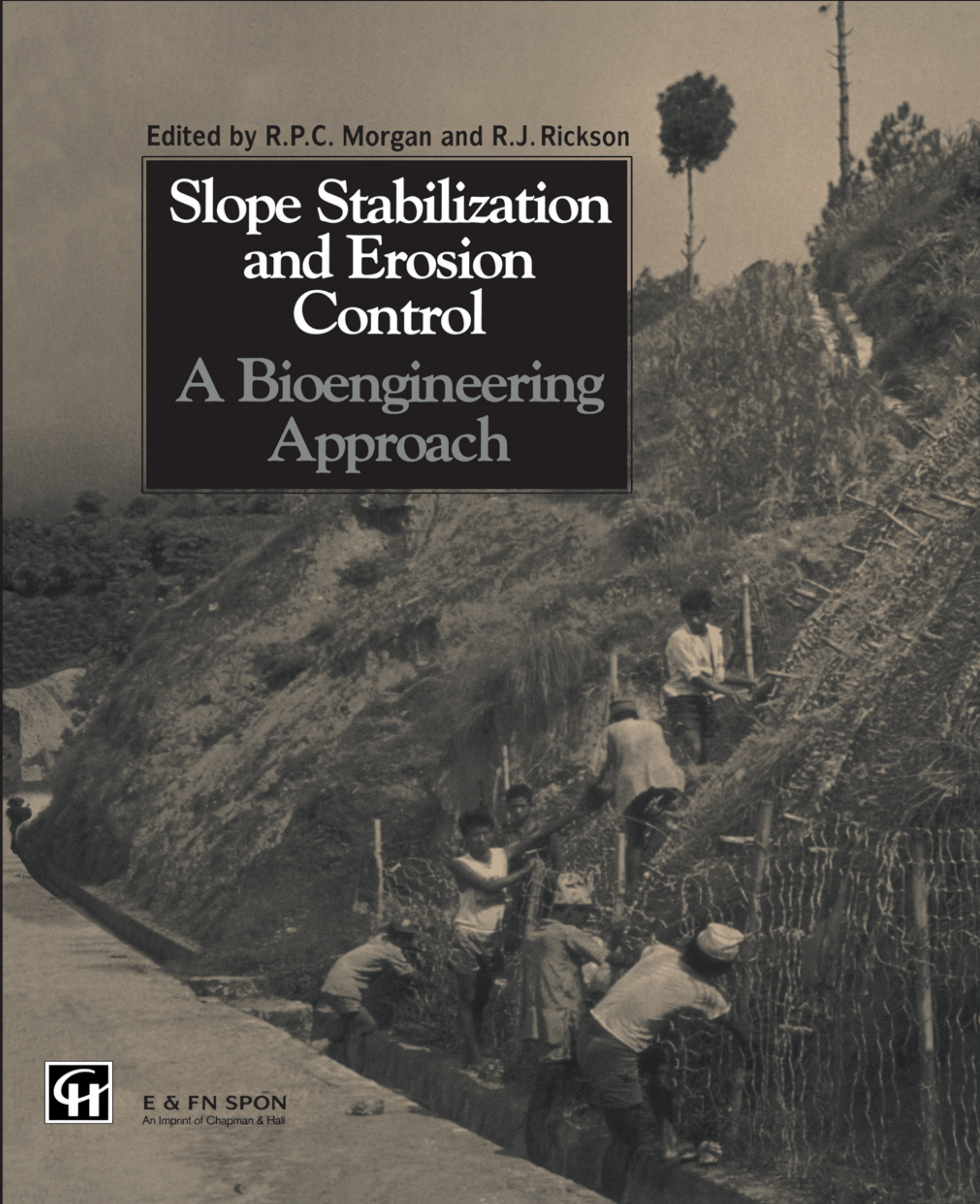

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Slope Stabilization and Erosion Control

A Bioengineering Approach

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SLOPE STABILIZATION AND EROSION CONTROL: A BIOENGINEERING APPROACH

Edited by

R.P.C.Morgan and R.J.Rickson
Silsoe College, Cranfield University, UK

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CONTRIBUTORS

N.J.Coppin

Environmental Consultancy Unit, Wardell Armstrong, Grove House Court, 11a King Street, Newcastle-under-Lyme ST5 1EH, UK

Nick Coppin is a Partner of Wardell Armstrong where he is Manager of the Environmental Consultancy Unit. After graduating as a botanist he took an MSc in environmental science and then followed a career as an environmental and landscape scientist in civil engineering projects. He has particular interests in restoration of non-metal mining sites and control of soil failures on cut and embanked slopes. He was the Coordinator and Joint Editor of the CIRIA project on the use of vegetation in civil engineering.

R.P.C.Morgan

Silsoe College, Cranfield University, Silsoe Campus, Silsoe, Bedford MK45 4DT, UK

Roy Morgan received his BA from the University of Southampton, his MA from the University of London and PhD from the University of Malaya. After a period as an Assistant Lecturer at the University of Malaya, he returned to the UK, taking up a post at Silsoe College, Cranfield University where he is currently Professor of Soil Erosion Control. His research interests are in the use of vegetation for erosion control and erosion modelling. He is Joint-Coordinator of the project to develop a European Soil Erosion Model. He has carried out research and consultancy work in many countries and is the author of two books on soil erosion and over 100 research papers. He is currently President of the European Society for Soil Conservation.

R.J.Rickson

Silsoe College, Cranfield University, Silsoe Campus, Silsoe, Bedford MK45 4DT, UK

Jane Rickson obtained her BSc degree from King's College, University of London and her MSc from Silsoe College, Cranfield University where she was appointed Lecturer in Soil Erosion Control. Her research and consultancy interests include the use of geotextiles for erosion control, mulching techniques, rainfall simulation, soil erosion risk assessment and the non-technical aspects of soil conservation. She has carried out research and consultancy work in a number of African and Asian countries, is Joint-Coordinator of the project on the development of a European Soil Erosion Model, and is author of several papers and confidential reports on geotextiles, mulching and related issues.

R.Stiles

School of Landscape, Department of Planning and Landscape, University of Manchester, Oxford Road, Manchester M13 9PL, UK

Richard Stiles is a Lecturer in the Department of Planning and Landscape at Manchester University where he is course leader for the Master of Landscape Design. He is an Associate Member of the

Landscape Institute. After graduating as a botanist, he studied landscape architecture at graduate level before going on to work as a landscape architect in the UK and Germany. It was during an extended stay in Germany that he became interested in the technical use of vegetation as a material for landscape construction. Since returning to the UK to take up a post at Manchester University, he has followed up this interest with further research which has resulted in a number of articles, papers and contributions to several recent publications on bioengineering.

M.E.Styczen

Dansk Hydraulisk Institut, Agern Allé 5, DK-2970 Hørsholm, Denmark

Merete Styczen received her MSc and PhD degrees from the Royal Veterinary and Agricultural University, Copenhagen. She is currently employed as an agronomist with the Danish Hydraulic Institute where she is responsible for the development of the soil erosion and soil physics components of hydrological models. She has acted as an adviser on land development and soil conservation in many projects in Africa and Asia. Her research interests include soil erosion modelling and watershed management.

T.H.Wu

Department of Civil Engineering, Ohio State University, 470 Hitchcock Hall, 2070 Neil Avenue, Columbus, OH 43210–1275, USA

Tien H.Wu received his BSc degree from St John’s University, Shanghai and his MSc and PhD degrees from the University of Illinois. He has been Professor of Civil Engineering at the Ohio State University since 1965. His research and consulting interests include reliability of geotechnical design and construction, stability of embankments and slopes, soil-reinforcement by natural and synthetic materials, and engineering properties of geotechnical materials. He is the author of some 60 papers on these topics and two books.

PREFACE

The inspiration for a text on the role of vegetation in slope stabilization and erosion control came when we were involved in a project for the Construction Industry Research and Information Association (CIRIA) to look at the use of vegetation in civil engineering. The results of that project were published in a multi-authored volume (Coppin and Richards, 1990), aimed as a guide to the practising civil engineer on the state-of-the-art of bioengineering. It seemed appropriate to us to complement this work with a more analytical treatment of the subject, aimed at both student and professional readership, written at a suitable level for undergraduates and postgraduate researchers and giving a more global view of the recent research on the engineering role of vegetation in the landscape. Given the interdisciplinary nature of bioengineering, the text endeavours to bridge the gap between the engineer and the vegetation specialist. It provides the engineer with a basic understanding of the principles and practices of vegetation growth and establishment, as well as explaining in detail how vegetation can be regarded as an engineering material. At the same time, the text aims to show the plant specialist how his or her skills can be applied to engineering problems and gives a background to the kinds of questions engineers need answers to before they can design vegetation-based systems for erosion control and slope stabilization.

In order to gain a global perspective and provide an up-to-date specialist coverage, we invited contributors to write certain chapters in their fields of expertise. Although we proposed a philosophy for the text and a synopsis for each chapter so as to give some continuity and cohesion, we did not attempt to impose strict editorial control on the content and the individual contributions represent a personal view of each of the authors.

We owe a special gratitude to Dr Andrés Arnalds who reviewed much of the material in Chapter 6, provided invaluable references on the work of the State Soil Conservation of Iceland and checked that the author's interpretations of articles available only in Icelandic were, in fact, correct.

We are also indebted for early ideas on Chapter 5 to the late Dr Clinton Armstrong of the University of Saskatchewan. He should have been a co-author of this chapter but unfortunately he died before any of the work came to be written.

Despite the lengthy gestation period for the text to emerge, we have enjoyed preparing the work. We hope that the readers will find the contribution useful and also enjoy reading it.

Roy Morgan
Jane Rickson

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INTRODUCTION
1

R.J.Rickson and R.P.C.Morgan

Slope instability and erosion of the soil by water and wind are major environmental hazards. Although they are the result of natural geomorphological processes, they are both affected by and have consequences for human activity, often incurring economic and social damage. In nature, vegetation is one factor maintaining equilibrium in the landscape between the destructive forces of landscape instability and the constructive or regenerative forces of stability. The risk of slope failures and erosion is enhanced when the vegetation cover is removed. The question is whether the situation can be repaired if the vegetation cover is restored. This book aims at tackling this important issue by examining the mechanisms by which vegetation plays its protective role in the landscape.

The use of vegetation for slope stabilization and erosion control can be referred to as bioengineering. Bioengineering and biotechnical engineering are terms which are commonly found in the literature, but there is much confusion as to their precise definitions. In this book, **bioengineering** refers to the use of any form of vegetation, whether a single plant or a collection of plants, as an engineering material (i.e. one that has quantifiable characteristics and behaviour). **Biotechnical engineering** refers to techniques where vegetation is combined with inert structures such as crib walls, so combining the structural benefits of both the vegetative and non-vegetative components of the scheme.

Bioengineering is a classic example of where there is a significant gap between the ‘art’ (or application of the techniques proposed) and the ‘science’ (or the scientific quantification and hence objective justification of the practices). In Europe (especially in Germany, Switzerland and Austria) and in the United States of America, pioneers have been using bioengineering and biotechnical engineering techniques for many decades (Schiechtl, 1973, 1980). These relatively few, but significant case studies have illustrated the success of bioengineering, but we cannot continue to wait a further 50 years or so, whilst new schemes become established and fully matured, to evaluate the potential of these techniques. This book aims to state the potential of bioengineering and demonstrate the science behind it as a means of justifying the techniques involved to practitioners.

As such, the book is not intended as a ‘stand-alone’ practical handbook of how to apply the diverse techniques of bioengineering. Instead, it aims to describe and analyse the research base underlying bioengineering in order to provide a better understanding of the role of vegetation and how it can be regarded as an engineering material. It is intended, therefore, that the book will answer many of the questions that engineers raise when expressing their uncertainty about the potential of bioengineering techniques and go some way towards showing how vegetation can be incorporated as quantifiable inputs to landscape engineering design procedures.

The book was partially prompted by the increasing awareness of the environment, and the sustainability of landscape management practice. Traditional civil engineering techniques (‘grey solutions’, such as concreting of welded wire walls for slope stabilization) may not be sustainable in the long term due to high initial capital expenditure and (more importantly) increasing maintenance requirements over time. Carefully selected and implemented bioengineering techniques are bound to be more sustainable over time as vegetation is self-regenerating and able to respond dynamically and naturally to changing site conditions, ideally without compromising or losing the engineering properties of that selected vegetation. Indeed, there are examples where a grey solution to a landscaping problem has been wholly replaced with a more natural, environmentally sensitive vegetative approach. Schürholz (1992) outlines a scheme for river channelization of the River Enz using vegetation and natural geotextiles, which were shown to have significant advantages hydraulically, aesthetically and financially compared with the original, concrete-based channelization scheme.

Any attempt to answer the question of whether vegetation can be used to alleviate landscape instability will be of interest to a wide audience, for whom this book is intended. Prior to the publication of this book, the only major reviews of bioengineering are those of Schiechtl (1973, 1980), Gray and Leiser (1982) and Bache and MacAskill (1984). This means that there has not been a substantive publication for nearly a decade, during which time much state-of-art material concerning vegetation and its effect on slope stability and erosion processes has been published in diverse and in some cases obscure academic journals. These are often not easily accessible to non-academics, and the formal presentation of such work is not in a format that is readily usable by the practitioner in the field. At the other extreme, our knowledge is often confined to a few experts' experiences, whose work may not have received the widespread exposure it deserves.

This is one consequence of the multi- and interdisciplinary nature of the subject matter being addressed. There are few publications or journals whose subject matter ranges from the detailed physics of soil erosion processes (important when attempting to understand the nature of the problem being faced) through to the techniques of vegetation establishment, for example. This book aims to encompass and integrate the diversity and complexity of the role and use vegetation for landscape protection and management.

There is increasing awareness by civil engineers of the potential role of vegetation in construction work, over and above the aesthetic qualities the vegetation may have. This awareness is reflected by the publication of books such as Coppin and Richard's *Use of Vegetation in Civil Engineering* (1990), initiated and supported by the United Kingdom's Construction Industry Research and Information Association (CIRIA). Geomorphologists will also find helpful the synthesis of the most recent research on the complex relationships between vegetation and erosion processes presented in this book. In this respect, the book will complement other recent expositions on the role of vegetation, notably those edited by Viles (1988) and Thornes (1990). Other users of the book may be involved with the expansion of the landscaping industry. The number of sites and applications where the techniques presented in this book could be utilized is growing rapidly, such as land reclamation of landfill and mine spoil. Such sites require environmentally sensitive solutions to reclamation, given the public's concerns over the ways we manage and restore our diverse and everincreasing wastelands. Recreational sites such as golf courses and ski slopes also have to be designed and maintained to cope with the increasing pressure as leisure time expands.

Although the book deals primarily with the engineering and geomorphological roles of vegetation, the cost implications of using bioengineering are not ignored. The economic differentials between conventional, grey solutions and the use of vegetation may be significant in areas where the availability of products such as concrete, sheet piling, rip-rap and gabions is severely restricted, as in inaccessible areas of

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developing countries. Already, bioengineering techniques have been used in developing counties such as Nepal, where experience has shown the conventional methods of slope stabilization are prohibitively expensive on implementation and in maintenance, as well as being inappropriate to the local technology and expertise used to combat slope instability of the area.

The book is organized into sections covering firstly the principles behind the use of vegetation, and secondly, the practices which have been founded on these principles. Chapter 2 reviews the scientific research which has built up a quantified database on the interactions between vegetation and both surface erosion and deeper seated processes and leads to a discussion on the salient properties of vegetation for engineering purposes. Chapter 3 covers the main considerations of whether the vegetation will establish and develop into a form which meets these engineering needs. No matter how effective vegetation may be in controlling rainsplash erosion, for example, the vegetation will never reach the design requirements unless the correct growing conditions exist for that vegetation type to establish and develop successfully. Chapter 4 concentrates on the practice of using simulated vegetation, which may circumvent the problems of achieving the required vegetation characteristics in hostile areas, or when time is limited for the vegetation to establish and reach maturity at which it realizes its potential, as outlined in Chapter 2. Chapters 5 and 6 report on the practices used for the control of erosion by water and wind, based on bioengineering and biotechnical engineering principles. Many of these techniques have been adapted from agricultural engineering practice, again reflecting the multidisciplinary nature of the subject, and the fact that the detrimental impacts of erosion were first felt on agricultural land. Hence the experience and expertise on using vegetation to control soil erosion originate from this discipline. This book aims to widen the audience to whom these proven techniques may be helpful. With increasing concern over sediment production from non-agricultural land uses, it is wise to adopt techniques already proven to be successful. The role of vegetation in slope stability is covered in Chapter 7, where particular emphasis is placed on how conventional approaches to modelling and calculating slope stability and instability can be modified and adapted to account for the role of vegetation.

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ENGINEERING PROPERTIES OF VEGETATION
2

M.E.Styczen and R.P.C.Morgan

2.1
INTRODUCTION

Vegetation provides a protective layer or buffer between the atmosphere and the soil. Through the hydrological cycle, it affects the transfer of water from the atmosphere to the earth's surface, soil and underlying rock. It therefore influences the volume of water contained in rivers, lakes, the soil and groundwater reserves. The above-ground components of the vegetation, such as leaves and stems, partially absorb the energy of the erosive agents of water and wind, so that less is directed at the soil, whilst the below-ground components, comprising the rooting system, contribute to the mechanical strength of the soil.

Traditionally, the role of vegetation has been viewed rather simplistically, as seen by the somewhat superficial way it is dealt with in water erosion studies. The most commonly used approach has been to assign to it a coefficient, such as the C-factor in the Universal Soil Loss Equation (Wischmeier and Smith, 1978) which, for a certain stage of growth and plant density, describes the ratio of soil loss when vegetation is present to the amount lost on a bare soil. Values of this soil loss ratio are derived experimentally from field trials and, while they are true values for those situations, they cannot be readily used to predict the effect of the same or other vegetation in different climatic and pedological conditions.

Wischmeier (1975) tried to split the C-factor into C_I, C_{II} and C_{III} subfactors (Figure 2.1). C_I describes the effect of the presence of a plant canopy at some elevation above the soil. C_{II} is defined as the effect of a mulch or close-growing vegetation in direct contact with the soil surface. Root effects are not included. C_{III} represents the residual effects of land use on soil structure, organic matter content and soil density, the effects of tillage or lack of tillage on surface roughness and soil porosity, and the effects of roots, subsurface stems and biological activity in the soil. This approach has been used in erosion prediction models (Beasley, Huggins and Monke, 1980; Park, 1981; Park, Mitchell and Scarborough, 1982) but is limiting because at least two of the three subfactors may influence more than one erosion process. It is difficult therefore to give them a precise physical meaning.

The conflicting views, provided by field and laboratory experiments (Figure 2.2) on what level of vegetation cover is required to reduce the soil loss ratio from 1.0 to 0.5, illustrate the inadequacy of the above approach. In order to understand the role of vegetation in combating erosion it is necessary to:

1. understand the erosion processes;
2. consider how each of these processes may be affected by vegetation;
3. determine the salient properties of the vegetation which most affect these processes;
4. try to quantify the combined effect of vegetation on the processes acting together in different situations.

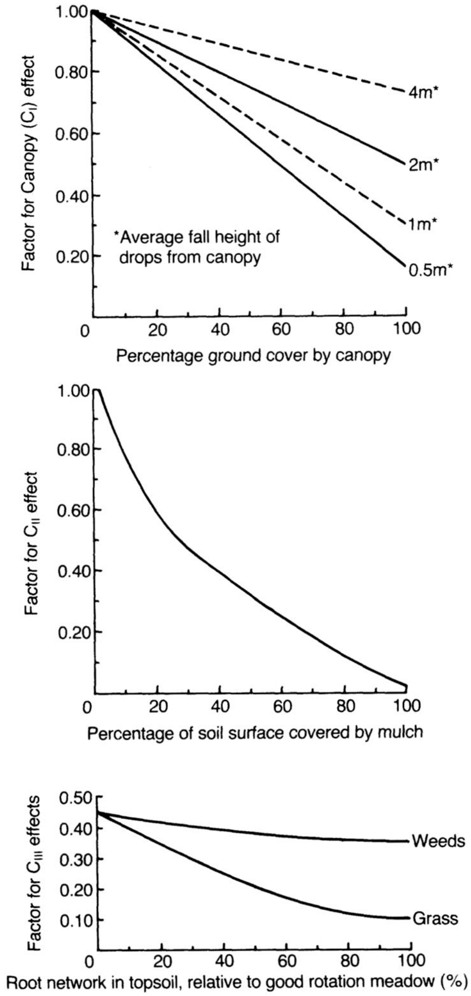

Figure 2.1 Soil loss ratios for subfactors of the C-factor in the Universal Soil Loss Equation (after Wischmeier, 1975). C_I describes the canopy effect, C_{II} the effect of plant residues and ground vegetation, and C_{III} the residual effects of previous land use. The graph shown here for the C_{III} effect applies to previously undisturbed land only and not to cropland or construction sites.

Such a detailed understanding is difficult to achieve. It is hampered by the fact that much previous research has concentrated on establishing C-factor values rather than on understanding how vegetation operates within the erosion system. Analysis is also hampered by the complexity of the interaction between vegetation, climate, soil properties and hydrology. Nevertheless, the relatively low rates of erosion observed

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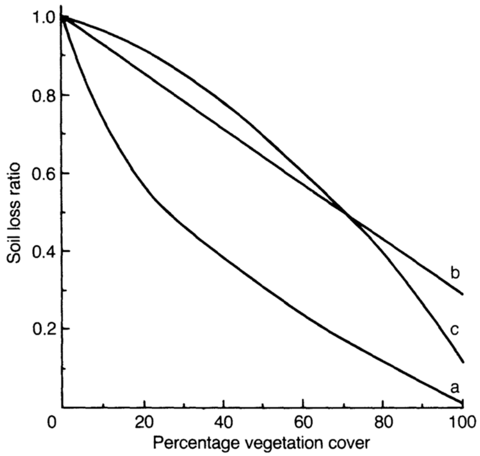

Figure 2.2 Examples of relationships between the soil loss ratio and percentage vegetation cover. a=ground level vegetation (Laflen and Colvin, 1981); b=vegetation canopy at 1 m above the ground (Wischmeier, 1975); c=oat straw mulch (Singer and Blackard, 1978).

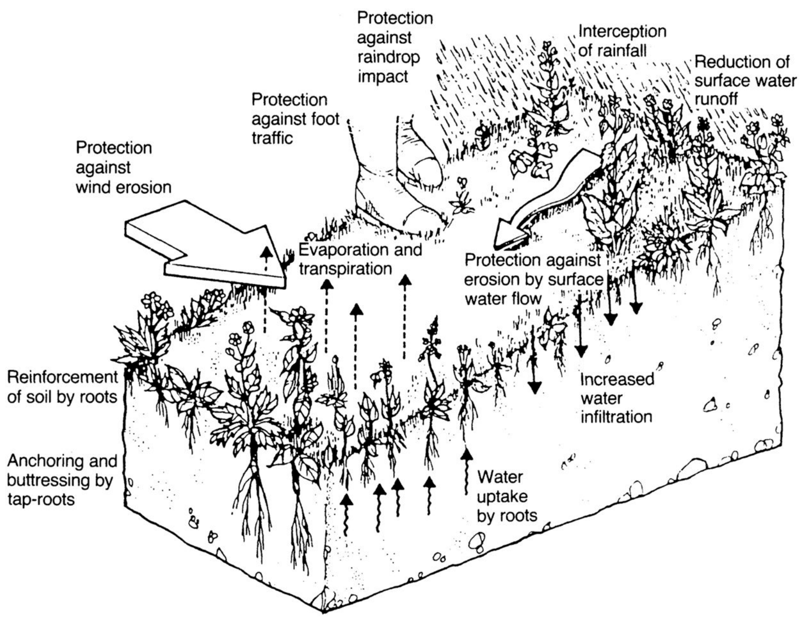

Figure 2.3 Engineering role of vegetation (after Coppin and Richards, 1990).

in well-vegetated areas compared with the catastrophic rates which can arise when vegetation is cleared, demonstrate that vegetation performs a major engineering role in protecting the landscape. This chapter aims to explore that role by reviewing its hydrological, hydraulic and mechanical effects. These are summarized diagrammatically in Figure 2.3.

2.2 HYDROLOGICAL EFFECTS OF VEGETATION

2.2.1 EVAPOTRANSPIRATION

Evapotranspiration is the combined process of the removal of moisture from the earth's surface by evaporation and transpiration from the vegetation cover. Evapotranspiration from plant surfaces is compared to the equivalent evaporation from an open water body. The two rates are not the same because the energy balances of the surfaces are markedly different. For example, the albedo value, defined as the proportion of incoming short-wave radiation which is reflected, is, depending on the altitude of the sun, about 0.1 for water, but varies between 0.1 and 0.3 for a plant cover. The effect of vegetation is expressed by the E_t/E_o ratio, where E_t is the evapotranspiration rate for the vegetation cover and E_o is the evaporation rate for open water. Table 2.1 gives some typical values for plant covers at different stages of growth and in different seasons (Withers and Vipond, 1974; Doorenbos and Pruitt, 1977).

The values of E_t/E_o ratios assume that evapotranspiration is not limited by the supply of water; in other words, it is taking place at the potential rate *(E_p)*. Where high rates of evapotranspiration occur, however, the top layers of the soil rapidly dry out and the plants find it more difficult to extract water from the soil by suction through the roots. To prevent dehydration, plants reduce their transpiration so that actual evapotranspiration *(E_a)* becomes less than potential. The ratio of actual to potential evapotranspiration *(E_a/E_p)* depends upon the soil moisture deficit (SMD) which is defined as the difference between the reduced soil moisture level and that pertaining at field capacity. The

Table 2.1 E_t/E_o ratios for selected plant covers (after Withers and Vipond, 1974; Doorenbos and Pruitt, 1977)

Plant (crop) cover	*E_t/E_o ratio*
Wet (padi) rice	1.35
Wheat	0.59–0.61
Maize	0.67–0.70
Barley	0.56–0.60
Millet/sorghum	0.62
Potato	0.70–0.80
Beans	0.62–0.69
Groundnut	0.50–0.87
Cabbage/Brussels sprouts	0.45–0.70
Banana	0.70–0.77
Tea	0.85–1.00
Coffee	0.50–1.00
Cocoa	1.00
Sugar cane	0.68–0.80
Sugar beet	0.73–0.75
Rubber	0.90
Oil palm	1.20
Cotton	0.63–0.69

Plant (crop) cover	*E_t/E_o ratio*
Cultivated grass	0.85–0.87
Prairie/savanna grass	0.80–0.95
Forest/woodland	0.90–1.00

amount of soil moisture which can be extracted by a plant cover when water is not limiting is defined by a root constant *(C)*; typical values are given in Table 2.2 (Grindley, 1969). Actual evapotranspiration taking place as a soil dries out can be estimated using the model of Penman (1949) whereby actual evapotranspiration equals potential $(E_a=E_p)$ as long as SMD<*C* but when SMD>*C*, a further 25 mm of moisture can be extracted at a reduced rate until, at SMD>3*C*, extraction becomes minimal (E_a=0.1E_p).

Although the ability of vegetation to reduce soil moisture is recognized qualitatively, it is hard to quantify. Reduced soil moisture increases soil suction which affects both hydraulic conductivity and pore-water pressure. Only limited information is available, however, on differences in the hydraulic conductivity of soils with and without a vegetation cover and the effect of vegetation on slope stability through soil moisture depletion is difficult to separate from that of soil reinforcement by the rooting system. Nevertheless, through modification of the soil moisture content, vegetation affects the frequency at which the soil becomes saturated which, in turn, controls the likelihood of runoff generation or mass soil failure. The strength of this effect depends upon the local soil and climatic conditions and the vegetation type. It will also show, often substantial, seasonal variation, being greatest in summer and lowest in winter or whenever the vegetation is dormant.

2.2.2 INTERCEPTION

On contact with the canopy of a vegetation cover, the rainfall is divided into two parts. These are (1) direct throughfall, that which reaches the ground after passing through gaps in the canopy, and (2) interception, that which strikes the vegetation cover. If it is assumed that

Table 2.2 Values of the root constant *(C)* for use in estimating evapotranspiration (after Grindley, 1969)

Vegetation	*Maximum SMD (mm)*[a]	*Root constant, C (mm)*
Cereals	200	140
Temporary grass	100	56
Permanent grass	125	75
Rough grazing	50	13
Trees (mature stand)	125–250	75–200

[a] SMD=soil moisture deficit. The actual value of maximum SMD varies with the depth of roots, being higher for deep-rooted vegetation than for shallow-rooted types.

the rain falls vertically, the volume of rainfall intercepted *(IC)* can be calculated from the simple relationship:

$$IC = \mathrm{RAIN} \cdot CC, \tag{2.1}$$

where *CC*=percentage canopy cover.

Some of the intercepted rainfall is stored on the leaves and stems and is later returned to the atmosphere by evaporation. The remainder of the intercepted rainfall, termed 'temporarily intercepted throughfall' (TIF), reaches the ground either as stemflow (i.e. that running down the stems, branches or trunks of the vegetation) or as leaf drainage.

Interception storage

Observed interception storage (IC_{store}) varies widely, depending upon the type of vegetation and the intensity of the rain, but, during a storm, it increases exponentially to a maximum value (IC_{max}) in a relationship similar to that proposed by Merriam (1973):

$$IC_{store} = IC_{max}(1 - \exp R_{cum}/IC_{max}), \qquad (2.2)$$

where R_{cum} is the cumulative rainfall received since the start of the storm. Values of maximum interception storage are difficult to determine but probably range from 0.5 mm for deciduous forest in winter to 1 mm for coniferous forest, deciduous forest in summer and many agricultural crops, 1–2 mm for grasses and 2.5 mm for a multi-layered tropical rain forest (Table 2.3). Since storage often returns to the maximum value between storms, its cumulative effect over a year can be considerable and can account for 10–15% of the annual rainfall in cool-temperate hardwood forests, 15–25% in temperate broad-leaved forests, 20–25% for cereals and grass covers, and 25–30% in temperate coniferous and in tropical rain forests. Interception storage thus reduces the volume of rainfall reaching the ground surface by these amounts.

Stemflow

The amount of water shed by stemflow depends upon the angle of the stems of the plant to the ground surface (De Ploey, 1982; van Elewijck, 1989). For plants where the stem diameters are less than the median volume drop size of the rainfall, such as grasses, stemflow is at a maximum when the stem angles are between 50° and 70°. For plants with larger diameter stems, the situation is less clear. Van Elewijck (1988) recorded maximum stemflow on maize leaves at stem angles between 10° and 20° and on simulated branches at stem angles between 5° and 15° whereas Herwitz (1987) found that stemflow on branches (>4cm diameter) of *Toona australis* and *Aleurites moluccana* increased linearly with stem angle to reach a maximum at a branch angle of 60°, the highest angle used in his experiments.

Very little information exists on volumes of stemflow. Measurements by Noble (1981) and Finney (1984) show stemflow volumes to be about 3–7% of storm rainfall for both Brussels sprouts with canopy covers of 40–50% and potatoes with 20–25% canopy. Higher values were observed for sugar beet at 42% of storm rainfall with 28% canopy cover (Finney, 1984). A figure of 55% was also recorded for sugar beet by Appelmans, van Hove and De Leenheer (1980). Values of 44% and 31% were recorded by Bui and Box (1992) in laboratory experiments under maize and sorghum respectively. High stemflow volumes can therefore be expected for plants with an architecture designed to concentrate water at their base and characterized by stems and leaves which converge towards the ground. De Ploey (1982) estimates that tussocky grasses may produce stemflow volumes that amount to 50–100% of the intercepted rainfall and Herwitz (1987) found that more than 80% of the impacting rain on tree branches inclined at 60° contributed to stemflow. Such concentrations of rainfall over relatively small areas can increase the effective rainfall intensity locally beneath tussocky grasses to 150–200% of that received at the top of the canopy (De Ploey, 1982). Even greater concentrations can occur in forests. Herwitz (1986) recorded an instance in the tropical rain forest in northern Queensland where stemflow fluxes measured during a rain

Table 2.3 Interception storage capacity for different vegetation types (after Horton, 1919; Leyton, Reynolds and Thompson, 1967; Zinke, 1967; Rutter and Morton, 1977; Herwitz, 1985)

Vegetation type	*Interception storage capacity, IC_{max}(mm)*
Fescue grass	1.2
Molinia	0.2
Rye grass	2.5
Meadow grass, clover	2.0
Blue stem grass	2.3
Heather	1.5
Bracken	1.3
Tropical rain forest	0.8–2.5
Temperate deciduous forest (summer)	1.0
Temperate deciduous forest (winter)	0.5
Needle leaf forest (pines)	1.0
Needle leaf forest (spruce, firs)	1.5
Evergreen hardwood forest	0.8
Soya beans	0.7
Potatoes	0.9
Cabbage	0.5
Brussels sprouts	1.0
Sugar beet	0.6
Millet	0.3
Spring wheat	1.8
Winter wheat	3.0
Barley, rye, oats	1.2
Maize	0.8
Tobacco	1.8
Alfalfa	2.8
Apple	0.5

fall of 11.8 mm in 6 min gave local depth equivalents of between 83 and 1888 mm. These large quantities of water beneath plants can play an important role in the generation of runoff.

Based on the work of van Elewijck (1988), the volume of stemflow (SF) may be estimated as a function of the average angle of the plant stems to the ground (PA) using the following equations:

for stem diameters<median volume drop diameter:

$$\mathrm{SF} = \mathrm{TIF}\ (\cos \mathrm{PA} \cdot \sin^2 \mathrm{PA}); \tag{2.3}$$

for stem diameters>median volume drop diameter:

$$\mathrm{SF} = \mathrm{TIF} \cos \mathrm{PA}. \tag{2.4}$$

In the above, sin PA expresses the effect of gravity and cos PA expresses the effect of the projected length of the leaves and stems on the plant.

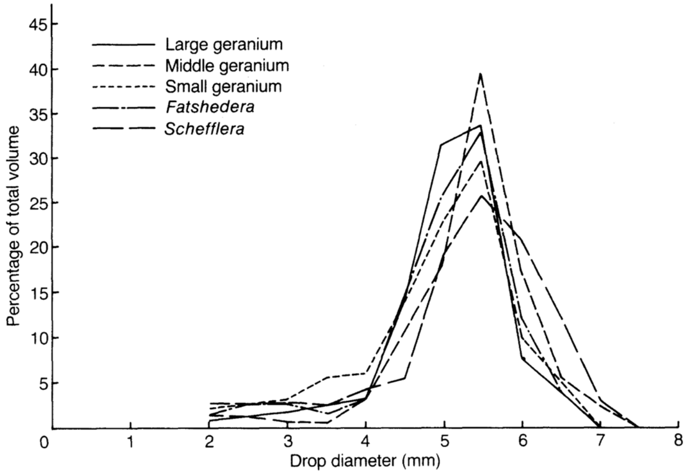

Figure 2.4 Drop-size distribution of leaf drainage (after Brandt, 1989).

Leaf drainage

The volume of leaf drainage is equal to the volume of temporarily intercepted throughfall less the volume of stemflow. Leaf drainage comprises raindrops that are shattered into small droplets immediately they strike the vegetation and large drops formed by the temporary storage and coalescence of raindrops on the leaf and stem surfaces before they fall to the ground. Thus the rainfall beneath a plant canopy has higher proportions of small (<1 mm) and large (>5 mm) drops and fewer medium-sized drops compared with the original rainfall. In this way the canopy cover changes the drop-size distribution of the rain.

For plants with long leaves, like maize, the drops are mainly channelled along the centre vein and form leaf drips with diameters of 5–5.5 mm. For soya beans, the average size of the leaf drips is smaller, at about 4.5 mm, partly because more raindrops are rejected instantaneously by the leaves (Armstrong and Mitchell, 1987). Brandt (1989), in a review of previous literature combined with results of her own laboratory studies, concludes that leaf drainage has a normal drop-size distribution with a mean volume drop diameter of between 4.52 and 4.95 mm and a standard deviation of 0.79– 1.30 mm (Figure 2.4).

Concentrations of water from leaf drip points can result in very high localized rainfall intensities, over 1000% greater than the intensity received at the canopy (Armstrong and Mitchell, 1987). These can exceed infiltration rates and result in surface runoff. This effect would be most marked in calm conditions. In strong winds, movement of the leaves and branches, as well as the falling water drops, will help to spread the leaf drainage more uniformly.

Soil detachment by raindrop impact

Soil detachment by raindrop impact has been related to various properties of the rain; *KE* (kinetic energy), EI_{30} (kinetic energy times the maximum intensity of the storm, measured over 30 min) and I^2 (intensity squared) being the most commonly used parameters. Vegetation affects these properties by altering the mass of rainfall reaching the ground, its drop-size distribution and its local intensity.

The energy of the rainfall available for soil detachment under a vegetation cover is dependent upon the relative proportions of the rain falling as direct throughfall and as leaf drainage. The ability of stemflow to detach soil particles is normally ignored. Thus the kinetic energy of the rain can be expressed by the simple arithmetical relationship:

$$KE = [(DT/TV) \cdot KE(DT)] + [(LD/TV) \cdot KE(LD)], \quad (2.5)$$

where KE=the kinetic energy (J/m^2 mm) of the rain; DT=the volume of direct throughfall; LD=the volume of leaf drainage; and TV=the total volume of direct throughfall and leaf drainage.

The energy of the direct throughfall is assumed to be the same as that of the natural rainfall. A reasonable approximation of the drop-size distribution of steady rain in temperate mid-latitude climates is that described by Marshall and Palmer (1948):

$$N(\delta) = N_0 \, e^{-\Lambda\delta}, \quad (2.6)$$

where $N(\delta)d\delta$=the number of drops per unit volume with diameters between δ and $\delta+d\delta$; $\Lambda(I)=41\ I^{-0.21}$, where Λ has units of cm^{-1} and I is the rainfall intensity (mm/h); and N_0=approximately 0.08 cm^{-4}.

Other drop-size distributions have been presented by Carter *et al.* (1974) for Florida, Hudson (1963) for Zimbabwe, and Kowal and Kassam (1976) for northern Nigeria. In the case of the Marshall-Palmer distribution, the kinetic energy (J/m^2 mm) of a unit rain can be estimated from (Brandt, 1990):

$$KE(DT) = 8.95 + 8.44 \log I, \quad (2.7)$$

where I=the intensity of the rain (mm/h).

If the drop-size distribution of the leaf drainage follows that described above, its energy may be calculated from (Brandt, 1990):

$$KE(LD) = (15.8 \cdot PH^{0.5}) - 5.87, \quad (2.8)$$

where PH=the effective height (m) of the vegetation canopy.

For non-cohesive soils, the rainfall energy is not spent on detaching individual soil particles from the soil mass. It is primarily used for deformation of the surface and the lifting and moving of the already-discrete particles. In this case, splash erosion can be expected to be proportional to the kinetic energy of the rain (Free, 1960; Moss and Green, 1987), which is approximately proportional to $I^{1.14}$. Soil detachment (DET; g/m^2), in the sense of dislodgement of soil particles by raindrop impact, can then be estimated from the simple relationship:

$$\mathrm{DET} = k \cdot KE^{1.0} \cdot e^{-ah}, \quad (2.9)$$

where k=an index of the detachability of the soil (g/J); h=the depth (m) of the surface water layer, if any; and a=an experimental coefficient varying between 1.0 and 3.0 in value, depending upon the soil texture (Torri, Sfalanga and Del Sette, 1987).

It follows from this analysis that the rate of soil detachment beneath a vegetation cover depends upon the percentage canopy area, which controls the volumes of direct throughfall and leaf drainage, and the height of the canopy, which determines the energy of the leaf drainage. Numerous studies have shown that the energy of rain under vegetation can exceed that of an equivalent rainfall in open ground, both for trees (Chapman, 1948; Wiersum, Budirijanto and Rhomdoni, 1979; Maene and Chong, 1979; Mosley, 1982) and for lower-growing agricultural crops (Noble and Morgan, 1983; Morgan, 1985) with consequent increases in the rate of detachment (Finney, 1984; Wiersum, 1985). Field measurements with rainfall simulation showed that soil detachment under maize increased with percentage cover to double that recorded on bare soil when the canopy reached about 90% cover and was about 2m above ground level (Morgan, 1985).

Recent research (Styczen and Høgh-Schmidt, 1988) has suggested that kinetic energy may not be the best parameter of the rain to explain soil detachment under vegetation or on cohesive soils. A different approach is proposed in which soil detachment is proportional to the sum of the squared momenta of the raindrops:

$$\mathrm{DET} = A(2\hat{e})^{-1} Pr \sum^{\delta} N_\delta p_\delta^2, \tag{2.10}$$

where A=a soil-dependent constant of proportionality; $\hat{e}$=the average energy required to

Table 2.4 Values of squared momentum for different intensities of rain

Rainfall intensity, I (mm/h)	*Squared momentum, M_R ((Ns)^2/m^{2}s)*
5	2.66×10^{-7}
10	8.88×10^{-7}
20	2.86×10^{-6}
35	7.11×10^{-6}
50	1.25×10^{-5}
75	2.32×10^{-5}
100	3.56×10^{-5}
125	4.92×10^{-5}
150	6.38×10^{-5}
175	7.93×10^{-5}
200	9.55×10^{-5}
225	1.12×10^{-4}
250	1.30×10^{-4}

break the bonds between two micro-aggregates of soil, and the energy lost by heat in the process; Pr=the probability that the kinetic energy received by the detached micro-aggregate(s) is large enough to make it measurable as splash, i.e. to make the micro-aggregate jump a minimum distance; N_δ=the number of raindrops of size (diameter) δ; and p_δ=the drop momentum $(m_\delta \cdot v_\delta)$.

A, $\hat{e}$ and Pr are related to soil properties, while N_δ and p_δ are rainfall properties; m and v refer respectively to the mass and velocity of the raindrop.

For the Marshall-Palmer drop-size distribution, $N_\delta p_\delta^2$ is proportional to $I^{1.63}$ for $0<I<100$ mm/h and $I^{1.43}$ for $100<I<250$ mm/h. Values for the squared momentum, $M_R = N_\delta p_\delta^2$, are listed in Table 2.4.

The squared momentum of the leaf drainage (M_{RC}) can be calculated in the following way (Styczen and Høgh-Schmidt, 1986), given that the amount of leaf drainage equals $CC \cdot I \cdot [1-(SF + IC_{\mathrm{store}})]$ and the number of drops equals $CC \cdot I \cdot [1-(SF + IC_{\mathrm{store}})/\mathrm{vol}(\delta)]$ (equation 2.11) where vol(δ)=the volume of a drop with diameter (δ); ρ_w=the density of water; $v_{\delta H}$=the velocity of the drop as a function of its diameter (δ) and fall height (H); and vol δ) $(\rho_a^2 \pi \delta^3 v_\delta^2/6)$ listed in Table 2.5.

$$M_{RC} = \frac{CC \cdot I \cdot [1-(SF + IC_{\mathrm{store}})]}{\mathrm{vol}(\delta)} \cdot \rho_w^2 \\ [\mathrm{vol}(\delta)^2 \cdot v_{\delta H}^2]. \tag{2.11}$$

When the sum of the squared momenta with and without a vegetation cover are known, the

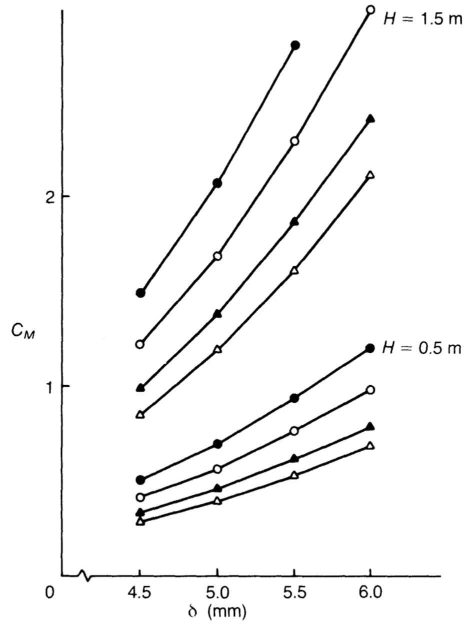

Figure 2.5 C_M as a function of the drop size of transformed rain *(δ)* for different rainfall intensities *(I)* and two canopy heights *(H)* (after Styczen and Høgh-Schmidt, 1988). The canopy cover is 100%. Storage and stemflow are estimated as 10% of the rainfall. ●, *I*=35 mm/h; ○, *I*=50 mm/h; ▲, *I*=75 mm/h; Δ, *I*=100 mm/h.

Table 2.5 Values of the parameter DH $(\rho_a^2 \pi \delta^3 v_g^2/6)(kg^2/m\,s)$ computed for different drop sizes *(δ)* and fall heights

Fall height (m)	*Drop sizes (δ)*			
4.5 mm	*5.0 mm*	*5.5 mm*	*6.0 mm*	
0.5	0.4180	0.5734	0.7633	0.9909
1.0	0.7942	1.1002	1.4787	1.9384
1.5	1.2120	1.6890	2.2836	2.9996
2.0	1.5720	2.1866	2.9508	3.8837
3.0	2.1291	2.9998	4.0757	5.4158
4.0	2.5706	3.6229	4.9526	6.6014
5.0	2.9029	4.1470	5.6452	7.4386
6.0	3.1459	4.4763	6.0883	8.0182
7.0	3.2949	4.6733	6.3533	8.4036
8.0	3.3907	4.7957	6.5331	8.6590
9.0	3.4554	4.8971	6.6696	8.8381
10.0	3.5125	4.9769	6.7768	8.9584
13.0	3.6530	5.1843	6.9936	9.2016
∞	3.8647	5.4080	7.2934	9.5310

relative effect of the vegetation on splash (equivalent to a C-factor for splash) can be calculated as:

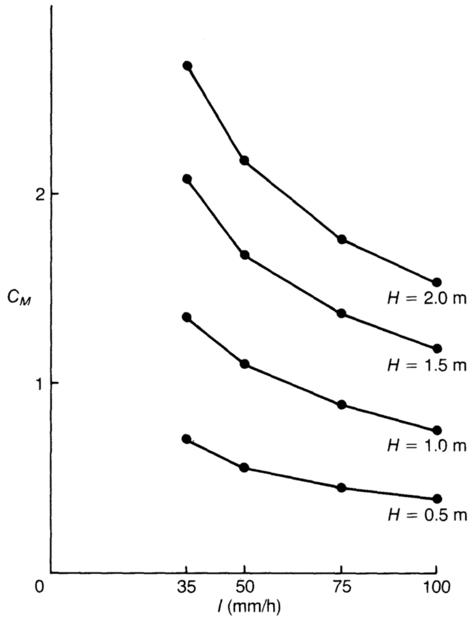

Figure 2.6 Changes in C_M with changes in rainfall intensity *(I)* for different canopy heights *(H)* (after Styczen and Høgh-Schmidt, 1988). Curves are calculated for 100% canopy cover and a drop size for leaf drainage *(δ)* of 5.0 mm.

$$C_M = \frac{(1-CC)M_R + C \cdot I \cdot (1-(SF+IC_{\text{store}})) \cdot DH}{M_R}. \tag{2.12}$$

Figures 2.5, 2.6 and 2.7 illustrate the calculated effect of different drop sizes, fall heights, stem-flow percentages and rainfall intensities on the value of C_M. Figure 2.8 shows how important the drop-size distribution of the rain can be when interpreting the effects of vegetation. As splash erosion is proportional to the drop diameter raised to the sixth power, leaf drainage may result in serious soil breakdown. Contrary to ordinary opinion, a plant canopy situated more than about 1 m above the ground cannot be expected to decrease splash erosion by itself; indeed, it is more likely to enhance it. Figure 2.9 shows this effect measured under maize (Morgan, 1985) and calculated according to equations 2.10 and 2.12.

Similar conclusions were reached by Moss and Green (1987) who, on the basis of empirical data, divided vegetation layers into the following categories:

1. Layer 1, <0.3 m: where, owing to the often high density of plant-ground contacts, leaf drainage volumes are usually small and the impact velocities too low to allow significant damage.
2. Layer 2, 0.3–1.0 m: where there is a transition from small to significant leaf drip and soil damage.
3. Layer 3, 1.0–2.5 m: from which leaf drips reach high erosivity and achieve a marked ability to cause soil damage.
4. Layer 4, 2.5–6.0 m: in which the ability of leaf drips to cause erosion and soil damage continues to increase but more slowly than in layer 3.
5. Layer 5, >6 m: where the free fall height is sufficient for leaf drips to attain 90% or more of their terminal velocity; hence, above this height there is little further increase in either their ability to cause soil damage or their erosivity.

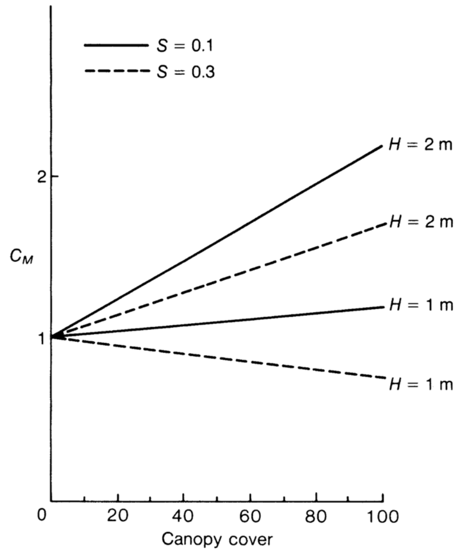

Figure 2.7 Changes in C_M with changing percentage permanent interception *(S)* for leaf drainage with a diameter *(δ)* of 5.0 mm and two heights of canopy *(H)* (after Styczen and Høgh-Schmidt, 1988). Rainfall intensity equals 50 mm/h.

If, in contrast to the above, it is assumed that splash erosion on sand is proportional to the incoming kinetic energy instead of the sum of the squared momenta, the apparent effects of vegetation become less drastic. For very tall vegetation, the energy impact approximately doubles compared to that on bare soil, but for most agricultural crops, the impact is reduced. The relative change in energy impact is shown in Figure 2.10 for four rainfall intensities, five fall heights, 10% stemflow and different cover percentages. From such calculations, a soil under a 0.5 m tall soya bean crop (80% cover, 10% stemflow) receives only 50% of the energy received by a bare soil. In the case of 1.5 m tall maize (also 80% cover and 10% stemflow), the soil receives 85–90% of the energy. For 6 m tall trees without any ground cover, the energy received by the soil reaches 200%.

It may seem strange that the amount of energy reaching the ground under trees is more than 100%. This is due to the difference in frictional resistance on small and large drops. Leaf drips are not only larger and heavier, they also gain a higher velocity so that the final impact energy is increased.

Equation 2.10 contains two soil factors that may be influenced by vegetation. These are *ê,* the average energy required to break the bonds between two micro-aggregates, and *Pr,* the probability that the kinetic energy received by the micro-aggregate is large enough to make it measurable as splash. The term, *k,* in equation 2.9, which expresses the detachability of the soil, also encompasses these factors which are discussed in more detail in section 2.4.1.

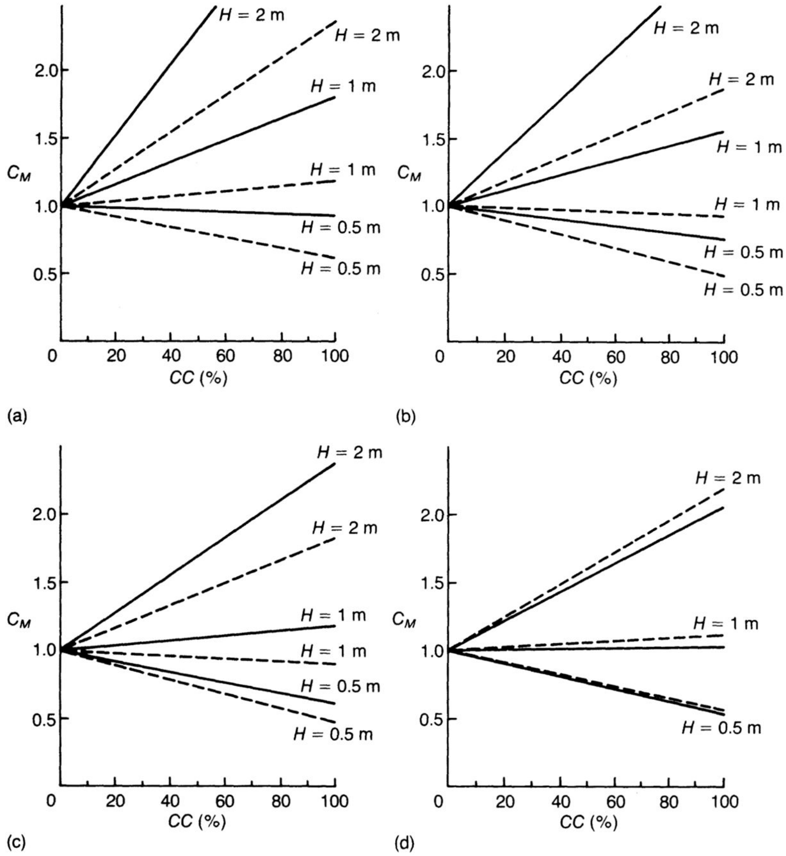

Figure 2.8 C_M as a function of percentage vegetation cover *(CC)* and canopy height *(H),* calculated for two drop-size-distributions (__, Marshall and Palmer, 1948; ----, Carter *et al.,* 1974) for leaf drainage of 5.0 mm diameter *(δ),* and percentage permanent interception storage and stemflow equal to 10% of the rainfall (after Styczen and Høgh-Schmidt, 1988). Rainfall intensities are (a) 35 mm/h; (b) 50 mm/h; (c) 75 mm/h; (d) 100 mm/h.

2.2.3 INFILTRATION

For serious erosion to take place, some amount of runoff must occur. The amount of runoff generated is closely related to the infiltration rates (unsaturated and saturated hydraulic conductivity) of the soil, the antecedent moisture content and, indirectly, to the direction of water flow within the soil.

When rain water reaches the ground underneath vegetation, it may stand a better chance of infiltrating than on unvegetated soil. Organic matter, root growth, decaying roots, earthworms, termites and a high level of biological activity in the soil help to maintain a continuous pore system and thereby a higher hydraulic conductivity. Through an increase in the infiltration rate, and perhaps also in the moisture storage capacity of the soil, vegetation may decrease the amount of runoff generated during a storm; it will probably also increase the time taken for runoff to occur. A bare soil may be compared to a bucket with few or small holes in the bottom, while the vegetated soil is rather like a slightly larger bucket with more and bigger holes. It is necessary to apply more water at a greater rate to make the second bucket overflow. Thus, a

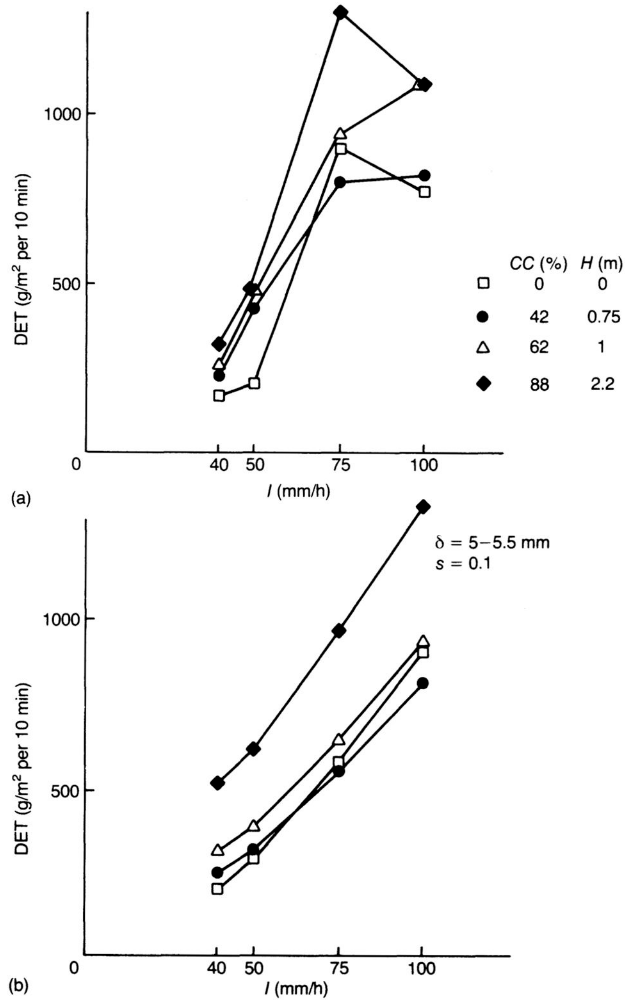

Figure 2.9 Splash erosion (DET) as a function of rainfall intensity for four combinations of percentage maize cover *(CC %)* and height *(H)* (after Styczen and Høgh-Schmidt, 1988). (a) Observed data (from Morgan, 1985); (b) calculated data. Based on equations 2.10 and 2.12 with a drop diameter *(δ)* of leaf drainage of 5.0–5.5 mm and percentage permanent interception storage and stemflow equal to 10% of the rainfall.

higher infiltration may decrease the number of erosive events per year because a greater storm is needed to produce the critical amount of runoff.

The saturated hydraulic conductivity of a soil (k_{sat}) depends on its texture and structure, the presence of cracks and the number of biopores it contains. McKeague, Wang and Coen (1986) present some guidelines for estimating k_{sat} from soil morphology. These are of interest here because the descriptions help in visualizing the changes occurring in a soil as a result of biological interference. Rawls, Brakensiek and Soni (1983) and Brakensiek and Rawls (1983) estimate k_{sat} for soils with different pore-size distri