McGraw-Hill.

CHORLEY, J.R. & A.B. Kennedy (1971), Physical Geography. A systems approach. London: Prentice-Hall International Inc.

COMMISSION DE PEDOLOGIE ET DE CARTOGRAPHIE DES SOLS (1967), Classification des sols. Grignon: Laboratoire de Géologie – Pédologie de l'E.N.S.A.

CROZIER, M.J. (1969), Earthflow occurrence during high intensity rainfall in Eastern Otago (New Zeeland). Engineering Geology 3, pp. 325-334.

CROZIER, M.J. (1973), Techniques for the morphometric analysis of landslides. Zeitschrift für Geomorphologie 17, pp. 78-101.

CRUDEN, D.M. (1976), Major rock slides in the Rockies. Canadian Geotechnical Journal 13, pp. 8-20.

DAVID, W.P. & C.E. BEER (1975), Simulation of soil erosion. Part 1: Development of a mathematical erosion model. Transactions of the American Society of Agricultural Engineering 18, pp. 126-199, 133.

DOTY, C.W. & C.E. CARTER (1965), Rates and particle size distributions of soil erosion from unit source areas. Transactions of the American Society of Agricultural Engineering 8, pp. 309-311.

D'SOUZA, V.P. & R.P.C. MORGAN (1976), A laboratory study of the effect of slope steepness and curvature on soil erosion. Journal of the Agricultural Engineering Research 21, pp. 21-31.

DUBOIS, R. (1970), Phases de serrage, nappes de socle et métamorphisme Alpin à la jonction Calabre – Apennin: La suture Calabro – Apenninique. Revue de Géographic Physique et de Géologie Dynamique 12, pp. 221-253.

ECKEL, E.B. (ed.) (1958), Landslides and engineering practice. Special Report on Highway Research, Bd. 29, Washington D.C.

ELLISON, W.D. (1944), Studies of raindrop erosion. Agricultural Engineering 25, pp. 131-136, 181-182.

ELWELL, H.A. & M.A. STOCKING (1976), Vegetal cover to estimate soil erosion hazard in Rhodesia. Geoderma 15, pp. 61-70.

EMMETT, W.W. (1978), Overlandflow. In: KIRKBY, M.J. (1978), Hillslope hydrology, pp. 145-176. New York: Wiley & Son.

EMMETT, W.W. (1970), The hydraulics of overlandflow on hillslopes. United States Geological Survey Professional Paper 662-A.

EPEMA, G.F., H. POT, J.M. ROELS & P.M. Schoot (1979), Respons van een stroomgebied op gesimuleerde en natuurlijke neerslag. M.Sc. thesis. Utrecht: Geografisch Instituut R.U.

EPSTEIN, E. & W.J. GRANT (1973), Soil crust formation as affected by raindrop impact. In: HADAS, A., D. SWARTZENDRUBER, P.E. REITEMA, M. FUCHS & B. YARON (1973). Physical aspects of soil, water and salts in ecosystems. Berlin: Springer Verlag, pp. 195-201.

ERGENZINGER, P., K.P. OBENAUF & K. SIJMONS (1975), Erster Versuch einer Abschätzung von Erosions und Akkumulation beträgen einer Torrente Kalabriens. Würburger Geographische Arbeiten 43, pp. 174-186.

EYLES, R.J. (1971), Massmovement in Tangoio conservation reserve Northern Hawkes Bay. Earth Science Journal 5-2, pp. 79-91.

F.A.O. (1966), Guidelines for soil profile description. Rome: Food and Agriculture Organization of the United Nations.

FELLENIUS, W. (1927), Erdstatische Berechnungen mit Reibung und Kohäsion. Berlin: Ernst.

FORREN, P.M. (1970), The development of two field instruments to measure erosivity: A simple rainfall intensity meter and an acoustic rainfall record tested with a rotating disk simulator. B.Sc. (Hons.) dissertation, National College of Agricultural Engineering.

FOSTER, L.R. & G.L. Martin (1969), Effect of unit weight and slope on erosion. Journal of the irrigation and drainage division. Proceedings of the American Society of Civil Engineers I.R.-4, pp. 551-561.

FOURNIER, F. (1960), Climat et Erosion. Paris: Presses Universitaires de France.

FREE, G.R. (1960), Erosion characteristics of rainfall. Agricultural Engineering 41(7), pp. 447-449.

FREE, G.R., G.M. BROWNING & G.W. MUSGRAVE (1940), Relative infiltration and related physical characteristics of certain soils. United States Department of Agriculture Technical Bulletin 729.

GABRIELS, D., J.M. PAUWELS & M. DE BOODT (1975), The slope gradient as it affects the amount and size distribution of soil loss material from runoff on silt aggregates. Medische Faculteit Landbouwwetenschappen. R.U. Gent 40, pp. 1333-1338.

GEIGER, R. (1975), The climate near the ground. Cambridge: Harvard University Press.

GERLACH, T. (1966), Développement actuel des versants dans le bassin du Haut Grajcarek (Les Hautes Beskides – Les Carpates Occidentales). Warsawa: Wydawnictwa Geologiczne (Travaux Géographiques 52).

GREEN, W.H. & C.A. AMPT (1911), Flow of air and water through soils. Journal of Agricultural Sciences 4, pp. 1-24.

GREGORY, K.J. & D.E. WALLING (1973), Drainage basin form and process. London: Edward Arnold.

GUNN, R. & G.D. KINZER (1949), Terminal velocity of water droplets in stagnant air. Journal of Meteorology 6, p. 243.

HADLEY, R.F. & G.C. LUSBY (1967), Runoff and hillslope erosion resulting from a high intensity thunderstorm near Mack, Western Colorado. Water Resources Research 3, pp. 139-146.

HENIN, S. (1938), Etude physico – chimique de la stabilité structurale des terres. Monograph National Centre of Agronomic Research, Paris, pp. 52-54.

HENIN, S. (1963), L'appréciation des proprietés physiques du sol. Annales Gembloux 3, pp. 631-633.

HENKEL, D.J. & A.W. SKEMPTON (1955), A landslide at Jacksfield, Shropshire, in an over-consolidated clay. Proceedings of the Conference of stability of Earthslopes (Stockholm) 1, pp. 90-101.

HORTON, R.E. (1945), Erosional development of streams and their drainage basins: hydrological approach to quantitative morphology. Bulletin of Geological Society of America 56, pp. 275-370.

HSÜ, K.J. (1975), Catastrophic debris streams generated by rockfalls. Bulletin of the Geologic Society of America 86, pp. 129-140.

HUDSON, N.W. (1963), Raindrop size distribution in high intensity storms. Rhodesian Journal of Agricultural Research 1 (1), pp. 6-11.

HUDSON, N.W. (1965), The influence of rainfall on the mechanics of soil erosion. M. Sc.Thesis, University of Cape Town.

HUDSON, N.W. (1973), Soil Conservation. New York: Cornell University Press.

HUDSON, N.W. & D.C. JACKSON (1959), Results achieved in the measurement of erosion and runoff in southern Rhodesia. Proceedings, Third Inter-African Soils Conference, Dalaba, pp. 575-583.

HUDSON, J.J. (1970), Land utilization in the Crati Valley (Calabria - Italy). Delft: ITC.

HUTCHINSON, J.N. (1967), The free degradation of London clay cliffs. Proceedings of the Geotechnical Conference Oslo 1, pp. 113-118.

HUTCHINSON, J.N. (1968), Field meeting on the coastal landslides of Kent. Proceedings of the Geological Association 791, pp. 227-237.

HUTCHINSON, J.N. (1969), A reconsideration of the coastal landslides of Folkestone Warren, Kent. Géotechnique 19, pp. 6-38.

HUTCHINSON, J.N. (1970), A coastal mudflow on the London clay cliffs at Beltinge, North Kent, Géotechnique 20, pp. 412-438.

HUTCHINSON, J.N. (1974), Periglacial solifluction: an approximate mechanism for clay soils. Geotechnique 24, pp. 438-443.

HUTCHINSON, J.N. & R.K. BHANDARI (1971), Undrained loading, a fundamental mechanism of mudflows and other massmovements. Geotechnique 21, pp. 353-358.

JOHNSON, A.M. & P.H. RAHN (1970), Mobilisation of debris flows. Zeitschrift für Geomorphologie. Supplement Band 9, pp. 168-186.

KAYSER, B. (1958), Recherches sur les sols et l'érosion en Italie Méridionale – Lucanie. Paris: Sedes.

KENT, P. (1966), The transport mechanism of catastrophic rockfalls. Journal of Geology 74, pp. 79-83.

KÉZDI, A. (1974), Handbook of Soil Mechanics. Volume 1 Soil Physics. Amsterdam: Elsevier.

KIRKBY, M.J. (1969), Infiltration, through flow and overlandflow. In: CHORLEY, J. (1969), Water, Earth and Man. London: Methuen & Co.

KNAPP, B.J. (1978), Infiltration and storage of soil water. In: KIRKBY, M.J. (1978), Hillslope hydrology. New York: Wiley & Son.

KOONS, D. (1955), Cliff retreat in the south-west United States of America. American Journal of Science 253, pp. 44-52.

LAL, R. (1976), Soil erosion on alfisols in Nigeria, the changes in physical properties and the response of crops. Geoderma 16, pp. 419-431.

LAMBE, T.W. & R.V. WHITMAN (1969), Soil mechanics. New York: Wiley & Sons.

LAURENS, F.M. (1958), Sediment transport mechanics in stable channel designs. Transactions of the American Society of Civil Engineers 123, pp. 195-206.

LAWS, J.O. (1941), Measurements of fall-velocity of water-drops and raindrops. Transactions of the American Geophysical Union 22, p. 709.

LAWS, J.O. & D.A. Parson (1943), The relation of raindrop size to intensity. Transactions of the American Geophysical Union 24, p. 452.

LEMOS, P. & J.F. LUTZ (1957), Soil crusting and some factors affecting it. Soil Science Society of America Proceedings 21, pp. 485-490.

LEEUWARDEN, F.J.M. van (1973), Een landschapskartering in Zuid-Italië (Calabrië). M.Sc. Thesis. Utrecht: Geografisch Instituut R.U.

LOHNES, R.A. & R.L. HANDY (1968), Slope angles in friable loess. Journal of Geology 76, pp. 247-258.

McCALLA, T.M. (1944), Water-drop method of determining stability of soil structure. Soil Science, 58, pp. 117-123.

McINTYRE, D.S. (1958), Soil splash and the formation of surface crusts by raindrop impact. Soil Science 85, pp. 261-266.

MEYER, L.D. (1965), Mathematical relationships governing soil erosion by water (Resumé). Journal of Soil and Water Conservation 20, pp. 149-150.

MEYER, L.D., G.R. FOSTER & H.J.H. RÖMKENS (1975), Soil-detachment by raindrops, in: Present and prospective technology for predicting sediment yields and sources. U.S. Department of Agriculture, Agricultural Research Service, Publ. ARS-S-40, pp. 177-189.

MEYER, L.D. & E.J. MONKE (1965), Mechanics of soil erosion by rainfall and overland flow. Transactions of the American Society of Agricultural Engineering 8, pp. 572-580.

MEYER, L.D. & W.H. WISCHMEIER (1969), Mathematical simulation of the process of soil erosion by water. Transactions of the American Society of Agricultural Engineering 12, pp. 754-758, 762.

MEYRIAT, J. (1960), La Calabre. Une région sous-développée de l'Europe méditerranéenne. Cahiers de la fondation nationale des sciences politiques 104. Paris: Armand Colin.

MIDDLETON, H.E. (1930), Properties of soils which influence soil erosion. U.S. Department of Agricultural Technical Bulletin 178.

MIHARA, Y. (1951), Raindrops and soil erosion. Bulletin of the National Institute of Agricultural Science, Series A, 1.

MILONE, F. (1956), Memoria illustrativa della carta della utilizzazione del suolo della Calabria. Napoli: Consiglio Nazionale della Ricerche, centrodi studi par la geografia economica.

MITCHELL, C. (1973), Terrain evaluation. London: Longman Group.

MORGAN, R.P.C. (1978), Field studies of rainsplash erosion. Earth Surface processes, 3, pp. 259-269.

MORGAN, R.P.C. (1979), Soil erosion. London: Longman.

MOSLEY, M.P. (1974), Rainsplash and the convexity of badland divides. Zeitschrift für Geomorphologie, N.F. Supplement Band 18, pp. 10-25.

MÜLLER, L. (1964), The rockslide in the Vaiont Valley. Rock Mechanical Engineering Geology 2, pp. 148-212.

MUSGRAVE, G.W. (1947), The quantitative evaluation of factors in water erosion: a first approximation. Journal Soil and Water Conservation 2, pp. 133-138.

MUTCHLER, C.K. & R.A. YOUNG (1975), Soil detachment by raindrops, in: Present and prospective technology for predicting sediment yields and sources. U.S. Department of Agriculture, Agricultural Research Service, Pub. ARS-S-40, pp. 113-117.

NASSIF, S.H. & E.M. WILSON (1975), The influence of slope and rain intensity on runoff and infiltration. Hydrological Sciences, Bulletin des Sciences Hydrologiques 20 (4), pp. 539-553.

NISHIKATA, T. & Y. TAKRUCHI (1955), Relation between physico chemical properties and erodibility of soil, part 2. Research Bulletin Hokkaido National Agricultural experimental station 68, pp. 49-54.

OSCHOWY, G. (1963), Bodenerosion und Bodenschutz auf Tertiären Tonböden unter besonderer Berücksichtigung Italienischer Erosionsgebiete. In: BUCHWALD, K., W. LENDHOLT & K. MEYER (1963), Beiträge zur Landespflege 1. Stuttgart: Eugen Ulmer.

OVENS, G. (1969), A study of soil erodibility by separation of the primary stages of the erosion process. M.Sc. Thesis, University of Reading.

PAIN, C.F. (1971), Rapid massmovement under forest and grass in the Hunua Range, New Zealand. Australian Geographical Studies 9-1, pp. 17-26.

PALMER, R.S. (1964), The influence of a thin water layer on waterdrop impact forces. International Association of Scientific Hydrological Publications 65, pp. 141-148.

PALMER, R.S. (1965), Waterdrops impact forces. Transactions of the American Society of Agricultural Engineering 8, pp. 69-72.

PEREIRA, M.C. (1956), A rainfall test for structure in tropical soils. Journal of Soil Science 7, (1), pp. 68-74.

PITAU, D.R. (1970), Geological factors significant to the stability of slopes cut in rock. In: RENBURG, P.W.J. van (1970), Planning Open Pit Mines, South Africa, Institute of Mining and Metallurgy, pp. 33-35.

PLOEY, J. de & SAVAT (1968), Contribution à l'étude de l'érosion des sols par les splash. Zeitschrift für Geomorphologie N.F. 12 band, pp. 174-193.

PLOEY, J. de & J. MOEYERSONS (1976), Quantitative data on splash erosion, simulated on unvegetated slopes. Zeistschrift für Geomorphologie, Supplement Band 25, pp. 120-131.

PLOEY, J. de, J. SAVAT & J. MOEYERSONS (1976), The differential impact of some soil factors on flow, runoff creep and rainwash. Earth Surface Processes 1, pp. 151-161.

PRIOR, D.B. & N. STEPHENS (1972), Some movement patterns of temperate mud flows from Northern Ireland. Bulletin of the Geological Society of America 38, pp. 2533-2544.

PRIOR, D.B., N. STEPHENS & G.R. DOUGLAS (1970), Some examples of modern debris flows from Northern Ireland. Zeitschrift für Geomorphologie 14, pp. 275-288.

RAO, D.P. & H.GHANEM (1972), A geomorphological survey of the Savuto and Oliva Basins, Calabria, Italy. Enschede: I.T.C.

RAPP, A. (1960), Recent development of mountain slopes in Kärkevagge and surroundings, Northern Scandinavia. Geografiska Annaler 42, pp. 65-200.

RIEZEBOS, H.Th. (1979), Geomorphology and soils of Sipalawini Savanna (South Suriname), Utrechtse Geografische Studies 12. Utrecht: Geografisch Instituut R.U.

RITCHIE, P. (1958), Recognition and identification. In: ECKEL, E.B. (1958), Landslides and engineering practise. Special Report on Highway Research Bd. 29. Washington D.C.

ROMEIN, A., (in preparation). Aspects of X-ray and thermal analyses of (clay)minerals.

ROMEIN, A. (1980), X-ray and therminal analysis of some samples from Calabria. 37th internal report. Geografisch Instituut R.U.

ROSE, C.W. (1958), Effects of Rainfall and soil-factors on soil detachment, and the rate of water penetration into soils. Ph.D. Thesis, University of London.

ROSE, C.W. (1960), Soil detachment caused by rainfall. Soil Sience 89 (1), pp. 28-35.

ROUGERIE, G. (1960), Le façonnement actuel des modelés en Côte d'Ivoire forestière. Diss. Paris.

ROUSE, W.C. (1975), Engineering properties and slope form in granular soils. Engineering Geology 9. pp. 221-235.

RUXTON, B.P. (1967), Slope wash under mature primary rainforest in Northern Papua. In: JENNINGS, J.N. & J.A. MABBUTT (1967), Landform studies from Australia and New Guinea. Cambridge, London.

SAVAT, J. (1977), The hydraulics of sheet flow on a smooth surface and the effect of simulated rainfall. Earth Surface Processes 2, pp. 125-140.

SCHUMM, S.A. (1956), Evolution of drainage systems on slopes of badlands at Perth Amboy, New Jersey. Bulletin of the Geological Society of America 67, pp. 579-646.

SCHUMM, S.A. (1964), Seasonal variations of erosion rates and processes on hillslopes in Western Colorado. Zeitschrift für Geomorphologie. Supplement Band 5, pp. 215-238.

SCHUMM, S.A. & R.J. CHORLEY (1964), The fall of Threatening Rock. American Journal of Science 262, pp. 1041-1054.

SEYHAN, E. (1977), Fundamentals of hydrology. Utrecht: Geografisch Instituut R.U.

SHARPE, C.F.S. (1938), Landslides and related phenomena. New York: Columbia.

SHREVE, R.L. (1968), Leakage and fluidization in air-layer lubrication avalanches. Bulletin of the Geologic Society of America 79, pp. 653-658.

SINGER, M.J. & J. BLACKBARD (1978), Effect of mulching on sediment in runoff from simulated rainfall. Soil Science of American Journal 42 (1), pp. 481-485.

SKEMPTON, A.W. (1953), Soil mechanics in relation to geology. Proceedings of the Yorkshire Geological Society 29, pp. 33-62.

SKEMPTON, A.W. (1964), Long term stability of clay slopes. Geotechnique 14, pp. 71-200.

SKEMPTON, A.W. & F.A. DE LORY (1957), Stability of natural slopes in London Clay. Proceedings of the 4th International Conference of Soil Mechanics and Foundation Engineering, London, 2, pp. 378-381.

SLONEKER, L.L., F.C. ALSON & W.C. MOLDENHAUER (1976), Effect of pore water pressure on sand splash. Soil Science Society of America. Proceedings 40, pp. 948-951.

SMITH, R.M. & C.F. CERNUDA (1951), Some applications of water-drop stability testing to tropical soils of Puerto Rico. Soil Science 71, pp. 337-346.

SOIL SURVEY STAFF (1951), Soil Survey Manual. U.S. Department of Agriculture. Agricultural Handbook 18, Washington D.C.

SOWERS, G.F. (1965), Consistency. In: BLACK, C.A. (1965), Method of soil analysis. Part 1. Madison: American Society of Agronomy, Inc.

SOWERS, G.F. (1979), Introductory soil mechanics & foundations: Geotechnical Engineering. New York: MacMillan.

STATHAM, I. (1977), Earth Surface sediment transport. Oxford: Clarendon Press.

SULEBAK, J.R. (1969), Mudflows in the low Alpine Region. Norsk Geografik Tidsskrift 23, pp. 15-23.

SREENIVAS, L., J.R. JOHNSTON & H.O. HILL (1947), Some relationships of vegetation and soil detachment in the erosion process. Soil Science Society of America. Proceedings 11, pp. 471-474.

TAKAHASHI, T. (1978), Mechanical characteristics of debris flow. Journal of the Hydraulics Division 104 (8) pp. 1153-1170.

TAYLOR, D.W. (1937), Stability of earth slopes. Journal of the Boston Society of Civil Engineers 24, pp. 197-246.

TER-STEPHANIAN, G. (1965), In-situ determination of the rheological characteristics of soil on slope. Proceedings of the 6th international Conference of Soil Mechanics and Foundation Engineering 2, pp. 375-377.

TERZAGHI, K. (1960), Mechanism of landslides. Bulletin of the Geological Society of America, Berkeley Volume, pp. 83-122.

TERZAGHI, K. (1962), Stability of steep slopes on hard unweathered rock. Géotechnique 12, pp. 199-208.

TERZAGHI, K. & R.B. PECK (1967), Soil mechanics in Engineering practise. New York: Wiley.

TICHY, F. (1962), Die Wälder der Basilicata und die Entwaldung im 19. Jahrhundert. Vorgänge, Ursachen und Folgen. Heidelberg, München: Keysersche Verlagsbuchhandlung.

TRIMBLE, G.R. & S. WEITZMANN (1967), Effect of a hardwood forest canopy on rainfall intensities. Transactions of the American Geophysical Union 35 (2), pp. 226-234.

UNESCO-FAO (1963), Bioclimatic Map of the Mediterranean zone. Explanatory notes. Paris: UNESCO.

VARNES, D.J. (1958), Landslide types and processes. In: ECKEL, E.B. (1958), Special Report on Highway Research, Bd. 29, pp. 20-47.

VINK, A.P.A. (1975), Landuse in advancing agriculture. Berlin: Springer-Verlag.

WARD, R.C. (1967), Principles of Hydrology. London: McGraw Hill.

WARD, W.H. (1945), The stability of natural slopes. Geographical Journal 111, pp. 170-191.

WISCHMEIER, W.H. (1962), Storms and soil conservation. Journal of Soil and Water Conservation, 17 (2), pp. 55-59.

WISCHMEIER, W.H., C.B. JOHNSON & B.V. CROSS (1971), A soil erodibility nomograph for farmland and construction sites. Journal of Soil and Water Conservation 26, pp. 189-193.

WISCHMEIER, W.J. & J.H. MANNERING (1969), Relation of soil properties to its erodibility. Soil Science Society of America, Proceedings 23, pp. 131-137.

WISCHMEIER, W.H. & D.D. SMITH (1958), Rainfall energy and its relationship to soil loss. Transactions of American Geophysical Union 39, pp. 285-291.

WISCHMEIER, W.H., D.D. SMITH & R.E. UHLAND (1958), Evaluation of factors in the soil loss equation. Agricultural Engineering 39 (8), pp. 458-465.

YAMAMOTO, T. & W. ANDERSON (1973), Splash erosion related to soil erodibility indices and other forest soil properties in Hawaii. Water Resources Research 9, pp. 336-345.

YARIV, S. (1976), Comments on the mechanism of soil detachment by rainfall. Geoderma 15, pp. 393-399.

YATSU, E. (1966) Rock control in Geomorphology, Tokyo: Sososha.

YATSU, E. (1967), Some problems of massmovement. Geografiska Annalar A 49, pp. 396-401.

YEN, B.C. (1969), Stability of slopes undergoing creep deformation. Journal of Soil Mechanics, Foundations Division American Society of Civil Engineers 95, pp. 1075-1093.

YODER, R.E. (1936), A direct method of aggregate analysis of soils and a study of the physical nature of erosion losses. Journal of the American Society of Agronomy 28, pp. 337-351.

YOUNG, A. (1974), The rate of slope retreat, In: BROWN, E.H. & R.S. WATERS (1974). London: Institute of British Geographers (Special Publications 7), pp. 65-78.

YOUNG, A. (1972), Slopes. Edinburgh: Oliver and Boyd.

ZARUBA, Q. & V. Meckl (1969), Landslides and their control. Prague: Academia & Elsevier.

ZING, A.W. (1940), Degree and length of landslope as it affects soil loss in runoff. Agricultural Engineering 21, pp. 59-64.

ZON, H.J.M. VAN (1978), Litter transport as a geomorphic process (a case study in the Grand-Duchy of Luxembourg). Publicaties van het Fysisch Geografisch en Bodemkundig Laboratorium van de Universiteit van Amsterdam, 24.

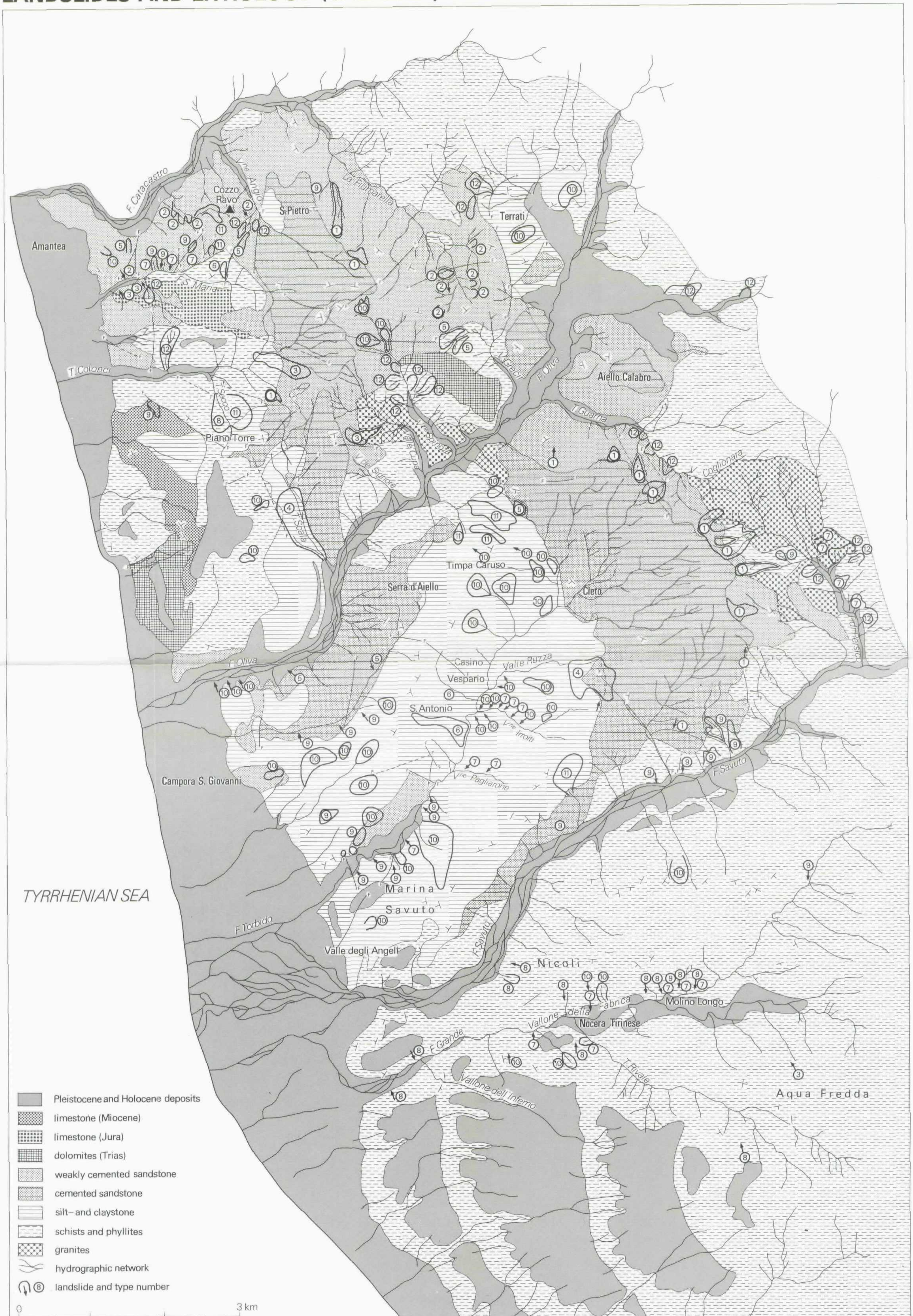
ZONNEVELD, I.S. (1972), Land evaluation and land(scape) science. ITC Textbook of photo interpretation VII-4. Enschede: I.T.C.

CURRICULUM VITA

De schrijver van dit proefschrift werd geboren op 29 januari 1944 te Baarn.
In 1962 behaalde hij het diploma H.B.S.-B aan het Constantijn College te Amersfoort. In 1966 werd het kandidaatsexamen Fysische Geografie afgelegd aan de Rijksuniversiteit te Utrecht. Het doctoraal diploma Fysische Geografie werd behaald in 1970. Sinds zijn afstuderen is de auteur als wetenschappelijk medewerker verbonden aan het Georgrafisch Instituut der Rijksuniversiteit te Utrecht.

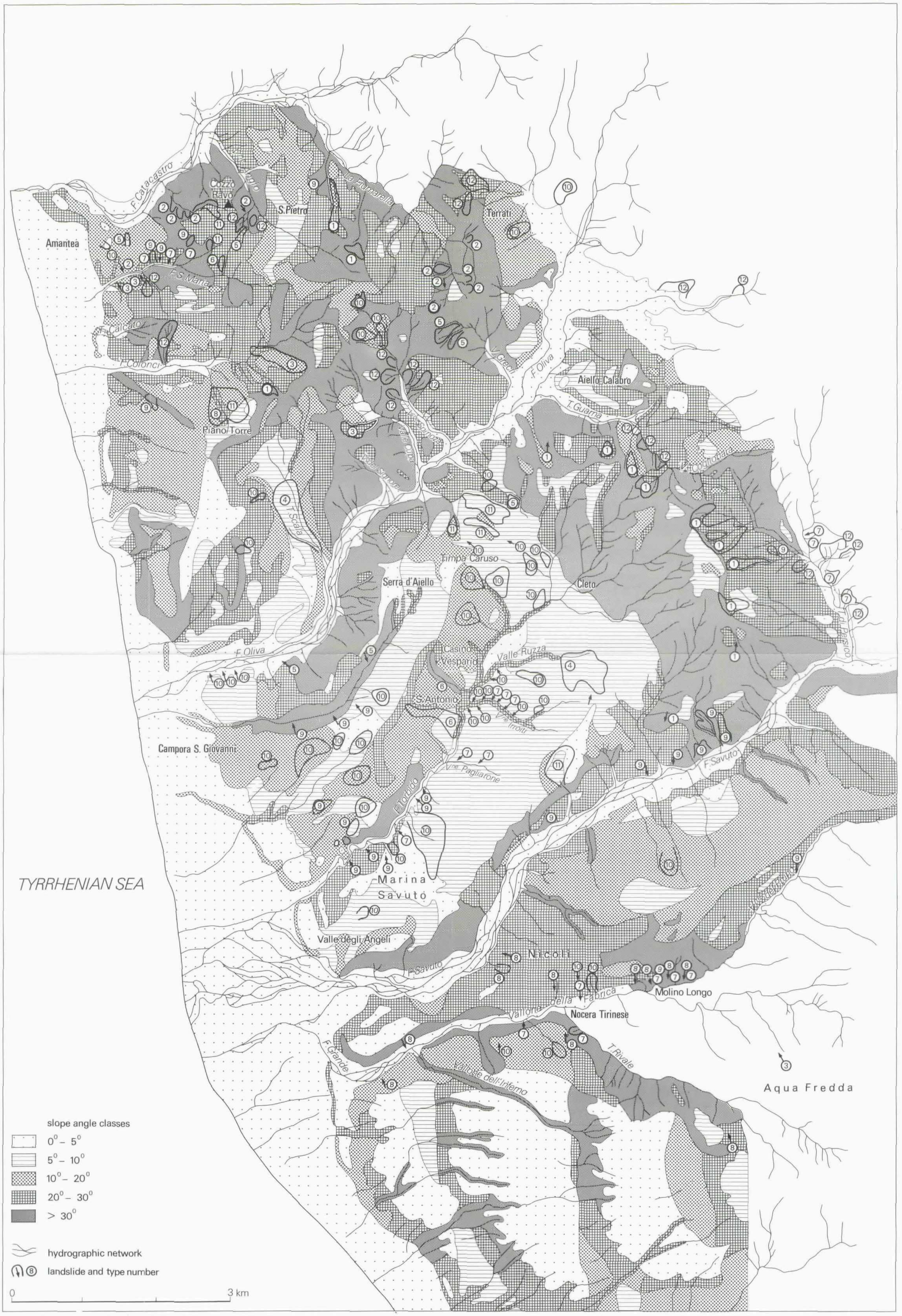
5735a

LANDSLIDES AND LITHOLOGY (CALABRIA, ITALY)



5735 b

LANDSLIDES AND SLOPE ANGLE CLASSES (CALABRIA, ITALY)



5735c

LANDSLIDES AND VEGETATION STRUCTURE / LANDUSE (CALABRIA, ITALY)

Appendix A7 Map III