Determining runoff potential
for assessing suitability for water harvesting

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For my parents, for inspiring confidence
and engendering a curiosity about this world.

To my father, for reading to me as a child.

To my mother, for making me aware of another realm

(and for giving birth to me; and without whom, therefore,
this study would have been considerably more complicated).
See, a King will reign in righteousness
and rulers will rule with
justice.
Each man will be like a
shelter from the wind
and a refuge from the
storm,
like streams of water in the
desert
and the shadow of a great
rock in a thirsty land

Isaiah 32: 1-2
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Abstract

This study investigates options for assessing suitability for water harvesting. A conceptual model has been developed to explain the results of a rainfall simulation campaign involving the use of two instantaneous kinetic energies, a range of rainfall intensities and various degrees of crust disturbance in order to test the hypothesis of a surface (crust) control on runoff reported for other semi-arid environments. The resultant conceptual model purports to explain runoff as a function of both the initial state of the surface and of rainfall instantaneous kinetic energy and rainfall intensity. The advantages and disadvantages of rainfall simulation as opposed to alternative possible techniques for assessing the relative runoff potential of various surface types in the study area are discussed, as well as the prospects of upscaling from ‘point’ hydrological measurements to surfaces of spectral data (satellite imagery), with which an entire area of interest can be surveyed in terms of runoff potential for water harvesting suitability assessment.
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Chapter 1
Introduction

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This chapter serves to introduce the major research questions addressed in this study, the methodology chosen to address these questions, the sampling strategy employed within that methodology and the nature of the study area to which the methodology is applied. In fact, this study is simultaneously about addressing the research questions described in the next section as well as developing, or assessing the relevance of, the methodology used to address the major research questions posed by this study. The relevance of the methodology is assessed with respect to and the major research questions posed in the context of the overall objective of how to best determine runoff potential of a study area in the context of a land evaluation exercise for water harvesting.

This chapter starts with an introduction to the major research questions, the methodology and sampling strategy employed, and then moves on to explain the importance of water harvesting, why one might want to determine the suitability of an area for this soil and water conservation practice. This chapter then continues with an introduction to a key topic in this study, the phenomenon of crusting as a characteristic feature of soils in semi-arid areas and then turns to the effects of this phenomenon on infiltration, and implications for runoff assessment and for the research design. This chapter then briefly addresses models of infiltration into crusted semi-arid soils and specifies the approach taken in this study and clarifies that this study is not about mathematical modelling of infiltration, which has been done in great detail by many other studies, but rather about the implications of crusting for determining runoff potential for assessing suitability for water harvesting. Finally, this chapter ends with a summary of the research approach taken, the nature of the study area and a brief overview of the thesis on a chapter by chapter basis as a way of making the structure of the thesis apparent to the reader as well as to introduce some of the key concepts employed in this study.

(1.2) Research questions addressed, methodology and sampling strategy employed in this study
There are a number of related research questions addressed in this study, revolving around the central problem of how to map runoff potential in a semi-arid landscape with soils which are prone to crusting. How to best determine runoff potential is the key challenge on the environmental side of the broader research question of how to identify suitable locations to implement to the soil and water conserving technique called water harvesting. The advantages of water harvesting, which multiplies the effective rainfall, for crop / range / reafforestation in semi-arid and arid areas are described in the next section. The importance of socio-economic factors in determining suitable locations for water harvesting is recognised, but not addressed in this study.

On the environmental side of a methodology for determining suitability for water harvesting the two key questions to be asked are:
(a) which areas in the landscape will produce runoff
(b) which areas in the landscape are best to receive and store that runoff for the purpose of vegetative production.

The latter question involves the assessment of ‘runon’ potential, which involves the assessment of the available water capacity and the fertility of the soil. This is recognised to be very important but is not the focus of this study. Secondary data on runon potential will be utilised in Chapter 9 to illustrate a GIS (Geographical Information System) based assessment of suitability for water harvesting for the study area, lowland Baringo, Kenya. The focus of this study, however, is on the first question, how to determine which areas of the landscape in the study area have potential as runoff producing surfaces.

As such, this study is largely about the testing and assessment of various techniques which are potentially relevant in the development of a methodology for assessing suitability for water harvesting, and in particular for assessing runoff potential. In doing so, however, this study also engages the literature on the importance of crusting and sealing as controls on the surface hydrology in semi-arid areas. This literature is reviewed in Chapter 3. A central precept of this study was that, on the basis of the review of the literature carried out prior to fieldwork, that there is most likely a surface state control on runoff production in the study area. This assumption was tested in various ways over the course of the fieldwork in order to confirm or deny it. Indeed, this is one of the major research questions addressed by this study, listed below.
The fieldwork comprised three periods totalling approximately eight months, always at a period including both the dry and rainy season. Rainfall simulators were employed together with 'simple' or rapid, low cost tests to determine runoff potential of various surface types around the study area. The former were employed to generate a quantitative assessment of the effects of crusting on infiltration and a comparison of runoff potential between sites, the latter to generate a qualitative ranking of runoff potential between sites. These results from the quantitative and qualitative assessments were then compared with each other in order to determine whether and under what conditions qualitative measures of runoff potential can substitute for the much more time consuming rainfall simulations in terms of ranking relative runoff potential of the sample sites. Indeed, this is one of the major research questions addressed by this study, listed below.

Related to this last research question is the issue of the relative importance of wetting and energy controls on sealing and therefore runoff potential in a semi-arid area. On the basis of the literature review carried out prior to fieldwork, it was found that kinetic energy was generally considered to be the single most important parameter explaining crusting, which occurs in semi-arid areas in part because of the lack of vegetation to dissipate the energy of raindrops (Casenave and Valentin 1989). As such, the differences between the results of the rainfall simulations, which reproduce up to 75% of the kinetic energy of natural rain events in the study area, and the essentially energy free water acceptance simple tests are potentially useful in assessing the importance of kinetic energy on runoff production for crusting soils. The issue of the influence of rainfall characteristics on runoff is important, and in particular a kinetic energy control on crusting and sealing, and therefore runoff, is hypothesised in this study and tested using rainfall simulation at various drop heights. As a raindrop, however, can be conceived of as a 'co-quanta' of moisture and energy, the interaction between the wetting and impact effects on crusting and sealing, expressed in terms of runoff response, was also investigated.

A fundamental dilemma presents itself, however, in that the objective of ascertaining the effects of and interactions between raindrop energy and wetting effects implies a detailed study with a large number of replicates in order to establish a statistical confidence level regarding treatment effects, as does the objective of characterising the spatially distributed nature of the infiltration in the study area. As both objectives require a large number of rainfall simulations, it is beyond the scope of this research to both gain a systematic understanding of the rainfall-crusting interactions at a process level in the study area and to address the question of the spatial variability in infiltration over this same area, such that the latter was prioritised, in accordance with the overall
goal of developing an approach to determine runoff potential as part of a water harvesting suitability assessment protocol, whilst keeping the former strongly in mind. The issue of the relative importance of rainfall and surface characteristics in determining runoff places this research within a wider debate on these themes within the soil science and hydrology of semi-arid environments, but attention must be drawn to the typical lack of rainfall (especially intensity) data in developing countries. Indeed the relative importance of rainfall and surface characteristics in generating runoff is one of the major research questions posed by this study, listed below. The various issues related to the rainfall characteristics which are most important to accurately simulate are addressed in Chapter 4.

Results from a rainfall simulation campaign carried out by Bryan (1994) in the study area using a five meter spray-type rainfall simulator with approximately 90% reproduction of the kinetic energy of natural rainfall were compared with the results from the rainfall simulations carried out in this study. This was done because it was believed that the rainfall simulations with the highest kinetic energy reproduction could reasonably be considered to be ‘reference values’ of runoff potential in the absence of data on actual rainfall – runoff relations in the study area. As it was discovered that the time to runoff initiation and the steady state infiltration rate were considerably longer and higher, respectively, with the 1.5 meter simulator employed in this study, a new design was developed and built. The results with the original design were still, however, found to be useful in a number of ways in shedding light on the research questions and as such the results from both are reported in Chapter 7. The comparison between the results of the improved, 3.5 meter drop height simulator and the simple tests are reported in Chapter 8 on a site-by-site basis.

The sampling strategy chosen, which resulted in the selection of the sites, revolved around two criteria:

(a) carrying out work where secondary data were available for comparison, meaning mainly the sites of the University of Toronto erosion study (Bryan 1994) and the water harvesting fields of the Rehabilitation of Arid Environments (RAE) project

(b) ensuring a representative range of surfaces (particularly crust types) found across the study area.

Details of the sampling strategy and of the sites chosen are presented in Chapter 6. The second criteria listed above, regarding the representativity of the surfaces at the study sites, relates to the question of inventorying, classifying and mapping the distribution of the crusts in an area.
Relevant research on classifying crusting soils in terms of their morphology and their infiltration characteristics have been carried out in greatest detail by French researchers in the Sahel. In fact, they have created a ‘catalogue’ of the relationships between the two, based on a long term and extensive rainfall simulation campaign. Indeed, one of the major research questions in this thesis, listed below, was to assess whether and to what degree their methodologies are relevant for the purposes of suitability assessment for water harvesting and whether the same crusts exist in the study area and, if so, whether the runoff characteristics are the same as in the Sahel.

Pursuant to this theme, the question of how to map the occurrence / distribution of the crusts identified and characterised, for the purpose of mapping runoff potential, implies extrapolating or interpolating between what are essentially point measures of runoff potential determined from rainfall simulation. The obvious possibility to achieve this objective is to link hydrological measures to a spectral map available for the entire landscape, in the form of widely available optical remote sensing such as Landsat TM or the French Spot imagery. The resolution of this imagery, however, is far coarser than that at which the hydrological measures are taken, which raises the question of how to bridge this difference in scale (really resolution). Indeed, this is one of the major research questions addressed by this study, listed below, and in particular whether the attempts by the French and other researchers in the Sahel to link the two are applicable to the study area and in the context of a suitability assessment procedure for water harvesting.

To summarise, the major, often interrelated, research questions posed by this study, all of which are relevant to the environmental aspect of assessing suitability for water harvesting, are:

- Is there a surface state, particular crusting, control on runoff generation in the study area?
- What is the relative importance of surface characteristics and rainfall characteristics as controls on runoff?
- Is it possible, and under what conditions is it appropriate, to substitute rapid, low cost, low energy water acceptance tests and other proxy measures of runoff potential for the higher kinetic energy reproduction but very time consuming rainfall simulations?
- Is, or to what extent is the crust classification system developed by French researchers for the Sahel relevant to the study area in terms of a) principles of classification b) presence of the same crust types and c) if so, whether the hydrological characteristics of these crusts are similar in the study area?
• Can ‘point’ measures of runoff potential be ‘upscaled’ across the entire study area by linking them to a measure available for the entire surface; specifically a spectral ‘map’ in the form of widely available optical remote sensing image products such as Landsat TM and Spot?

(1.3)

Water Harvesting and determining runoff potential in areas of crusting soils in order to identify suitable areas for Water Harvesting

It has been estimated that some 200 - 500 million cubic meters of rainfall is lost in the form of runoff in the Sahel every year, which could potentially irrigate up to 40,000 hectares (Ben-Asher and Berliner, 1994). Some of this runoff could be utilised by arresting the runoff at suitable points in the landscapes - pockets of deeper, more fertile soils - by means of soil and water conservation structures. This possibility describes the practice of water harvesting. Water harvesting is a term which is commonly understood to mean the collection and therefore concentration of runoff from a larger area than the cropping area. A basic distinction consists between micro and macro water harvesting. The former refers to ‘within field’ and the latter to external catchment runoff collecting areas. For examples of both, see Plate 1. Determining runoff potential for assessing suitability for micro water harvesting, based both on fieldwork - using rainfall simulation and simple tests which could possibly substitute for these time consuming simulations – together with remote sensing and Geographical Information Systems (GIS) – is the focus of this study.

Water harvesting, and particularly macro water harvesting, has been used widely in the Middle East for at least 2,500 years, but is not as common in Sub-Saharan Africa (Pacey and Cullis, 1986), where it is largely an introduced technology by way of development projects. There are, however, also many cases in Sub-Saharan Africa of ‘indigenous’ water harvesting, particularly micro water harvesting (Reij et al., 1996). The US Office of Technology Assessment, in a systematic study of promising techniques for agriculture in the Sahel, found water harvesting to be the most likely to succeed as an introduced technology on criteria of cost, technical knowledge required (OTA, 1988). On purely agronomic criteria, water harvesting is an unqualified success, having repeatedly been shown to enhance soil moisture in the root zone over the growing season and as such to increase crop yield, particularly in dry years, as will be examined in Chapter 2. Furthermore, as will be seen in Chapter 2, a decrease in annual rainfall from 700 mm to 300 mm
Plate 1 Water harvesting systems
Clockwise from upper left: a) Zai pits
b) Level basins (note uneven water distribution)
c) World Bank contour earth bunds d) External catchment
from south to north across the Sahel results in an increase in dry spells, where a dry spell is defined as the interval between two storms of greater than 10 mm, from 11 to 18 days. Thus, in theory, the lower the annual rainfall the more advantageous, ceteris paribus, water harvesting would be.

In practice, however, there are physical considerations regarding the minimum effective catchment area as rainfall declines; and the larger the catchment area the greater the velocity of the flows generally will be, leading to risks of erosion of the runon area, and that an excess of water harvested in wet years by large catchments can depress yield beyond that of rainfed crops (Ben-Asher 1988). Furthermore, it is important to note that the level of social organisation required to control the runoff is substantially increased as the size of water control structures increases; water harvesting is both a social and technical phenomenon. Nevertheless, the relevance and potential of water harvesting for rural development in drylands is reflected in the fact that the FAO (1994) hosted an international workshop on water harvesting in the Middle East and North Africa and UNESCO for the Arab world (1986).

It is apparent that in order to identify areas which would be suitable for investment in the development of water harvesting, that it is essential to be able to predict runoff yield from a surface or catchment, be it natural or delineated by the user by way of structures. This, therefore, is the central research question addressed in this study, starting from a selective review of relevant work on runoff generation on crusting soils in semi-arid Africa in particular. In addition, an examination of the potential for using remotes sensing, as a relatively inexpensive and widely available spectral map of the surface of the earth, to identify the runoff potential of crusting surfaces is investigated for a study area in semi-arid Kenya. The implicit question upon which such an investigation rests is whether the demarcation of a landscape in hydrological terms corresponds to the demarcation of that same landscape in spectral terms. If so, then the former can potentially be derived from the latter.

This issue of a surface control on runoff is of particular interest in the present study, as crusting is a widespread in semi-arid areas, as will be demonstrated from the literature review in Chapter 3, and a fundamental hypothesis made is that of crust controlled hydrology in the study area, which is tested by destroying the crust in various ways. In addressing runoff assessment in semi-arid environments, it is salient to review in particular the work of Orstom (French research for development) groups working in dryland North and West Africa on these theme, with an
emphasis on crust classification in Chapter 3 and on the relationships between hydrological and 'spectral maps' (satellite imagery) of dryland African landscapes in Chapter 5. The fundamentals of the effects of the crusting phenomenon on infiltration will also be addressed in Chapter 3. From the hydrological basis thus established one can then turn in Chapter 5 to attempts to relate the hydrological characteristics of a study area to the spectral classification of the same area, inevitably at a far coarser resolution (400 or 900 m$^2$ as opposed to 1m$^2$ hydrological units), and the problems of trying to marry these two 'classifications' of the landscape across the scale divide. Furthermore, this study is carried out in the context of the integration of various data sets, both primary and secondary, in a Geographical Information System, which provided some surprising but intriguing and revealing results discussed in Chapter 9.

(1.4)
The phenomenon of crusting as a characteristic feature of soils in semi-arid areas

To summarise crudely, the formation of crusts in temperate climates is the result principally of slaking (Bresson 1995), of the gradual loss of aggregate stability through the gradual wetting of the soil in these environments by low intensity, low energy rainfall with short interval between rain events. In semi-arid environments in the tropics, on the other hand, crusting is believed to be primarily due to the kinetic energy of rainfall; the sudden destruction of the structure of the soil surface under high intensity high energy bursts of rainfall and the lack of the buffer effect of vegetation.

The conclusion of the review of crusting soils in arid and particularly semi-arid Africa, found in Chapter 3, is that there is a great amount of evidence of the central importance which crusting plays at the level of the crop water balance as well as at coarser scales of analysis. In the Sahel, one could cite in particular the work of Casenave and Valentin (1989), which serves as the launching pad for the work of the present study was carried out, as well as and the integrative work of Bresson and Valentin (1994) on crust classifications.

In short, the review of the literature presented in chapters 3 and 5 and the accompanying application to a test area in Kenya concerns the mapping of runoff potential in a semi-arid environment. As infiltration and runoff occur at the interface between the atmosphere and the soil, at the surface of the soil, the widely reported phenomenon of the sealing of this interface in soils in semi-arid environments must be of central relevance to the research problem.
Crusting, sealing, effects on infiltration, and implications for runoff assessment and for the research design

This study starts from the nature of crusting and the approaches which have been taken to understanding crust formation and, specifically, to incorporate these into a crust classification system. This is an essential prerequisite to mapping crusting soils and therefore, on the hypothesis that crusting dominates surface runoff response in the study area, to mapping runoff potential for the purpose of determining the suitability of water harvesting. The factors which influence the sealing behaviour of crusting soils receive particular attention, as it is this characteristic of crusts which is of interest to the present study. Note that a distinction is made here between crusting, the result of a change in the organisation of the surface and evident upon drying, and sealing, the processes which cause a reduction in infiltration during a rain event. The link between process and pattern, between crust morphology and sealing behaviour, is seen to be the key to mapping infiltration and thus runoff potential, and as such this relationship is a central consideration.

The issue of the scale of investigation and of spatial variability in crusting and infiltration is introduced. The implications of the dynamic nature of crusting soils for the development of a crust classification system is addressed, and the preferred crust classification system to be described. This system, developed by Orstom in the Sahel, is tested in the Baringo lowlands, Kenya in this study, an area outside the zone outside the area for which it was developed. As such, this is considered to be a test of its versatility, as well as of the variability of crusting soils in dryland Africa.

Models of infiltration into crusted semi-arid soils, approach taken in this study

Both as a simplistic conceptual model and as a practical empirical manner of characterising infiltration behaviour, and due to the number of studies of infiltration in semi-arid soils which have found this model to prove useful, the Horton-type model is the favoured approach in the present study. One must add to this, of course, as an empirical model, the caveat that the specific
conditions of the surface must be characterised at the various sites investigated. This is precisely the approach taken by Casenave and Valentin (1989), which is the Sahelian equivalent of the well known, theoretically informed but essentially empirical, U.S. SCS curve number and USLE systems, both the result of major research and data synthesising efforts over broad areas of the U.S. The emphasis on the specific nature of the surface derives from the hypothesis that it is the organisation of the surface which principally explains infiltration in semi-arid soils.

Simulation models are not reviewed here because the data requirements are so great to run them that they are not practical in the context of rapid environmental survey, as would be required as an input for assessing the potential for surface water development in Africa. On the contrary, simple curve fitting provides a rapid way to approximate the key relationships in the system for a particular site under particular conditions, which is the objective of the approach chosen. This then allows comparison between sites and treatments, where rainfall intensity and soil surface type are considered to be the key independent variables, and infiltration and runoff the dependent variables of interest, primarily as a function of time, cumulative rain depth and cumulative energy.

The parameterisation of many of the these models is time consuming, and it will be argued that in practice crust behaviour is so complex, even for one specific type of crust, that in practice it will be more useful to map the variability in infiltration empirically using, for example, a rainfall simulator, together with remote sensing (aerial photography and/or satellite imagery). Hence, the focus in this study is on the use of rapid techniques to provide local values, with the emphasis on rainfall simulation, and with comparisons made to quicker and cheaper alternatives in order to assess whether these could possibly substitute for or complement rainfall simulation. It is argued that this approach best meets the objectives set out, in both allowing for a relatively rapid assessment of the spatial distribution of infiltration in the study area while also affording some insight into the factors influencing the infiltration behaviour of these soils and the predominant mechanisms involved.

(1.7)
The implications of crusting for determining runoff potential for assessing suitability for water harvesting
Two concepts of central importance to this present study are the ideas that a) crust morphology is a function of environmental variables controlling crust genesis and b) that a crust's appearance in the field (and ideally its spectral characteristics from earth observation platforms) can therefore be linked to infiltration values. If such a relationships exist, it would potentially allow a predictive association to be established between landscape variables which occur at a scale appropriate for mapping from satellite images and the crusts which occur within those units across the landscape. This procedure has been developed in particular in the work of Escadafal (1989) for arid southern Tunisia. There is much promise in terms of assigning runoff values to a landscape from remote sensing imagery once a relationship has been established between crust types and infiltration values in a study area, as determined for example from rainfall simulation. Procedures for attaining this valuable goal in arid and semi-arid Africa have been developed in particular in the work of Escadafal et al. (1994), Puech (1994, 1997) and Lamachere and Puech (1995). In the case of Puech and Lamachere, this has taken the form of extending to the realm of remote sensing the inventory of crust morphology - infiltration relationships established by Casenave and Valentin (1989) for the Sahel. This same approach also serves as both a conceptual and practical starting point for much of the fieldwork carried out in this present study, but applied to a different semi-arid region of Africa.

In short, this study is concerned with the effects of soil surface conditions such as crusting on infiltration, but is not focussed on mathematically modelling this relationship, as it is more engaged with the problem of the identification, classification and mapping of crusted runoff producing hydrological units in the context of environmental survey, specifically in order to map infiltration and hence runoff potential.

(1.8)

Research approach taken

- Establishing an inventory of crusting soils in a study area
- Definition of these surface states in terms of the effects of sealing, using rainfall simulation
- Assessing the potential of remote sensing and GIS to ‘upscale’ these values

Relationships between crust properties, when dry, particularly their morphology at a scale discernible at the resolution of satellite imagery, and the effects of sealing on infiltration when
exposed to rainfall, are central in this study, and also serve as a basis for the inventory of surface types in the Sahel established by Casenave and Valentin (1989). This inventory describes each surface in terms of its observable and distinctive characteristics from simple field observations, and supplies associated hydrological parameters (with a typical range for each) elucidated from an extensive and long term rainfall simulation campaign, such that the latter can be deduced from the former. The inventory attempts to systematise this relationship for commonly occurring crust forms in the Sahel, and the extrapolation of this system to another semi-arid environment, lowland Baringo, Kenya, is attempted in the present study.

Rainfall simulation is one of the most important tools by which crusting soils have been investigated. They have been widely used in both the laboratory and in the field. They are used in order to examine both the effects of rainfall characteristics on crust formation and the dynamics of sealing on a real time basis. The methodological issues concerning the advantages and disadvantages of various designs and the associated errors will be reviewed. A widely used portable 1 - 1.5m drop height design, developed at the University of Amsterdam, was employed in the first field season, but unsatisfactory results compared to a high energy 5m simulator previously used in the study area (Bryan 1994) led to the design and use of a 3.5m simulator, described in Chapter 4. The infiltration values obtained with this simulator were considered to be 'reference values' against which to compare the relative rankings of runoff potential obtained using a range of rapid, inexpensive tests developed for this study as a possible alternative to the time consuming rainfall simulation protocol. The appropriate role of each is then discussed in Chapter 8.

In addition, ways of relating the results of ground-based hydrological investigations to their spectral characteristics was attempted. Essentially, an attempt was made to determine whether the classification of the landscape of the study area in hydrological terms, based on point measurements of infiltration, corresponds to the demarcation of the same landscape into spectral classes, in particular using indices found to be useful for this purpose elsewhere in dyland Africa.

(1.9)

Study Area

The location of Baringo District within Kenya and of the study area within Baringo District is presented in Figure 1.1. As is evident from Figure 1.2, this area is dominated by Lake Baringo,
Figure 1.1
The Study Area

Study area in heavy boxed area
(after Bryan 1994)
Figure 1.2
Lowland Baringo; physiognomonic units and water management interventions

The red circles indicate the major fans, (1) being an exception, an outwash gravel plain (Logumukum), identified by an FAO survey in 1967 as a suitable area for water spreading. That same survey identified many of the fans as potential irrigation sites; of which those lettered are (pre president Moi) (b) the Pekerra scheme, and Moi era, (a) the Chemeron (c) Loboi and (d) Sandai schemes; some of which were traditional ‘shifting irrigation’ systems, amongst other locations. Another fan (2) is the site of a water harvesting scheme.
at the bottom of a drainage system from the surrounding step faulted hills to the east and west, with a number of major rivers cutting through the volcanic materials in this tectonic fault zone, carrying with them alluvial deposits which spread in classic fans on flattened piedmont slopes, dissected by gullies, around the lake. Colluvial material is interspersed with this material due to mass movement down the slopes. In terms of physiognomic units, therefore, the study area consists of a set of fans at various intervals around the lake, interspersed by the horst and grabben cliff series which reach the Lake at various place, most noticeable to the northeast. More details about the previous studies carried out in this area and about the physical environment of the region (rainfall, nature of the soil surface) will be presented in Chapter 7 in conjunction with the introduction to the rainfall simulation sites and the sampling strategy selected.

(1.10)

Overview of each chapter

Chapter 2

The objective of this chapter is to introduce the practice of water harvesting and particularly the rationale for assessing suitability for water harvesting. The rationale for developing a suitability assessment methodology derives from the potential value of this mode of soil and water conservation (SWC) to semi-arid areas. This chapter serves to demonstrate the potential value of water harvesting to these environments in terms of the effectiveness of enhancing soil moisture for a given rainfall input by multiplying the effect of rainfall by concentrating it through runoff from a larger collection area than the receiving area. Water harvesting, however, is a term which has been used in many ways by many authors. Therefore this chapter then goes on to specify the definition to be used for the purposes of this study. This is followed by a section in which a distinction is made between water harvesting and other forms of SWC, and then a discussion of issues of sustainability with respect to this practice. Finally, this chapter serves as an introduction to water harvesting projects carried out in the study area, lowland Baringo, leading to a discussion of the factors which need to be considered in a suitability assessment procedure, which in turn serves as a basis for the rest of the study. Note that the key physical processes governing water harvesting are dealt with and serve as an introduction to the subsequent chapter, on crusting and sealing and implications for runoff.
Chapter 3

This chapter focuses on the nature of crusting and the approaches which have been taken to understanding crust formation and identifying the key processes involved. The factors which influence the sealing behaviour of crusting soils receive particular attention, as it is this characteristic of crusts which is of interest to the present study. The particularity of crust sealing in terms of its expression, in various ‘classic’ and crust specific models of infiltration is also addressed, without attempting to develop a new numerical model within the scope of the present work. A distinction is made between crusting, the result of a change in the organisation of the surface and evident upon drying, from sealing, the processes which cause a reduction in infiltration during a rain event. The link between process and pattern, between crust morphology and sealing behaviour, is seen to be the key to mapping infiltration and thus runoff potential, and as such this relationship is emphasised. The implication of the nature of crusting and sealing and of the method-dependence of assessing crusting and its effects on infiltration are spelled out with a view to identifying those approaches most apt for the purposes of this study, whilst noting the limitations and caveats associated with these various approaches as revealed by the findings of and/or a critical analysis of the findings of the crusting and sealing studies reported here.

Chapter 4

This chapter, on a chronological basis, starts with an introduction to the research design, then turns to the role of simple tests as tests of the wetting effects on sealing in crusting soils, before addressing the question of rainfall simulation in some detail. Relevant properties of rainfall to be simulated are discussed, the design options for doing so compared and their advantages and disadvantages noted and then the design chosen described and its shortcomings noted with respect to an hypothetical ‘ideal’ design. The calibrations carried out on this design before putting it to use in the field are detailed and the implications of the findings discussed. The protocol employed with each of the two simulator designs used are outlined and then questions of how to validate the results addressed. Finally, general conclusions are drawn about the approach taken and the instruments employed and the implications for mapping runoff potential highlighted. This leads naturally to the subsequent chapter, where various attempts to map runoff from point measurements of infiltration are reviewed and the approach favoured in this study explained.
Chapter 5

This chapter is a combination of (a) a review of relevant attempts to ‘upscale’ point measures of infiltration in semi-arid and arid environments to spectral ‘maps’ of the landscape, in the form of optical remote sensing, together with (b) an explanation of the approach(es) attempted in this study. As a necessary background to this topic, however, one must first examine how surface controls on runoff, in the form of crust types, can be identified, classified and their distribution in the landscape mapped, as an ‘intermediary’ scale or bridge between a 0.5 or 1 m² rainfall simulation plot and the pixel size of the remote sensing imagery used (400 to 900 m²). That background work takes two forms in this chapter; first a discussion of a systematic crust classification system developed by French researchers for the West African Sahel, followed by a description of attempts by French research groups in Tunisia, the Sahel and in France to link infiltration and spectral properties in the landscape, either directly or indirectly. Similar attempts by other researchers, principally those using the French crust classification system, are also examined. The few attempts to date to map runoff potential specifically for water harvesting suitability assessment, using the French crust classification system, are described and the relevance to the present study discussed. Finally, from amongst the various options presented, those considered most relevant and practical to the present study are highlighted; the results from which are presented in Chapter 9.

Chapter 6

This chapter aims to convey a feeling of the nature of the physical environment of the study area and particularly of the ‘reference sites’, the principal rainfall simulation sites where the simple tests described in Chapter 4 were also carried out for the sake of comparison, together with and finally details of rainfall characteristics and some results from relevant previous research in this area. The reference or ground verification sites are those used in the second field season, which are mainly but not exclusively the same as those used in the first season, allowing comparison between the 1.5 m (first field season) and 3.5 m (second field season) simulations in most cases. The sites will be presented in the form of one or two plates of terrestrial photographs dedicated to each, together with the same site from aerial photography and/or satellite imagery. The physical evidence of the effects of the crust removed treatments will be included for some sites as a preview of the presentation in graphical form of these treatments in the subsequent chapter.
This chapter will also cover what is known about the rainfall characteristics of the study area, with an emphasis on those measures of relevance to assessing water harvesting suitability and calculating runoff yield. Secondary data on runoff characteristics of some of the key sites and previous work on runoff yields are also presented.

Chapter 7

This chapter presents representative results from sites described in Chapter 6, the principal sites employed in this study, sites where both the 1.5 m the 3.5 m simulators were used, and from a few minor sites not described in Chapter 6. Space does not permit a full presentation of all results, but those examined here have been judiciously selected as ones illustrating the principal findings of the rainfall simulation campaigns.

The 1.5 m simulator results are first described using a range of parameters considered relevant for the comparing between sites for the purpose of assessing runoff potential. These parameters are described and then the results of the rainfall simulations compared ‘statistically’ in scatterplots across all sites in order to highlight any potential relationships between them which would warrant further examination. All sites are then compared on the basis of common conditions – medium intensity storms, antecedent dry and crust intact – and on the basis of a number of measures of runoff potential such as time and depth to runoff, maximum runoff potential, average runoff potential and others. From these analyses the same conclusion are arrived at as when discussing the myriad possible crust definitions and classifications and the contradictions in the literature regarding crust genesis and behaviour, the model / assumption / method / measurement dependence of the results. This became readily apparent when attempting to rank sites in terms of ‘runoff potential’.

This chapter then turns to an examination of the results of simulations carried out at the same sites (or nearby, as agricultural fields expanded onto the original sites in some cases in the meantime). This is done on a site-by-site basis, and comments often made regarding differences in runoff response to the two simulators and between sites where contrasts in responses are particularly striking. Results of simulations carried out at the fenced reference site, previously used by the University of Toronto, but on a part of the site not utilised, are then reported. At this same site overland plots were set up to assess the conveyance loss cost of runoff over longer distances than could be simulated. This was done under natural rainfall, which posed some
restrictions due to the inability to monitor real time rainfall-runoff relations. As such, runoff plots were also set up at the residence and the results of rainfall and runoff measurements carried out during natural rainstorms are reported at this point in this chapter. This is followed by a general discussion of the key findings in the form of conclusions.

Chapter 8

As rainfall simulation is so time consuming, it is not possible to characterise any surfaces other than the dominant etat de surface elementaire (ESE) at each site, to use the conceptual model and terminology of Casenave and Valentin (1989), explained in Chapters 3 and 5. A major motivation in this study was, as outlined in Chapters 1 and 4, to attempt to substitute rapid, cheap and replicated measures of runoff potential for rainfall simulation. Therefore the relative ranking of surfaces (i.e. of the study sites) was compared using both measures, the results of which will be presented in this chapter. As such, it was also of interest to determine whether handspraying with a control and crust removed treatment, exactly like the rainfall simulation protocol, would highlight processes such as surface control of runoff. If they did, then the handsprayer could be considered to be a potentially useful tool when working with crusting soils. In addition, the water acceptance values of the surfaces generated by handspraying, which are essentially measures of the wetting-only effect on sealing, could be contrasted with the rainfall simulation values for the purpose of separating wetting and energy effects.

Chronologically, this chapter begins by reporting the results of handsprayer tests used to determine the variability in infiltration between the ESE’s occurring around the rainfall simulation sites, conceiving of this low energy water acceptance as a proxy measure for runoff potential. The objective of this exercise was to determine how representative the dominant (in terms of the proportion of the surface of the Etats de Surface occupied by) ESE is at each site, as the dominant ESE was chosen at each site for rainfall simulation. A concomitant objective was to determine the relative variability in infiltration with each effective pixel (200 x 200 m area) corresponding to the area around each rainfall simulation spot. This would aid in assessing whether the ES or effective pixel at each location could be separated on hydrologic criteria, which serves as a basis for a corresponding study of the separability of the sites on spectral grounds, in order that a comparison could be made between the two, which is reported in Chapter 9.
This topic is then followed in this chapter by a comparison between the rankings in runoff potential of the study sites according to rainfall simulation and according to various ‘simple’ tests, particularly the handsprayer, as well as an evaluation of the usefulness of the handsprayer to reveal infiltration trends over larger areas of the landscape, in this case along a transect towards the Lake. The potential advantage of a simple measure of runoff potential at such a scale of investigation is the rapidity of the test and thus the number of locations which can be assessed. The idea behind such an investigation is to achieve a greater representative of the variability across a study area by increasing the number of sample sites, as well as the number of replicates at each site, in order to reduce the disparity in spatial coverage between the hydrological and spectral measures. Finally, some conclusions are drawn about whether and under what conditions rapid, low cost measures of runoff potential could substitute for quantitative, high kinetic energy reproduction rainfall simulation values in the context of a suitability assessment for water harvesting.

Chapter 9

This chapter starts out with an examination of the characteristics of the ‘reference’ image, with a view to anticipating the degree of spectral variability across the study area and particularly the degree to which the bands are separated, as an indication of the ease with which the variety of surfaces can be separated. The image of the study area is then presented using the indices developed by Orstom for southern Tunisia and for the Sahel, which were found to separate areas of hydrologically distinct behaviour. The degree to which the indices appear to be worthwhile in the case of the study area is investigated.

The next part of this chapter reports the results of investigations into hypothesised relationships between spectral and hydrological variability around and between rainfall simulation sites, using the same resolution instruments and at the scale of the ‘natural’ variability of the crusting surfaces, the ‘ESE’, to use a concept developed by the French for the Sahel. This is followed by a discussion of a physiognomic approach to landscape mapping, in other words, using the same concept as the fine scale investigations, based on the ESE’s, but this time at a scale ‘visible’ with remote sensing, which corresponds to the Etats de Surface in the French system of crust classification. The ES is an association of ESE’s, and corresponds to a ‘mixel’ in spectral terms, as the hydrological characteristics of the surface covered by an effective pixel varies at a subpixel level.
This chapter subsequently addresses the issue of how to assign ‘point’ (equivalent to ESE’s) measures of runoff potential to a spectral map of the study area (a satellite image) covering the entire surface, in units much larger than the size of the rainfall simulation plots. The results of the map of runoff potential of the study area created by linking the rainfall simulation values to the imagery, according to a procedure developed for this study but based on one of the approaches taken by the French in the Sahel, is compared to secondary data on runoff potential in order to validate the method employed. A visual comparison is made between the two and then other datasets from that same study (a range management study in a GIS format) are utilised to illustrate how a suitability assessment procedure in a GIS based analytical environment incorporating various datasets would work. Finally, the resulting classification in terms of suitability for water harvesting is compared for validation to the locations chosen by various water harvesting projects for their fields and some interesting conclusions arrived at implicating the importance of social factors in an assessment methodology.

Chapter 10

The concluding chapter reviews the conclusion from chapters 2 through 9 and then ends with a summary discussion of the main findings of the study.
Chapter 2

Review of Water Harvesting

- Value of Water Harvesting
- Definition of Water Harvesting
- Advantages and disadvantages of Water Harvesting
- Water Harvesting in Baringo and factors to be assessed in this study

Chapter Outline

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Chapter Overview

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Introduction to Water Harvesting

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Why harvest water?;
Effectiveness of Water Harvesting

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Definition of Water Harvesting

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The specificity of Water Harvesting as a water management techniques

(2.6)
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Water Harvesting in Baringo

(2.8)
Conclusions
Chapter Overview

The objective of this chapter is to introduce the practice of water harvesting and particularly the rationale for assessing suitability for water harvesting. The rationale for developing a suitability assessment methodology derives from the potential value of this mode of soil and water conservation (SWC) to semi-arid areas. This chapter serves to demonstrate the potential value of water harvesting to these environments in terms of the effectiveness of enhancing soil moisture for a given rainfall input by multiplying the effect of rainfall by concentrating it through runoff from a larger collection area than the receiving area. Water harvesting, however, is a term which has been used in many ways by many authors. Therefore this chapter then goes on to specify the definition to be used for the purposes of this study. This is followed by a section in which a distinction is made between water harvesting and other forms of SWC, and then a discussion of issues of sustainability with respect to this practice. Finally, this chapter serves as an introduction to water harvesting projects carried out in the study area, lowland Baringo, leading to a discussion of the factors which need to be considered in a suitability assessment procedure, which in turn serves as a basis for the rest of the study. Note that the key physical processes governing water harvesting are dealt with and serve as an introduction to the subsequent chapter, on crusting and sealing and implications for runoff.

Introduction to Water Harvesting

Water harvesting in the arid and semi-arid tropics have often been implemented with a negligible amount of supporting research. This has been partly because donor organizations, financing institutions and government agencies were in too much of a hurry to obtain tangible results. Lack of appreciation of design criteria and of the social and economic aspects of water harvesting has frequently led to failure. Projects have been destroyed or abandoned because they have been found to be too expensive to construct or to maintain. Even where thought has been given to design, essential technical data have often been lacking. If water harvesting is to be taken seriously as a technique for improving food production in arid and semi-arid areas, and the waste of donor and government funds is to be avoided, there is an urgent need for more research. Essential missing information must be collected, and existing but unprocessed data, on rainfall for example, must be collated and analysed.
P.D. Smith (1993. pp. 156), soil and water engineer for an ultimately unsuccessful FAO water harvesting project in the study area

Water harvesting is a term which is commonly understood to mean the collection and therefore concentration of runoff from a larger area than the cropping area (Figure 2.1, a). Issues of definition and terminology and typology / classification, which in turn implicitly serve as a basis for any suitability assessment methodology, will be discussed in more detail below, however a basic distinction consists between micro and macro water harvesting. The former refers to ‘within field’ and the latter to external catchment runoff collecting areas (Figure 2.1 c for micro, a and b for macro, and d, which is ambiguous, which might be described as ‘meso’ water harvesting).

(2.3)

Why harvest water?;

Effectiveness of Water Harvesting

In terms of the physical effectiveness of water harvesting, this has been established beyond a doubt both by the use in semi-arid and arid areas around the world for at least 10,000 years, as will be seen from the review below, and by modern studies of soil water balance and yield improvements vis-à-vis in situ rainfall receiving controls. Water harvesting has always received much greater attention from practitioners than researchers, and as the ‘twain often n’er will meet’, the amount of documented research into water harvesting is remarkably small compared to both its historical importance and its current potential. One suspects that this disparity is likely due to: the lack of familiarity with the technique by researchers from temperate climates, who are more familiar with practices of in situ water conservation; the relatively large areas which would be require on-station for controlled experiments, with high costs of fencing and maintenance etc; and the research funding and publication incentive structure, which rewards process-based studies which in turn require high degrees of experimental control on a narrowly defined question at a fine scale. Until relatively recently, as well, there has been strong research and development funding in developing countries for irrigation and fertilisation, which has caused water harvesting to be overlooked.
Figure 2.1 Water harvesting systems (counterclockwise from upper left): a) Idealised system (Lovenstein 1991) DPER = deep percolation b) Macro and micro systems (Tauer and Humborg, 1992) c) Tied contour bunds used in World Bank project in Baringo (Critchley, 1987) d) Lunettes or crescents used in FAO project in Baringo (BPSAAP 1984).
The US Office of Technology Assessment, in a systematic study of promising techniques for agriculture in the Sahel, found water harvesting to be the most likely to succeed as an introduced technology on criteria of cost, technical knowledge required (OTA 1988). A major international convocation of water harvesting experts took place in Cairo in 1993 (FAO 1994), involving academics and practitioners from 13 countries and five international agencies, indicating the widespread interest in the promise of water harvesting. On purely agronomic criteria, water harvesting is an unqualified success, having repeatedly been shown to enhance soil moisture in the root zone over the growing season and as such to increase crop yield, particularly in dry years (Ben Asher 1988) when this biomass is most needed. It is important to note that the interval between (runoff producing) storms increases as the annual rainfall decreases, as can be seen from Figure 2.2.

From this figure it is apparent that for a decrease in annual rainfall from 700 mm to 300 mm results in an increase in dry spells, where a dry spell is defined as the interval between two storms of greater than 10 mm, from 11 to 18 days. Thus the lower the annual rainfall the more advantageous, ceteris paribus, is water harvesting. In practice the lower the rainfall the more that grazing rather than cropping is to be the economic mainstay, and the former implies mobility and hence a disincentive to invest in creating structures at a particular locality. In addition, there are physical considerations regarding the minimum effective catchment area as rainfall declines; and the larger the catchment area the greater the velocity of the flows generally will be, leading to risks of erosion of the runon area and the technical and economic requirements, as well as the level of social organisation required to control the runoff is substantially increased.

The study of the effectiveness of water harvesting in terms of soil moisture has been most researched in the 'cross over' area between micro water harvesting and quasi in situ water conservation, in so far as the latter involves topographic modification so as to create a runoff contributing zone. Studies of 'pure' water harvesting, particularly the well known stone lines used successfully in Yatenga, Burkina (which were a successful adaptation of an Israeli technique (Atampugre 1993), and subsequently extended elsewhere in the Sahel, have also demonstrated the effectiveness of water harvesting from an agronomic perspective. In Figure 2.2, a it can be seen that in comparison with rainfed agriculture in Mali, the plot under water harvesting quadruples available soil water, which in turn is two thirds of the figure of irrigated agriculture. The question of runoff efficiency, which is not really subject to human control at least at an economic cost, in spite of many such trials in the U.S. in the 1970's and Israel until present, is particularly germane
Figure 2.2
Considerations in assessing suitability for water harvesting
(from left)
a) Comparison of available water in root zone under three modes of water supply, Mali. Upper and lower bars represent saturation and wilting point. The extra soil water under water harvesting allows survival during dry spells in the rainy season (Klemm 1986).
b) The length of dry spells within the rainy season increase, as can be seen from this data from the Sahel, with decreasing annual rainfall; Baringo has a relatively high average rainfall of 630 mm, but with a bimodal distribution, and thus a lengthy dry spell (Tauer and Humborg, 1992).
to this present study, which is more focused on the assessment of suitability end of water harvesting than the structure design and optimisation modelling end of the water harvesting, as the latter has received far more attention than the former.

(2.3.1)
Water Harvesting as a development intervention in Kenya

the Sahelian droughts of the late 1960’s and 1970’s, with an international awareness of the problems of the semi-arid lands culminating in and promoted by the U.N. Conference on Desertification (UN 1977) held in Nairobi in 1977. This may also partly explain the widespread interest in water harvesting in Kenya, although this interest dates back to late 1950’s with the pilot and pioneering work of USAID work in Turkana and the US funded extension of the Israeli experience to Turkana in the 1960’s (Pacey and Cullis, 1986) and a UNDP / FAO funded range management survey in Baringo including an Israeli water harvesting expert (FAO 1967). The Turkana region eventually received a massive investment, much of it directed at large, mechanically constructed macro water harvesting designed by Israeli engineers, and paid for by NORAD. In spite of a tradition of indigenous water harvesting (opportunistic water spreading) by the Turkana, the project was a disaster, but a long term (> 10 year) Salvation Army water harvesting project in the same area, taking an evolutionary approach to project design and strongly based on interaction with the local water harvesting traditions, proved to be successful in this challenging (political and physical) environment (Cullis and Pacey 1992, Crichley pers. Comm., 1996).

This contrasts with the ‘engineering approach’, characterised by the need to control nature, in this case large flows of energy (floods), implied massive earth moving which was only sustainable with outside expertise and funding. As observed in Baringo and attested to by the albeit scarce literature on indigenous water harvesting traditions, a more common indigenous approach involves the dissipation of energy by water spreading, the most famous example of which are the spate irrigation systems of Yemen (FAO 1987).

(2.4)
Definition of Water Harvesting
In spite of a great diversity of definitions of water harvesting encountered in the literature, there are some characteristics common to most authors’ implicit conceptions of water harvesting, which include most or all of the following elements:

- Water harvesting consists of a relatively impermeable runoff area and a runon area, which are either physically contiguous or connected by a delivery system such as a channel, as governed by the landscape.

- Water harvesting is particularly well suited to ASAL areas as it facilitates taking maximum advantage of (the temporal and spatial) variability of rainfall in these areas. Water harvesting accomplishes this by effectively multiplying the rainfall falling in situ by concentrating in the form of runoff the rain which has fallen on a larger area than that of the runon area. The spatial variability of rainfall inherent to ASAL areas is potentially mitigated and effectively spatially redistributed.

- Because of the ephemeral nature of the water input in ASAL areas, water harvesting systems have an important storage (runon) component, by which the moisture from a few storm events is released to the ‘crop’ over time; as such the temporal variability of rainfall is potentially mitigated and effectively redistributed.

- Water harvesting systems involve relatively small engineering works, and as such are not capital intensive and therefore potentially well-suited for developing countries.

To summarise from two authoritative reviews of water harvesting:

‘...rainwater harvesting is a method to induce, collect, store and conserve local surface runoff for agriculture in arid and semiarid regions’

(Ben-Asher, 1988 p.4)

‘Concentrating runoff water allows agricultural activities in areas in which otherwise no such activities could take place...The amount of water that can be collected during a rainfall event depends on rainfall characteristics such as quantity, intensity and distribution, and on the generating area such as size, geomorphology and surface characteristics. The main difference between runoff irrigation and conventional irrigation is that the timing and amount of the application cannot be determined a priori. The variability in available water can be minimized by adjusting the size of the plots receiving runoff...’
As in the case of terminology, there are as many classification systems for water harvesting as there are authors attempting to classify it; nonetheless there are not a great number who have attempted to go beyond a brief descriptive statement to a ‘systematic’ classification. Even in the case of these authors, however, the criteria on which the classifications are based are rarely explicitly stated. The organising principle, however, can generally be deduced by studying the classifications. The classifications are all environmentally deterministic, however different aspects of the environmental parameters seen to be controlling water harvesting are emphasised in different classifications. These include:

- the type of flow
- the size of the catchment
- the technique used to control the runoff and/or runon water
- the nature of the storage system
- the slope
- the use of the water.

See Plate 1 (in Chapter 1) and Plates 2 and 3 for photographs of some of these systems in Baringo

(2.5)
The specificity of water harvesting as a water management techniques

The specificity of water harvesting is sometimes disputed, as it shares many characteristics in common with other soil and water conservation (SWC) techniques. The main distinction between the two sets of practices, at least in theory, is reflected by the terms themselves; water harvesting is primarily, and usually exclusively, concerned with water, whereas SWC typically focuses on
Plate 2 Results of some water harvesting projects

a) (above) Bund breakage at World bank site, marked by vegetation growth

b) (below) Water retension marking flattened contour bunds of FAO project

c) (above) Dead trees on FAO water harvesting scheme, possibly due to disease
d) (below) Water retension marking flattened mini crescent bunds of FAO project
Plate 3  Water harvesting plots of the RAE project

a) (top) RAE tied contour stone bunds, east of Lake Baringo b) (middle) RAE field with earth contour bunds at Ongata Mara, dry season, showing contrast with surrounding area c) (bottom) As above, but wet season
soil conservation and the prevention of erosive flows of water. In practice the two may become synonymous. For example, in the case of the study site, Bryan et al. (1994), in a study of erosion, concluded that the most effective way of reducing soil loss is through the use of water harvesting, as it a) provides the soil moisture necessary to re-establish the ground cover, which impedes soil detachment by raindrop impact and b) because water harvesting structures break up overland flow, the transport component in the (hydraulic) erosion process.

(2.5.1)
Advantages and disadvantages of water harvesting in comparison with SWC

The principal disadvantage of water harvesting vis a vis in situ SWC practices is higher labour demand in the form of the preparation and maintenance of structures, at least in the case of many macro water harvesting systems, as they involve the management of large, erosive flows, and hence a major investment in earth works. This will be seen to be a significant factor in terms of the water harvesting projects in Baringo. The principal advantage of water harvesting, clearly, is that more water is potentially made available to the rootzone of the soil. The advantages of this are obvious, but include:

1) Significant effects of immediate interest to the local resource user:

- Higher yield per crop, as a function of the particular crop response to the extra increment of water (FAO 1986); and higher total yields by allowing for a higher planting density and (Tabor 1995) extending the growing season by making use of any light early season rains and potentially providing sufficient soil moisture to bridge the first and second rains; this also allows a spreading of the labour demand peak;

- Biomass production possible even in very dry years when rainfed cropping fails (Ben-Asher 1988, Reij et al. 1988);

- Potentially more profitable because the prices of cereals and stalks (for fodder) increase in drought years, when it may still be possible to produce biomass under water harvesting (Tabor 1995)

2) Longer term benefits (Brady 1984, Rowland 1993):
• More efficient use of often limited soil nutrients (where efficiency is defined as uptake per unit water or biomass); including fertilizer (organic or inorganic)

• Greater nutrient cycling and the building up of soil organic matter due to increased root biomass and litter, increasing soil water holding capacity

• Greater possibilities for intercropping, allowing, for example, legumes in addition to cereals, increasing nitrogen input into the soil system, although it should be noted that legume nodulation can be sensitive to dry spells between storms, as was discovered by this author in southern Tunisia at the periphery of oasis irrigation systems.

• Intercropping tree and cereal crops, whereby the trees exploit deep soil water input during large runoff events which is beyond the crop rootzone, thereby increasing diversity of and total yield, in part by providing the crops with a reduced evaporation demand microclimate (Lovenstein et al. 1991)

• Nutrient input, transported with runoff waters, in the form of silt (Stroosnidjer pers. Comm., 1995) and manure (Roose 1994), an often overlooked benefit

The advantages and disadvantages of particular water harvesting systems will not be dealt with in this study, as this work is more oriented towards general principles from which suitability guidelines can be deduced as part of a suitability assessment methodology. There are a number of technical manuals and publications on water harvesting which are available (if one is lucky enough to be able to get a copy of one) for this purpose (cf. Critchley and Siegert 1991.)

(2.6)
Sustainability of Water Harvesting

Issues of environmental sustainability, which should serve as criteria in any suitability assessment procedure but which are poorly covered in the water harvesting literature, include:
• Possible leaching of nutrients over time due to large storm events (Stroosnijder pers. Comm., 1995), although this can be mitigated by careful selection of bund height and thus ponding depth. In soils with low cation exchange capacity and hence a low total nutrient 'storage' capacity, as in much of the Sahel (Tabor 1995), this could be a major risk. Although no work has been done in this area to one’s knowledge specifically for water harvesting, the appropriate calculations could be made for a particular site and such chemical data should be collected at the detailed end of a survey exercise. In a situation of excess leaching a lowering of pH could occur, eventually out of range of some cereals (Brady 1984) depending on the initial pH. Initial pH can be tested at low cost in potential runon areas as part of a suitability assessment procedure.

• Possible salinisation or alkalinisation, either in the case of runoff waters which pick up salts as they flow over the soil surface (for macro water harvesting systems) or in the case of soils with high initial exchangeable sodium. Furthermore, in the case of soils with a low CEC and high initial ESP, leaching could cause an increase in the ESP to toxic levels for more sensitive crops. These are familiar considerations in assessing suitability for irrigation (FAO 1985, FAO 1986, Landon 1991), and indeed the large volume of research on irrigation suitability and management can be drawn upon when creating guidelines for land evaluation for water harvesting. The suitability of the study area for irrigation is detailed in Gerrits (1994), which concludes that there are pockets of saline soil scattered throughout the Njemps Flats, requiring laboratory analysis before any major work should be carried out. Indeed, in certain areas salt efflorescence was observed by the present author, which was also very apparent in the satellite imagery (but not the aerial photography).

(2.7)
Water Harvesting in Baringo

The disappointing results of some of these projects are evident from Plate 2, partly attributable to technical problems but more a case of abandonment due to inadequate or nonexistent assessment of socio-economic suitability before commencing. A more successful system to date, that of the RAE (Rehabilitation of Arid Environments) approach (1,200 ha planted between 1989 and 1993; www.kenyaweb.com/kenyagov/landrecl/ba_landr.html) is represented in Plate 3.
According to a World Bank funded range study tour:

Baringo Fuelwood and Fodder Project [now RAE]. This project was totally rehabilitating hundreds of hectares of devastated rangeland, and thousands more in the works. During our wide-ranging study tour we had everywhere seen demonstration plots and numerous 'proofs' that rangeland can be turned around, but this project provided one of the few concrete examples of such a process on a practical scale.

Kuchar 1990 (pp.1)

The RAE project is particularly interesting, as it has been running for almost twenty years, and yet only recently does a breakthrough in sustainability appear to be within sight. Similar time frames were involved in other ‘classic’ water harvesting successes such as the Salvation Army project in Turkana (Cullis 1994) and Oxfam project (Atampugre 1993) in Burkina Faso. This implies that assessment of suitability for Water Harvesting is not a straightforward and purely technical procedure; although this study will focus on identifying the key hydrological variables to be assessed and the most appropriate ways of doing so, it must be borne in mind that any water harvesting project takes place in a certain historical, socio-economic and political setting. In the next chapter this study will start from the environmental, particularly hydrological, controls on water harvesting and how to understand and assess the effect of these processes for the purpose of mapping runoff potential in a semi-arid area characterised by crusted, sealing soils.

(2.7)

Conclusions

In terms of the physical effectiveness of water harvesting, this has been established beyond a doubt both by the use in semi-arid and arid areas around the world for at least 10,000 years, and by modern studies of soil water balance and yield improvements vis-à-vis in situ rainfall receiving controls. For the purposes of this particular study, a working definition of water harvesting has been proposed which is based not on a description of particular systems but on common physical bases underlying their operation, which are common to most if not all practices covered by the term. Such a process-based approach, it is hoped, can relate water harvesting to a land suitability assessment methodology, which itself is predicated on an understanding of the environmental requirements necessary for the successful (on technical criteria) implementation of a water harvesting programme.
The runoff efficiency of soil surfaces, which is not really subject to human manipulation at an economic cost, in spite of many such trials in the U.S. in the 1970's and Israel until present, is particularly germane to this present study, which is more focused on the assessment of suitability of water harvesting than on the structure design and optimisation modelling side of research into water harvesting, as the latter has received far more attention than the former. Given that runoff efficiency is not normally subject to alteration at an economic cost, the prediction of runoff from small surfaces throughout a study area is essential for planning micro water harvesting. The determination of both the fact of and relative degree of runoff and possibly (at a detailed stage in the suitability assessment procedure) the absolute amount of runoff are components in predicting runoff. Ways to determine these parameters will be discussed throughout this study.

Furthermore, as it is not possible to sample every location in a landscape, it is also important to investigate options by which runoff potential can be mapped for a continuous surface, which are reviewed in Chapter 5 and the most attractive option applied to the case study, as reported in Chapter 9.

In focusing on ‘technical’ aspects of suitability assessment, it must not be forgotten that water harvesting, as a production system within a real world social context, has implications that extend well beyond hydrologic and agronomic considerations. Ideally these factors should be operationalised in a suitability assessment methodology, with suitability of a given physical and social environment matched to the opportunities and constraints presented by each particular water harvesting system, and classified in these terms. To create such a ‘universal’ typology, however, would be utopian given the multifarious combinations of the various relevant factors. The scope of work of this particular study is focused on the environmental side of determining suitability.

In spite of apparent confusion about what exactly constitutes water harvesting, the definitional variety reflects a great strength of water harvesting; the simplicity of the concept and the relatively low cost of the technique, resulting in a profusion of systems adapted to local conditions. The nature of indigenous water harvesting in particular is important in appreciating the issue of adapting to local conditions, which is understood in this study to represent the essence of land evaluation, yet relatively little documentation of indigenous systems (in the context of the social organisation of production, in particular) exists. Again, this is not the focus of this particular study, but attention needs to be drawn to the fact that any suitability assessment,
as part of a planning process, must be related in practice to local conditions, be they environmental, social or economic.
Chapter 3

Crusting, sealing and infiltration in semi-arid environments

- Key physical processes governing water harvesting

- Crusting soils in semi-arid environments: a review of the anglophone and francophone literatures

- Methods of assessing the effects of sealing; rainfall simulation

- Implications for runoff assessment and for the research design and methodology used in this study

Chapter Outline

(3.1)
Key physical processes governing water harvesting

(3.2)
Crusting, sealing and infiltration; An overview of this chapter

(3.3)
The phenomenon of crusting as a characteristic feature of soils in semi-arid areas; geographical distribution

(3.4)
The implications of crusting for predicting runoff yield:
Models of infiltration into crusting soils

(3.5)
Recent process based simulation models
(3.6) Crusting: Definitions, Mechanisms and Methods of investigation

(3.7) Classification of crusts

(3.8) What is a crust?; A 'functional' perspective: hydraulic properties; the approach taken in this study

(3.9) Rainfall simulation. A key tool to investigate the 'functional' definition of crusting soils; quantifying hydraulic properties

(3.10) Mechanisms of crusting and sealing

(3.11) The definition, model and method dependence of results; implications for research design

(3.12) What is a crust? Some tentative conclusions

(3.13) Temporal dynamics of crusting and implications for mapping crusting soils

(3.14) Conceiving crusts as transient entities over time and space

(3.15) Crust transformations and implications for mapping runoff potential over time and space
(3.1)
Key physical processes governing water harvesting

(3.1.1)
The importance of the nature of the runoff surface

Explicit consideration of the nature of the runoff surface was found in very few classifications of water harvesting systems encountered in the literature, which is extraordinary given the central role (as will be discussed) of the soil surface in semi-arid areas in generating the runoff upon which water harvesting is based. This is a more important consideration in the case of planning small water harvesting systems than with large systems based on channel flow, as in the latter case the existence of channels is evidence of areas of sufficiently impermeable surface feeding the channel system. In the case of small surfaces, on the other hand, it is difficult to know a priori whether a surface would generate runoff under rainfall. Therefore the prediction of runoff from small surfaces is essential for planning micro water harvesting; determining both the fact of and relative degree of runoff and possibly (at a detailed stage in the suitability assessment procedure) the absolute amount of runoff. Ways to determine these parameters and the context within which each is assessed will be discussed in this chapter as well as in chapters 4, 5 and 6.

(3.1.2)
The partial area contribution phenomenon

In small catchment water harvesting systems, as defined in Ben-Asher et al.'s (1985) classification, runoff which starts in third or fourth order channels typically suffer from high infiltration losses en route, as the channels in which they are concentrated are either non crusted or the crust is broken up by the turbulent flow and debris carried with it. In other words, runoff yield is affected by the partial area contribution (PAC) phenomenon, which in semi-arid areas refers to the fact that not all areas of the potential catchment contribute to the runoff which arrives at the runon area. This phenomenon is implicit in any classification of water harvesting systems which distinguishes between them on the basis of the size of the catchment area.

PAC is an extremely significant phenomenon for larger water harvesting systems; the implications of PAC for water harvesting and in particular for water harvesting planning will be
returned to when discussing the results of attempts to upscale in the mapping of crusted surfaces in semi-arid areas. PAC is caused (Tauer and Humborg 1992), in semi-arid areas, by a combination of (a) varying degrees of impermeability (relative runoff potential) between different areas of the catchment) and (b) the probability, due to the typically compact size of convective rain cells in semi-arid areas, that rain will only fall on a portion of a larger catchment. The implications for ‘upscaling’ runoff values from rainfall simulation plots should be apparent if the PAC phenomenon is not taken into account. This issue was addressed in this study by setting up plots of various length under natural rainfall, which is discussed in Chapter 4.

(3.2)

Crusting, Sealing and Infiltration; An overview of this chapter

This chapter focuses on the nature of crusting and the approaches which have been taken to understanding crust formation and identifying the key processes involved. The factors which influence the sealing behaviour of crusting soils receive particular attention, as it is this characteristic of crusts which is of interest to the present study. The particularity of crust sealing in terms of its expression, in various ‘classic’ and crust specific models of infiltration is also addressed, without attempting to develop a new numerical model within the scope of the present work. A distinction is made between crusting, the result of a change in the organisation of the surface and evident upon drying, from sealing, the processes which cause a reduction in infiltration during a rain event. The link between process and pattern, between crust morphology and sealing behaviour, is seen to be the key to mapping infiltration and thus runoff potential, and as such this relationship is emphasised. The implication of the nature of crusting and sealing and of the method-dependence of assessing crusting and its effects on infiltration are spelled out with a view to identifying those approaches most apt for the purposes of this study, whilst noting the limitations and caveats associated with these various approaches as revealed by the findings of and/or a critical analysis of the findings of the crusting and sealing studies reported here.

The investigation technique to be prioritised in the present study is rainfall simulation and as such a large number of rainfall simulation based crusting and sealing studies are included in this review. Other modes of investigation, which are seen as possible alternatives to rainfall simulation, which have been utilised in or adapted for or devised for the present study of runoff
variability in lowland Baringo are introduced here, with further details and calibrations to be presented in the Methods chapter. The temporal nature of crusting is addresses, and the implications for the time limited validity of any survey of crusting surfaces. The potential advantages of remote sensing as a monitoring instrument in the face of the dynamic nature of the surface of the soils of semi-arid environments are presented. The issue of the scale of investigation and of spatial variability in crusting and infiltration is introduced. The implications for the development of a crust classification system of the dynamic nature of crusting soils and of the method dependence of the difficult-to-observe sealing phenomenon and of the crusting and sealing model implied in the definition of a crust are discussed, with the preferred crust classification system being referred to, to be described in more detail in the Methods chapter.

(3.3)

The phenomenon of crusting as a characteristic feature of soils in semi-arid areas; geographical distribution

As this study concerns the mapping of runoff potential in semi-arid environments for the purposes of assessing water harvesting suitability, and as infiltration and runoff occur at the interface between the atmosphere and the soil, the surface of the soil, the widely reported phenomenon of the crusting and sealing of this interface in soils in semi-arid environments must be of relevance to the issues of infiltration and runoff. Ben-Hur et al. (1985) report that crusting is a widely occurring phenomenon, particularly in arid and semi-arid areas. It also occurs in temperate environments, although the mechanisms responsible may be different, as will be seen when reviewing crust classification systems, due to the lengthy periods which the soils remain moist, unlike in semi-arid zones. In short, and crudely summarised, crusting in temperate climates is the result principally of slaking, of the gradual loss of aggregate stability through the gradual wetting of the soil in environments of low intensity low energy rainfall and where the length of the rains, the interval between rain events, and relatively weak solar radiation. In contrast, in semi-arid environments in the tropics, crusting is primarily due to the kinetic energy of rainfall; the sudden destruction of the structure of the soil surface under high intensity high energy bursts of rainfall and the lack of the buffer effect of vegetation.

The following geographical survey is in no way intended to be comprehensive, nor is there any benefit to be gained from compiling an exhaustive list without integrating these studies into a
comparable format in the form of a standardised crust classification procedure (such an attempt has been made (Bresson 1995), and will be examined later). The following list is a selection of studies intended to illustrate the geographical spread of this very important phenomenon. In the Low Counties, crusts have been noted and studied by Mucher and De Ploey (1977) and by Poessen (1985); and in France (Boiffin 1984, Le Bissonnais 1988, Bresson 1995).

In the USA, across a wide range of climatic conditions, crusts have been observed; indeed, the effects of this phenomenon was first noted here (Duley 1939). In Israel crusting soils have received a great deal of attention and from an early period (Hillel 1969, Agassi et al. 1981, Mualem et al., 1990, Agassi et al. 1981, Patrick and Berliner 1993, Berliner and Ben-Asher 1994). The sealing process which explains the effects of crusting on infiltration was first observed at a microscopic scale in Australia, and has received widespread attention there because of the importance of agriculture to the economy and the problems of ‘hardsetting soils’, a particular form of crusting quite different from crusting elsewhere (McIntyre 1958, Tongway 1994, Hairsine and Hook 1994, Bresson 1995).

The principal focus of the present study is arid and particularly semi-arid Africa, and there is a great amount of evidence of the central importance which crusting plays at the crop level water balance as well as at higher scales of analysis. In the Sahel, where the work on crusting (Casenave and Valentin 1989) serves as the launching pad for the work of the present study was carried out, but many related studies on erosion have been carried out. In southern Africa there is also much evidence of the importance of crusting, cf. Metelerkamp (1974) and Elwell (1986) in Zimbabwe and Bowyer-Bower (1993) in Swaziland.

In North Africa, particular attention in the present work has been paid to Escadafal and Fedoroff (1989) and Escadafal (1989) and Escadafal et al. (1994, 1996), who developed the concept of the ‘Etats de Surface’ or soil cover complex in the particular context of arid environments, which has proven so central to the understanding of runoff processes in this zone and a key to mapping such environments in terms of runoff potential by using them as a link between the hydrological and spectral classifications of the landscape. The presence and hydrological and geomorphological significance of crusting in the study area of the present research, lowland Baringo District, Kenya, has been indicated by the work of the University of Toronto / Moi University soil erosion research programme, the principal results from which are presented in Bryan (1994).
The implications of crusting for predicting runoff yield: Models of infiltration into crusting soils

Two concepts of central importance to this present study are the ideas that a) crust morphology is a function of environmental variables controlling crust genesis and b) that a crust's appearance in the field (and ideally its 'appearance' from earth observation platforms) can therefore be linked to infiltration values. If such a relationships exist, they would potentially allows a predictive association to be established between landscape variables which occur at a scale appropriate for mapping and the crusts which occur in that landscape element. This procedure has been developed in the work of Escadafal (1989) and Escadafal et al. (1994, 1996), which will be examined in more detail in the Methods chapter as regards the potential for mapping infiltration from remote sensing. There is promise in terms of ground verification remote sensing imagery once a local relationship has been established between crust types and infiltration values as determined from rainfall simulation. This procedure has been developed in particular in the work of Escadafal et al. (1994), Puech (1994) and Lamachere and Puech (1995), extending to the realm of remote sensing the 'catalogue' of crust morphology - infiltration values assembled by Casenave and Valentin (1989) for the Sahel. This latter approach also serves as both a conceptual and practical starting point for much of the fieldwork carried out in this present study.

This study is concerned with the effects of soil surface conditions such as crusting on infiltration, but is not focussed on mathematically modelling this relationship, as it is more engaged with the problem of the identification, classification and mapping of crusted runoff producing hydrological units in the context of environmental survey, specifically in order to map infiltration and hence runoff potential. Nevertheless, the question of modelling infiltration into crusting soils deserves some attention in any study on crusting and runoff assessment, as the two are clearly linked by infiltration, and this process, or more precisely the result of this process needs to be described quantitatively as a basis for calculating potential runoff yields from various hydrological response units making up the landscape under consideration.

Hence, the modelling of infiltration into crusted soils will only briefly be reviewed below, and in so far as it is of relevance to the objectives of the present research. Ideally, from the point of view of this study, such models would require data which are readily collectible in the field.
without expensive apparatus, are sufficiently accurate in their prediction of runoff behaviour under different rainfall intensities, and which account for differences in behaviour between a variety of crusted (and non crusted or crust damaged, as in small stock trampling) surface types. None of the models examined (not all are reported here, apart from the most widely emulated) explicitly account for the large variety of possible crust types (many do not even mention this issue); however the classic empirical models reviewed implicitly accommodate this variability through calibration of their parameters, whilst process based models account for crust to the degree that they have adequately modelled the processes involved.

There has been surprisingly little work specifically directed at adapting infiltration theory to account for a sealing effect, perhaps because of the complexity of the multiple variables involved and their interactions, which makes it difficult to isolate the key controls, although this is changing with the advent of powerful personal computers. In addition, the fact that sealing develops under unsaturated conditions further complicates the objective of modelling. In this study the net effects of this sealing phenomenon, namely infiltration and thus runoff, is the principal data of interest, and hence seal formation for practical purposes is taken here to be proportional to and expressed by the decay rate of the infiltration curve.

(3.4.1)

Conceptual and numerical models of infiltration: the ‘classic’ models

In temperate environments, the infiltration rate into soils are generally considered to be controlled by the soil water capacity, which is essentially a function of soil texture and soil depth (Baver et al. 1972). The rate of decrease in infiltration in soils with a good structure is a result primarily of the decrease in matric potential as the soil moves to a saturated state (Figure 3.1, a). The infiltration rate for a particular soil texture and depth, subjected to rainfall of various intensities, results in various initial infiltration rates (= the rate of rainfall application, up until the moment of ponding), but eventually all the infiltration curves will tend towards one, final, minimum infiltration rate, which is a stable and characteristic of this soil type, the saturated hydraulic conductivity (Figure 3.1, b). The bounding values of this set of curves in known as the infiltration envelope. This relationship is expressed as infiltration as a function of time in a number of well known equations such as those of Kostiakov (1932), Green and Ampt (1911) Horton (1940) and Phillips (1957); some empirical, and some mechanistic models of infiltration.
Figure 3.1
Standard model of infiltration applicable to temperate environments

a) The stages in the infiltration process for an idealised infiltration curve; pre-ponding infiltration until the ponding point is achieved resulting from an ever diminishing soil water storage capacity, the excess rainfall generating runoff, with the balance infiltrating at a declining rate minus surface water detention due to surface roughness, 'non-pond' infiltration. The ratio of runoff:infiltration increases asymptotically until the infiltration rate equals the saturated hydraulic conductivity, a characteristic property of the soil. (Bowyer-Bower 1989)

b) An idealised infiltration envelope, characteristic for a given soil; irrespective of the intensity of the rainfall, a final, common steady state infiltration rate equivalent to the saturated hydraulic conductivity of the soil would eventually be reached, albeit following a curve the rate of decline of which is proportional to the rainfall intensity. (Smith 1972)
There is much debate about the conditions under which these equations are valid, but this will not be addressed here apart from examining the relevance to crusting soils. Horton (1940) was the first to recognise the importance of surface features on infiltration and to model their infiltration. His infiltration equation often accurately describes the infiltration decay function commonly observed in the field with such soils in this empirical model, with the exponent alpha (which will be referred to in this study as 'Horton's alpha', which is proportional to the rate of decay), proving to be highly correlated in the present study on crusted soils in Baringo to other infiltration parameters. A number of influential models of infiltration into sealing soils are based on the Horton equation.

Green and Ampt (1911), on the other hand, produced an equation based on a mechanistic model of infiltration incorporating a number of simplifying assumptions, mainly that the soil in the wetted region has constant hydraulic properties and that the matric potential head at the wetting front is constant. Phillip, in turn, (1957) showed that the Green and Ampt equation is a special case of the general analytical solution of infiltration from a ponded surface into an infinitely deep homogeneous soil, even though it was formulated before the development of the Richards equation. Many models of infiltration into sealing soils are also based on the Green and Ampt equation.

(3.4.2)
The applicability of the 'classic' infiltration models to crusting soils

In semi-arid environments, in contrast to the assumptions underpinning some of the models described above, infiltration rates into the soil is typically surface controlled due to the low permanent vegetation cover, resulting in low organic matter and hence poor structure as well as lack of a buffer for rainfall energy. The rate of decrease in infiltration in soils with a poor structure is commonly due to changes in soil structure at the surface, also known as crust formation or sealing. The hydraulic conductivity of the crust, then, effectively determines the infiltration rate of the soil profile (Baver et al, 1972). Almost certainly the most commonly used approximation of this latter phenomenon is that of Morin and Benyamini (1977), which is a Horton-type equation substituting cumulative rain for cumulative time as the independent variable.
The infiltration curve, however, has also been shown to be a function of rate of rainfall application, rainfall intensity, both in terms of the initial infiltration rate, as in the storage saturation models of infiltration, but also in terms of the final (or, more accurately, steady state or equilibrium) infiltration rate (Bowyer-Bower 1993); see Figure 3.2, based on work in semi-arid Swaziland. This finding has important implications in terms of the ability to compare between crusted soils in terms of relative runoff capability unless the rainfall simulations used to assess all the surfaces concerned can be maintained within a narrow intensity window. Bryan and Adar (1980), however, working in the Negev, highlight the importance of geology and surface characteristics in determining differences in runoff between sites in these environments.

A review of 36 ‘authoritative’ studies on runoff (not focused on semi-arid environments and therefore mainly of temperate environments) (Seyhan 1982) reveals that the parameters most commonly found in these rainfall-runoff models are drainage area, peak discharge and channel length, in that order, with some form of rainfall intensity measure being included in 15 of the 36 models and soil type included in only 2 of the models. The soil surface is not a category, but surface and channel roughness is featured in 8 models and, of relevance to the present work, 9 models included soil permeability or imperious / pervious areas as variables. Although somewhat dated, this review indicates that little emphasis has been directed specifically at crusting in the mainstream modelling world.

Horton-type model is the favoured approach in the present study, with the caveat that the specific conditions of the surface must be characterised at the various sites investigated, as has been the protocol of this work along the lines of the system of Casenave and Valentin (1989), to be discussed in more detail in Chapter 5. The emphasis on the specific nature of the surface derives both from the hypothesis that it is the organisation of the surface which principally explains infiltration in semi-arid soils and from the objective of linking process and pattern, and at various scales from field to satellite pixel, in order to map hydrological behaviour from morphology (field scale) and from spectral characteristics of the surface (‘earth observation scale’)

(3.4.3)  
Some ‘Horton-type’ models

In 1970 Seignen and Morin proposed an influential Horton-type model of surface sealing into a bare, saturated soil for laboratory conditions under simulated rain, where the rate of change of
Characteristics and mechanisms of infiltration in semi-arid environments

Infiltration curves under rainfall simulation in the lowveld of Swaziland. This figure illustrates the fact that, for semi-arid environments, not only is the time-dependence of the infiltration curve related to the state of the surface, but the steady state infiltration rate or saturated hydraulic conductivity as well; this is not, in fact, a characteristic of a soil (a particular soil texture), but rather a function of the state of the surface of that soil at a given moment in time as well as rainfall intensity.

(Bowyer-Bower 1993)
surface properties is proportional to the surface not yet affected by rain drops, represented by a constant, \( a \), which is dependent on soil and drop characteristics. The model is predicated on a process based but simplifying and likely unjustified assumption that the first rain drop which hits a point on the surface will switch the hydraulic conductivity from an initial value \((K_i)\) to the final, saturated hydraulic conductivity of the crust \((K_c)\). However, the subsequent drop will temporarily switch the surface back to \( K_i \) as it opens up the crust. The original equation is as follows:

\[
K_t = K_c + (K_i - K_c)e^{-nat} \quad (3.1)
\]

where

- \( K_t \) = the average hydraulic conductivity at time \( t \)
- \( K_c \) = the final hydraulic conductivity
- \( K_i \) = the initial hydraulic conductivity at \( t = 0 \)
- \( n \) = the raindrop number flux (rain intensity)
- \( a \) = a constant

When a crust of constant thickness is assumed, the result is a Horton-like relationship between infiltration and time. The problem of assuming crust thickness was avoided by other authors (Farrell and Larson 1972, Ahuja and Ross 1983) by using seal conductance or 'resistance' (an ambiguous term not favoured in the present study) rather than hydraulic conductivity. An extension of the basic equation allowed Seigner and Morin (1970) to account for the influence of turbidity and scour to counteract seal formation, first suggested in the classic study of McIntyre (1958), by assuming that this is proportional to rainfall intensity. This assumption is an early and not widely recognised contribution towards the development of our understanding of the intensity dependence of infiltration into crusted soils. Thus \( K_t \) was seen as the sum (over space and time) of the conductivities of the sealed and unsealed (scoured) areas, where \( @ \) is a function of soil and drop characteristics:

\[
K_t = @nK_i + (1 - @n) [K_c + K_i - K_c e^{-nat}] \quad (3.2)
\]

Another not widely recognised implication of this model and its underlying assumptions is that the spatial distribution of rainfall will be critical in determining infiltration patterns, and thus that
variability in the spatial distribution of rainfall over time (i.e. between runs or sites) during rainfall simulation will potentially influence the apparent relative runoff potential of the sites so described. Ideally, therefore, the spatial distribution of simulated rainfall should be monitored over the course of a field season, if not within each run. The parameter $\alpha$ can be calibrated empirically, but its *theoretical* import is ambiguous, as it combines the key factors in crust formation, infiltration and runoff, soil and drop characteristics into a single term.

Morin and Benyamini (1977), in testing the model in practice, dropped the seal destruction component in order to simplify it. Although the model was based on the assumption of an initially saturated soil, *it was believed that it was robust enough to apply to unsaturated boundary conditions*, as is typically the initial state in semi-arid areas, as long as there were several orders of magnitude difference between the hydraulic conductivity of the crust and the subcrust. This is a reasonable assumption and supported by other studies which will be examined below. Mualem et al. (1990) criticise this assumption and their revision of the equation on a number of theoretical grounds which will not be engaged in here, but the basic model fits data collected from other sources (Eigel and Moore 1985). Morin and Benyamini (1977), working in an arid area of Israel, found that *infiltration curves converged when plotted against cumulative rain depth, irrespective of the initial soil conditions*. This finding contradicts the results of Bowyer-Bower (1993), working in semi-arid Swaziland, who found that, even at a given rainfall intensity, antecedent moisture conditions had a significant effect on the steady state infiltration rate (Figure 3.2).

Analysing the data presented by Morin and Benyamini, however, Mualem et al. (1990) found that *different infiltration curves had to be fit to storms with different time intervals between them*, and hence attributed this to soil moisture boundary conditions, which are not accounted for in this model. It is also possible, as will be argued here and assessed as part of the present study, that this phenomenon may also be due at least in part to a qualitative change in the organisation of the soil surface itself, quite apart from questions of antecedent moisture conditions. The temporal evolution of crust types and the associated changes in infiltration (and thus relative runoff potential) is one of the major advances in our understanding of soil crusting, first noted and systematised by Boiffin (1984) on crusted loams in France and then by Casenave and Valentin for the Sahel (1989). This important issue will be discussed in more detail below, bracketing, as it does, the validity of any runoff potential survey result within temporal boundaries, a factor not often explicitly considered. This is still an area of relatively little research and few hard numbers
in terms of the timeframes involved. The present research, however, will demonstrate the relative variability within one rainy season.

Morin and Benyamini (1977), in an important and influential model, make seal development a function of cumulative rainfall and include intensity as a variable, to allow for application to different rainfall events. They also make the equation an explicitly Horton-type relationship:

\[ q (I \times t) = q_f + (q_i - q_f) e^{-\& t} \]  

(3.3)

where

- \( q_i \) = initial infiltration rate
- \( q_f \) = final infiltration rate
- \( I \) = rainfall intensity
- \( \& \) = a constant
- \( t \) = time

Another important variant of the basic Seigner and Morin (1970) model, the work of Linden et al. (in Moore 1981) was to replace the constant (a) with a ‘soil stability factor’ (S) and cumulative energy, the units of S being area per unit rainfall energy, calculated from Wischmeier and Smith (1958). Brakensiek and Rawl (1983) then added the factors surface roughness and crop cover. None of these models, however, attempted to model a system where the seal is in the process of formation, nor under various conditions of seal soil moisture content. On the latter point, Sloneker and Moldenhauer (1974) demonstrated the influence of matrix potential on sealing; they found, again, that this was a function of the interval between rain events; the longer the interval, the greater the kinetic energy required to attain steady state infiltration. Furthermore, even once ponding has occurred, Morin et al. (1981), showed that seal formation continued to increase as the depth to the phreatic level increased, which they attributed to subseal suction assisting seal formation. Finally, one could question the assumption of a unique relationship between hydraulic conductivity and energy applied, as the work of Romkens et al. (1985) found that k at incipient ponding, which occurred at approximately the same cumulative energy levels regardless of the rainfall intensity, was directly related to the intensity of the rainfall. The comparison between infiltration results on the basis of cumulative (in relative – proportional to cumulative
rain depth, in the case of a comparison between events using similar rainfall intensities - or absolute units, otherwise) was also carried out, where relevant, in the present study.

(3.5)
Recent process based simulation models

With the advent of powerful computers, modelling of infiltration into sealing soils now focuses more on numerical solutions of the Phillips equation, such as the Soil Water Infiltration and Movement ('SWIM') model (Bristow et al 1994, Ross 1990). See also the dynamic model of Hairsine and Hook (1994) (Figure Group 3.5). As an example of the potential of this new class of models, SWIM is designed to account for:

- Layered and gradational soils
- Unsaturated conditions
- Surface ponding
- Runoff removed from the system
- Sealing (as a function of energy)
- Variable intensity rain storms

These simulation models are not reviewed here because the data requirements are so great to run them that they are not practical in the context of rapid environmental survey. On the contrary, simple curve fitting provides a rapid way to approximate the key relationships in the system for a particular site under particular conditions, which is the objective of the approach chosen. This then allows comparison between sites and treatments, where rainfall intensity and soil surface type are considered to be the key independent variables, and infiltration and runoff the dependent variables of interest, as a function of time, cumulative rain depth and cumulative energy.

The parameterisation many of the these models is time consuming, and it will be argued that in practice crust behaviour is so complex, even for one specific type of crust, that in practice it will be more useful to map the variability in infiltration empirically using rainfall simulation or possible alternatives, together with remote sensing (aerial photography and/or satellite imagery). Hence, the focus in this study is on the use of rapid techniques to provide local values, with the emphasis on rainfall simulation and with comparisons made to quicker and cheaper alternatives to
Figure 3.3 A dynamic model of crust formation

A dynamic model of the 'circular' seal formation and erosion processes. Again a layered model, but with the key processes identified
(Hairsine and Hook 1994)
assess whether these could possibly substitute for rainfall simulation and if so with what degree of loss of accuracy in ranking relative runoff potential of various surface types (where the ranking based on rainfall simulations is considered to be the reference ranking). It is argued that this approach best meets the objectives of this study, in both allowing for a relatively rapid assessment of the spatial distribution of infiltration in the study area while also affording some insight into the factors influencing the infiltration behaviour of these soils and, with reference to the literature, the predominant mechanisms involved.

Having established the widespread occurrence of crusting in semi-arid areas, and having investigated the effects this phenomenon has on infiltration (and hence on runoff) within the context of models of these effects, it is now time to turn our attention to the nature of crust formation and the myriad ways in which crusts have been defined and classified. This will both help to identify the key controls on crusting, which would serve to inform our runoff assessment techniques, as well as confirming that, indeed, crusting is the key control on infiltration and runoff in the study area, as hypothesised; and as a basis on which to establish modes of mapping spatial variability in infiltration, which is hypothesised to relate to spatial variability in the nature of the soil surface. The dynamic and visual classification system which will serve as the basis of the present work is that of Casenave and Valentin (1989) (see Figure Group 3.5 for the temporal relationships between these crust types along an idealised unilinear evolution) will be referred to in the following discussion, but a more detailed description of the crust types will be reserved for Chapter 5.

(3.6)
Crusting: Definitions, Mechanisms and Methods of investigation

(3.6.1)
What is a crust?; Introduction and definitions

A soil crust is defined for the purposes of this study for practical purposes facilitating identification in the field as a layer at the top of the soil horizon which has a distinct appearance when the soil is dry and which is associated with reduced infiltration during water application. A soil crust is normally discernible to the trained eye, as it has a characteristic appearance in spite of having many particular forms. A distinction is made between a crust and sealing. Sealing is
Figure 3.4
Temporal changes in crusting surfaces
(counterclockwise from upper right)

a) Accelerated degradation by cattle trampling around a borehole; 2 = erosion crust, 3 = ‘aeolian’ type surface (micro dunes), 4 = gravel crust (exposed b horizon, and in this case linear erosion).

b) Implications in terms of runoff of such a transformations; possibly sometimes advantageous from the point-of-view of water harvesting.

c) Processes responsible for an idealised crust evolution sequence in a time and slope dependent model.

d) As (c), for sandy and loam soils; a ‘universal’ model combining work in France and the Sahel.

(a Casenave and Valentin 1989, b Valentin 1992, c van der Watt and Valentin 1992, Valentin and Bresson 1992)
defined here as the actual effect of reducing infiltration during the course of water application. A seal is defined for the purpose of this study as a layer with a substantially lower infiltration rate and hydraulic conductivity than soil underneath during water application.

It should be noted that crusts are not simply dry seals, as is often assumed in the literature (Bristow et al., 1994), as seals represent only a partial expression of hydrological processes that may influence soil surface morphology and properties; crust formation also involves processes of drainage and evaporation. Gusli et al. (1994) demonstrated the little known fact that during drying crusting soils undergo processes of structural transformation which may result in even lower porosity and pore continuity, and hence infiltration, than the seal. The influence of wetting and drying cycles will be returned to in the results section, as a simple, non destructive technique for monitoring seasonal changes in relative infiltration / runoff potential has been devised for this study. It should also be noted that crusts, due to their much greater thickness, have greater mechanical strength than seals.

The study of sealing involves assessing the functional impacts of this process on water movement, an aspect prioritised in this review, as this is the source of interest in crusting soils, whilst crusts have principally been studied with respect to their micromorphology and (mechanical) strength. As sealing cannot be ascertained directly from field scale observation (requiring greatly magnified depictions of the surface profile), it is precisely the relationship between sealing and crusting (where the latter is readily apparent, and has been defined as such, above, for the purposes of this study) which is of interest. The 'method-dependence' and 'definition-dependence' of the results of the studies of crusting soils reviewed here, which is inevitable given the differences in scales and processes involved in sealing and crusting, as well as the complex nature of these phenomenon, will serve as an optic with which to examine the literature on crusting, as this present study is particularly interested in the 'tradeoffs' in accuracy between various possible crust assessment methods in a real-world environmental survey context, on criteria of cost, speed and scale dependence. This will be discussed in more detail in Chapter 4.

In practice, studies of crusting soils often address the soil both during a rain event and in a dry state, with little distinction made between the seal (affecting the results of the former) and the crust (the phenomenon being observed in the latter, but resulting from the former). As mentioned already, however, there may be a change in the soil structure between wet and dry states; thus,
any relationship established, for example, between infiltration characteristics of the seal and the mechanical properties of the crust, may be misleading in terms of prediction of infiltration rates.

Therefore, in order to estimate the error involved in establishing 'one-off' relationships between crusts and sealing, a longitudinal study of crust development was carried out for one widely occurring crust type in the study area which will be reported in Chapter 7. Relationships between crust properties when dry on the one hand, particularly their morphology at a scale discernible to the naked eye, and the effects of sealing on infiltration on the other hand, are at the heart of this study, and serve as a basis for the 'catalogue' of surface types in the Sahel of Casenave and Valentin (1989), which describes each surface in terms of its observable and distinctive characteristics from simple field observations, and supplies associated hydrological parameters (with a typical range for each) elucidated from a rainfall simulation campaign, such that the latter can be deduced from the former.

The definitions chosen for crusting and sealing for the purposes of this study are intentionally functional, as the object of this study is to relate the occurrence of crusting to its implications in terms of runoff potential and hence infiltration. The assumption is made, which will be investigated in this study, that crust morphology is related to crust function (there are multiple functional effects of crusting, but this study is only concerned with the degree to which it reduces infiltration), and that morphology, at least at a certain level, is subject to useful field investigation by ocular observation. If this relationship can be established, then clearly the assessment of runoff would be greatly simplified.

The work of Casenave and Valentin (1989), as described above, attempts to systematise this relationship for commonly occurring crust forms in the Sahel, and the extrapolation of this system, directly or indirectly, to another semi-arid environment, in lowland Baringo, Kenya, attempted in the present study, without pretending to develop a systematic set of relationships for 'East African drylands' or whatever, as the Sahel programme was a heavily funded, and long term research effort involving scores of individuals, whereas the present work merely involves one researcher and two field assistants and the part time assistance of one undergraduate student. This is, however, a realistic scenario in the absence of the politically enabling research environment from which the Orstom group in the Sahel benefited, and as such is a useful example of the possibilities of local development driven research to identify and adapt to local conditions relevant approaches and findings of the well funded long term research programmes.
The issue of the definition of a crust is important for this study, as the assessment and mapping of crusted soils is contingent upon defining what a crust is and defining the bases on which to distinguish between various forms of crusting. In other words, to create some form of classification system. The section will therefore review the most relevant literature on crusting soils in the light of an interest in relating the mechanisms of crust formation to the effects on infiltration and to their properties, as identifiable in the field. As such the review of the literature will be organised principally on the basis of the method(s) employed, as it is hypothesised, as implied above, that the results are highly method-dependent, and furthermore that the method chosen pre-defines the concept of a crust for any particular investigation. Not only this, but as the present work is interested in identifying the most appropriate techniques for the purpose of rapid, cost-effective but accurate assessment of the runoff potential of various surface units, and as such the question of methodology is primordial.

(3.6.2)
Methods for assessing the effects of sealing

Rainfall simulation is one of the most common modes of investigation employed in the studies on crusting reviewed which also satisfies the criteria of field application of the present study. In investigating crusting at a more fundamental level, however, it is also necessary to relate the characterisation of crusts under these particular conditions to other perspectives on crusting made possible by other modes of investigation.

In the present research, crusts are removed from their in situ position with the use of two types of simple hand held sampling devices developed for this research, which are designed not to minimise disturbance (as this is essentially impossible unless resin impregnation is used, which is only applicable to microscopic studies of micromorphology), but rather to ensure separation of the crust from the subcrust soil. These samples were then subjected to various simple ‘field laboratory’ tests devised for the present study or adapted from other research. These test results were then compared with data from rainfall simulation, to determine whether and to what degree such simple tests could substitute for rainfall simulation, or at the very least to help explain the behaviour of these sites in the absence, for budgetary reasons, of textural, chemical and mineralogical laboratory data.
Soil samples (to a much greater depth) were also removed from the field to the field laboratory using specially designed plots the same dimensions as the field rainfall simulation plots, for observation of simultaneous rainfall-runoff relationships in the absence of automated monitoring equipment (not necessarily a disadvantage; when this author was working in Israel, data were sometimes lost from a sophisticated water harvesting monitoring experimental design due to unknown or freak problems with the data loggers, tipping buckets etc. This was also the case with the present research, however, on simple and therefore supposedly robust, 'appropriate' technology such as noninstrumented 'hillslope' upscaling validation plots: frogs deciding to live in the Gerlach trough, ants eating through the covers placed on reserve rainfall simulation plots set aside in case of the early arrival of the rains, baboons attacking the validation plots etc.,).

(3.6.3)
**Implications for mapping crusting soils**

Definitions are the basis for classification, which in turn is the basis for mapping, as well as being inextricably linked to conceptual models and defining techniques appropriated for identifying them, and as such represents the interface between the theoretical and applied aspects of the study of crusting soils.

In short, one would hope to define and therefore compare or classify crust types and assess their influence on runoff in a way which incorporates an appreciation of the mechanism involved; in other words a crust classification system predicated both on morphology and genesis. Just such a set of definitions, organised into a classification system, has been developed for the semi-arid zones of West Africa (Casenave and Valentin 1989). This system will be examined in Chapter 5 together in the context of research efforts to upscale it to the resolution available from earth observing sensors, and then explored in the study area across a number of sites to assess its applicability, as reported in Chapter 9.
(3.7) Classification of crusts

(3.7.1) Highest level classification of crusts

At a highest level of classification, crusts can be distinguished for the purposes of this study on the basis of genesis into chemical, biological and physico-chemical classes. The latter only will be dealt with here, classified along a number of axes or criteria, as the former have not been observed to any great extent in the study area.

(3.7.2) Physico-chemical crusts: the principal crust type in the study area and worldwide

Crusts which are the result of physical and/or chemical processes have been approached with a large variety of methodological protocols, each of which bears on the understanding of the processes involved and the definition and classification of crust types as well as the means by which they are identified. The following section is organised in terms of the approaches taken by the studies considered in their investigations of crusting processes, with a particular emphasis on the method-dependence of the results. These have been classed as 'micromorphological investigations' (the study of crusts in terms of their structure and changes thereof under various conditions); investigations using crust strength as a key parameter; and finally 'functional investigations', by which we mean studies of the effects of crusts on infiltration. It is this last conception of and approach to defining and differentiating between (classifying) crusting which will be favoured in this study.

(3.8) What is a crust?;
A 'functional' perspective: hydraulic properties; the approach taken in this study

The concept of crusting which is most important in this current work is that of a layer (or layers) of soil, at the soil surface, with lower infiltration rates than the subcrust horizons. The literature
on crusting essentially consists of studies of the effects of crusting on seedling emergence (in the field of agricultural engineering, not addressed in this study), the effects of crusting on and the description of the crusting process in terms of changes in soil structure, and the effects of crusting (really sealing) on infiltration. Many studies in fact combine some or all of these perspectives but generally emphasise one of them. Attention shall be focussed on those studies, and the relevant aspect of other studies, which examine crusts in terms of their hydraulic properties. This will help shed a light on the mechanisms responsible for the effect of reduced infiltration as observed at field 'resolution', thus providing a link between process and behaviour and therefore a sound basis on which to explain differences observed, in terms of infiltration, between the various crusts investigated in the present study.

The studies selectively reviewed below include both laboratory and field studies of the hydraulic properties of crusts, but are predominately the former, due to the greater control they allow. Probably the earliest study of the effects of crusting on infiltration is that of Duley (1939), who used a mulch and a control treatment to demonstrate the effects of crusting in terms of reducing infiltration (Figure 3.5, top). Figure 3.5 (bottom) presents a similar but much more recent experiment which demonstrates the kinetic energy and surface structure dependence of infiltration. Studies of mulches as a means by which to ascertain the effects of raindrop impact on crust formation are fairly abundant in the literature (cf. Duley 1939, Epstein and Grant 1973; Farres 1978), as well as specifically with respect to soil surface permeability resulting from crust development (cf. Russel 1973). One such study was also carried out for the Baringo study area (Kamar 1994).

Returning once again to the classic study of McIntyre (1958), in addition to examining the appearance of the crust in thin section, the mechanisms and effects of crusting were also investigated by measuring changes in the hydraulic conductivity through the upper soil profile. McIntyre (1958) placed tensiometers at 1 cm and 4 cm below the soil surface, from which he calculated the hydraulic conductivity of the washed in layer and surface skin by extrapolation. The resulting calculation showed that the hydraulic conductivity of the sub crust soil (ie at 4 cm) was 36 mm/hr, and that of the washed in and skin layers 200 and 2000 times less, respectively. Although important in terms of revealing a dramatic decline in the hydraulic gradient, the actual values are suspect due to the limited number of depths for which values were available.
Figure 3.5 Assessing the presence and function of crusts

(Top) The classic experiment (Duley 1939) using various mulches over bare soil to reveal the effect of direct rain impact on infiltration rates

(Bottom) A similar experiment but in the Sahel, with the critical infiltration rate (for runoff initiation) being dependent on the type of surface subjected to which the kinetic energy of rainfall is subjected. These surface types are principally defined in terms of their layering in the top few mm, which in turn is the product principally of their 'parent material' and their position in a microcatena, mirroring soil development. (Valentin and Ruiz Figueroa 1987)
The morphological and functional (by which is meant here the effect on infiltration) approaches to the examination of soil crusting can be and are indeed complementary, and have been used together in many studies. Each reveals different aspects of crust formation as well as different implications for the management of these soils. The studies of the structure of the upper layer of crusting soils signals the importance of the impact of rain drops on crust formation. The studies of crust hydraulic conductivity reveal that the sealing effects of crusting extend beyond the area of obviously compacted soil as observed in the field and even under laboratory conditions.

(3.9) Rainfall simulation. A key tool to investigate the ‘functional’ definition of crusting soils; quantifying hydraulic properties

Rainfall simulation is one of the most important tools by which crusting soils have been investigated. They have been widely used in both the laboratory and in the field (in Africa particularly the Swanson boom type (Swanson 1965), both in southern and western Africa). They are used in order to examine both the effects of rainfall characteristics on crust formation and the dynamics of sealing on a real time basis. The methodological issues concerning the advantages and disadvantages of various designs and the associated errors will not be discussed here but will be returned to in Chapter 4.

Although subject to less experimental control, it can be argued that the disturbance effect in removing soils to the laboratory has important drawbacks given the delicate and complex structure of the uppermost part of the crust as opposed to rainfall simulation \textit{in situ} in the field. But interestingly, as compared to both laboratory and field based rainfall simulation, crust thickness under natural rainfall in the field (\textit{cf.} Hadas and Frenkel 1982, Boiffin 1984) is often considerably thicker than that developed under laboratory conditions, even after prolonged rainfall at high intensities. This indicates that certain aspects of crust formation may not be active when a small, isolated core of a given sieved aggregate class, or even undisturbed but artificially bounded soil, is exposed to constant intensity rainfall.

On the boundary issue, the effect of deposition on the sealing process is hindered when there is no flow from neighbouring areas, but the threshold plot size is not known for which these effects are no longer significant. The degree to which standard one meter plots can be upscaled and the
'falloff' factor in terms of runoff yields are both important questions which will be addressed later, as well as within the experimental protocol adopted by this study, in the form of overland flow plots of various slope lengths. The effects of cumulative crust development through the course of a rainy season both due to energy input and wetting / drying cycles can, however, be simulated, although are surprisingly few studies which have done so. The temporal evolution of crusts under natural rainfall has been explored most systematically by Valentin (1981, 1986, 1992, 1994) (Figure 3.4).

(3.9.1)
Rainfall simulation to investigate variation in infiltration in a vertical plane

Quite a few studies have used rainfall simulation together with tensiometers, but the relatively slow response time of tensiometers make this questionable as a guide to the dynamic effects of rainfall (Bresson 1995), although many of these studies in any case measure the hydraulic gradient in a saturated state. Another approach taken is to monitor soil water distribution using a neutron probe (Patrick and Berliner 1993). All such devices must, of course, be calibrated carefully, and there is the additional problem of trying to isolate very shallow depth increments if the crust itself is to be examined rather than simply a two layer crust / subcrust conceptual model. Bosch and Onstad (1986) used a microtensiometer pressure transducer to improve depth discrimination, but the results were obscured by noise.

The experimental protocol typically taken in monitoring the dynamic effects of sealing is to measure various soil properties believed to indicate sealing after simulated rainfall of various durations. For example, bulk density was found by Tackett and Pearson (1965) to increase as a function of rain depth, but with the rate of growth decreasing exponentially. Similarly Farres (1978) showed that crust thickness increased during the course of rainfall as a function of the logarithm of the cumulative rain depth. Farres also introduced the interesting idea of an 'equilibrium crust', posited on his conception of the crusting process as the downward translocation of particles until the passage was physically blocked, negating any further thickening. As one might expect from the above studies, Boiffin (1984) confirmed that the void ratio of the upper soil decreases in a hyperbolic fashion as a function of time when exposed to rainfall, and this rate is greater the larger the initial porosity. This relates to the usefulness of pore characteristics as an accessible diagnostic feature both in micromorphology and in the field. Vesicular porosity, evidence of trapped gasses and hence rapid sealing and thus high runoff.
potential, was readily discernible with a magnifying glass in the present study both in profile (with some difficulty due to the millimetric thickness of the crust) and in plane view once the very top of the crust was carefully brushed away with a soft paintbrush.

(3.9.2)

**Variation in infiltration and crusting in a horizontal plane**

This orientation in variability is of particular relevance to the present study, although the vast majority of the studies reviewed examined these variations at a much finer scale than that conceived of for the present study, which operates at a mapping scale on the order of kilometres. However, this study also involves the characterisation of reference sites at the scale of the variability in ESE’s (elementary hydrological response units), on the order of centimetres, and yet of surface characteristics and runoff values integrated over the pixel size of Spot and TM (20 x 20 and 30 x 30 m, respectively; and when taking georeferencing errors into account, on the order of a hectare).

**Levy et al.** (1988) developed a micropermeameter (9mm diameter) to differentiate between various surface features formed under rainfall simulation in a crusting soil on the basis on their hydraulic conductivity. The initial state of the soil surface in terms of spatial variability in surface roughness influences infiltration both by way of uneven sealing during a rainstorm and variable microdepression storage (Larson 1964, Moldenhauer and Kemper 1969). Particularly strong sealing takes place in depressions into which particles flow from aggregates standing above the rest of the soil surface (Larson 1964). Farres (1978) found a sigmoidal relationship between seal area and rain depth, across three different aggregate size groups.

Crusting is also influenced by slope; hence micro variations in slope can partly account for variability of crusting across a soil surface. Poessen (1985) showed that crusting intensity is inversely proportional to slope, which he attributed to increasing erosion (other authors use the term scouring). Romkens et al.’s (1985) work also shows that slope inhibits crust formation. This effect will be investigated indirectly in the present work by examining crust characteristics down a shallow catena to Lake Baringo. Interestingly, crust development in rill areas was compared with inter-rill areas on a slope by Young and Onstad (1985), which confirms Poessen’s hypothesis by demonstrating reduced crust formation in the rills. In the present study, this hypothesis will be further investigated by comparing rill and interrill infiltration values. This
dichotomy between rill and interrill, extended across scales, accounts for the fractal landscape of the study area and other land systems fashioned by the regularity of water moving in response to differences in potential energy. Young and Onstad attribute the reduced crusting in the rills to the protection from raindrops offered greater water depth.

Slope, or more accurately the location occupied along micro catenas at the base of crops, was found to be very strongly correlated to crust type in the Sahel (Casenave and Valentin 1989). As the work of Kooistra and Siderius (1986) on crusts at various positions along a piedmont slopes in Burkina Faso demonstrates, there is a dramatic increase in system complexity when moving from laboratory to plot to field scale. The work reviewed above on large scale (i.e. over small areas) spatial variability in crusting prefigures the question of how to map crust distribution over larger areas, which will be examined in light of French experience in arid and semi-arid Africa.

To summarise the key implications of these studies, crust status and the associated sealing effect and hence infiltration value can be conceptually modelled to be a space and time specific condition, at given moment a the function of the relationship between factors of crust formation and factors of crust breakdown, which in turn is dependent on soil conditions, the direct effects of precipitation, the inputs of water and sediment (and therefore energy) from upslope and losses thereof downslope. During a rainstorm the crust is being repeatedly broken and reformed under raindrop impact (Patrick and Berliner 1993, Luk et al. 1993). At a micro level the system could be described as chaotic (Verboom 1991) due to the large number of factors and interactions involved and the great difficulty of isolating them experimentally Mualem et al. (1990). This does not mean, however, that on a statistical basis there are not consistent relationships which can be identified.

(3.10)
Mechanisms of crusting and sealing

The effects of rainfall on soil will be considered in the present study by conceptualising this relationship at the level of the individual drop, which will be viewed as a co-quanta of moisture and energy. Thus the effects of rain on the soil surface will be examined in the experimental design by attempting to distinguish between the constituent contributions of the moisture and energy components of the rainfall. This will be done implicitly and explicitly when comparing
different rainfall intensities under simulators with different drop heights, which along the state of
the soil surface at the moment preceding the rain event are the two key variables in the crusting
and sealing process according to the conceptual model constructed to guide this study. In
particular the influence of the rate of application (rainfall intensity) and size of the quanta (drop
height) will be investigated by comparing simulation results on a common axis of cumulative
depth (for simulations with different intensities but the same drop height), or cumulative energy
(for simulations with different intensities and different drop heights). The details of the
experimental design will be outlined in Chapter 4. For the sake of distinguishing between the
moisture of wetting effects of rainfall and the energy effects of dropping water from a height, the
literature on each will be briefly examined separately below; however, the effects of the
chemistry of the soil-water solutions may influence the apparent wetting or energy effects of
rainfall, and thus must be included in this discussion.

(3.10.1)
Wetting effects

In an air-dry state, particle attractions are mediated almost exclusively by 'gluing' agents such as
polysaccharide gums and cementing agents like carbonates and sesquioxides (Emerson 1959).
The addition of a wetting agent such as water influences the strength of the individual contact
points in the matrix structure and introduces an electric double layer at the colloid surfaces along
with surface tension and van der Waals's forces into the system (Sposito 1984). Thus it is
observed, as will be seen, that the chemical state of the soil and the wetting agent and the
dynamics of the wetting process influence matrix breakdown. This is an essential element in the
washing-in concept of sealing and in the formation of a depositional crust, issues which will be
explored below, as it releases material into the water flux, which then takes one or more of
several possible paths.

The importance of the 'wetting effect', as it will be termed in this study, is highlighted by the
work of Cernuda et al. (1954) and Panabrokke and Quirk (1957), who demonstrated that
aggregate breakdown occurs across a wide range of soils even under vacuum conditions when
exposed to rapid wetting with distilled water. The same authors also reported that aggregate
stability is strongly dependent on the initial moisture content, but even more so when immersed
under normal air pressures than under vacuum conditions; from this it is apparent that the effects
of wetting rate are due both to swelling of the finer fraction of the aggregate and to the escape of
encapsulated air, an interpretation confirmed by Trapnell and Webster (1986), working with red earth microaggregates. Studies of soils as a integral unit by Collis-George and Figuerroa (1984) indicate that pore space change upon wetting occurs predominately with the macropores, and these changes were incorporated in structural index ratios; diagnostic methods will be discussed later. The effects of macropore collapse induced by wetting, strongly reducing a soil's hydraulic conductivity and infiltration rate were demonstrated by Collis-George and Lal (1971). It is this last effect which is central to this present study and hence will be examined across a range of crusting soils in the field at different wetting rates, that is to say, at low, medium and high rainfall intensities.

(3.10.2) Kinetic energy and water chemistry

Agassi et al. (1981) concluded that crust formation is a function of both the kinetic energy and chemical properties of the rainwater as well as the chemical properties of the soil. They found that when solutions of high concentration were applied, the impact energy of the drops is the main force causing breakdown of the soil aggregates and the consequent formation of a compacted surface layer, and that the rate of sealing is relatively slow. The importance of kinetic energy as a factor in crust formation is confirmed by the results of the studies presented in Figure 3.5, just a selection of a few of many such studies which came to similar conclusions. At low salt concentrations, however, the pores just beneath the surface rapidly became plugged with chemically dispersed materials and the infiltration rate dropped off quickly, a function primarily of rainwater chemistry. With depositional crusts, which is the most common crust type (with various subclasses) in the study area, Shainberg and Singer (1985) argued that the hydraulic conductivity is strongly influenced by the state (flocculated or non flocculated) of the clay in suspension. In the latter case, the clay will settle in a manner oriented parallel to the surface of the soil, a phenomenon observed in other studies such as Chen et al. (1980), which minimises infiltration.

This effect is investigated in a simplistic way in the present study by sampling crusts from the key rainfall simulation sites, dry sieving them and then allowing a given volume of the finest fraction to stand for 12 hours. The expansion (or not) of the samples was then compared between sites and between rainwater and well water (the same water used in the rainfall simulations) treatments. This, of course, is a very different protocol from the sudden application of water to
aggregated soils (crusts) and thus simple immersion tests were also employed, using two types of water chemistry, on the largest fraction of the sieved crusts. It should be noted, however, that these are all low energy treatments, an unrealistic scenario, but the objective of this study, in part, is to assess the tradeoffs in accuracy in relative runoff rankings between sites as a result of gains in speed and cost and simplicity of such tests or other similar tests which could be devised. The key, of course, is to be aware, from a knowledge of the literature, which important processes of crust formation under natural rainfall are or are not or the degree to which they are being reproduced with a particular test. The outcome of these tests and comparison to the rainfall simulation data will be reported in the Chapter 8.

The interactions between rain energy and chemistry and soil chemistry are complex; for example, Emerson (1967), using a test adapted for the present study, showed that aggregates with clays dominated by kaolinitic mineralogy will not spontaneously disperse irrespective of chemical environment, however they are subject, of course, to mechanical dispersion. Thus interpretation of crust formation and sealing behaviour should ideally be done in the context of data about the chemistry and energy of rainwater and the water used in rainfall simulation as well as soil chemical and physical properties. Such a requirement, however, poses problems in environmental survey, particularly for survey methodologies such as the ones used in this present study, which emphasise low-cost rapid assessment for areas of relatively low economic value; semi-arid environments in developing countries. Thus one is faced with a choice of taking detailed measurements at a few reference sites or a few parameters which are both relatively quick and informative at a larger number of sites.

(3.11)
The definition, model and method dependence of results; implications for research design

As shall be seen, the definitions of and explanations for crusting by various authors are heavily dependent not just on the methods employed and conceptual models assumed, but also the particular environmental conditions predominant at the time the observations took place. Mualem et al. (1990), in reviewing a large number of crusting studies, complained that, as most studies were only interested in identifying one aspect of crusting or sealing, one would expect that the other factors would be held constant, which was not the case. As there is so little agreement
about these factors, however, this may in part be a question of 'ignorance' and in part a physical impossibility given the large number of potential variables and the fact that they are likely interdependent. Mualem et al. (1990) cogently points out that, for example, most studies of the chemical aspects of soil sealing use physical variables such as infiltration rate, conductance, particle migration and bulk density as indicators of these effects. They call for a clear distinction between dependent and independent variables, although it is not clear how this would be achieved in a complex system.

They do suggest that researchers recognise that their results are system-dependent, both chemically and physically; that the geometry and flow configuration of the experimental setup will influence the results; that initial conditions are important; and that boundary conditions dominate the flow processes and should be observed as a function of time. These suggestions are more plausible in a laboratory setting, however we shall argue that the loss of control under field studies is more than compensated for by respecting contextual factors destroyed when the soil and/or crust structure is disturbed (and, in particular, sieved, as is typical). Nonetheless, these suggestions can still be applied in the field, and in the case of this current study, as will be outlined in greater detail in the Methods section, the boundary conditions were controlled for by carrying out rainfall simulations on dry soil, except when antecedent moisture was a variable under investigation. Similarly, the effect of plot size was investigated by comparing the effects of various lengths of slope. Chemical influences were checked by comparing rainfall simulations using rainwater and well water, where the latter was the normal source of water.

(3.12)

What is a crust? Some tentative conclusions

The many apparent contradictions in the literature can probably be accounted for in part by clarifying the definition of the entities described, specifying the precise methods employed, adopting a standardised protocol in terms of the measurements taken. Bresson and Valentin (1994), in their review of 50 studies of crusting referred to earlier, were unable to make a statistical comparison because of the lack of common categories of data provided by the authors (Bresson 1995). They had hoped to systematise our knowledge of crusting mechanisms by comparing these studies on the basis of the soil and environmental conditions of formation; namely, the soil texture, initial structure, initial microrelief, antecedent moisture, intensity and
kinetic energy of the rainfall, and state of development of the crust (Bresson 1995). The last point is particularly interesting, as it is not apparent from many of the papers reviewed for this present study whether the authors conceptualise crusts as temporary, dynamic states; during formation, yes, but the implicit assumption seems to be made that once formed (taken to be by the end of the experiment), they are in some final state.

Thus, in addition to the issue of common experimental protocol, some of the apparent contradictions in the literature could potentially be resolved by recognising that any crust is the net product of various forces operating at a particular point at the soil - atmosphere interface, and which vary in time, and which are affected in turn by conditions in neighbouring areas of time and space. Thus a particular crust observed by researcher A under conditions B may in fact be the 'same' crust as that observed by researcher X under conditions Y. Hence, any crust must be described with respect to its position in time and space, for example its location along a micro or macro catena; its management history, if any; and its place in any cycle of crusting observed from longitudinal studies and/or from general models of crust development.

A generic within-event multiple path temporal sequence is proposed by West et al. (1992) for a cultivated soil. In the study area the crusted soils examined are used primarily for grazing, however the widespread trampling (apparent in the aerial photography) breaks up the crust and hence the initial stage in West et al.'s (1992) system of a cloddy aggregated surface with large variability in surface morphology is often a valid initial condition.

Stage 0

Freshly tilled soil before rainfall

Stage 1

Aggregate breakdown and particle rearrangement due to slaking (wetting effect) and raindrop impact (energy effect), resulting in a 'disruptional' layer, which is the same as structural crust. Soil and rainfall characteristics determine the thickness, porosity and continuity of this layer

Stage 2
Further crust development is now controlled by soil dispersibility (chemistry effect); there are two possible pathways, effectively controlled by the chemistry of the soil-water system. In soils with low dispersibility, the disruptive layer continues to develop and aggregate coalescence may occur below the disruption zone as part of this process. Raindrop impact may cause particle disjunction, with the released fines removed in runoff. The lateral water movement results in washed-out layer, but no washed-in layer, as these fines are removed from the system. In dispersible soils, on the other hand, extensive particle disjunction occurs early in the rain event, resulting in the clogging of what porosity remains in the disruptive layer. Thus a washed-in layer forms, which may be accompanied by a washed-out layer above it.

Stage 3

Because of the low permeability of the disruptive and/or washed-in layer, runoff is maximum at this stage. This is the stage of particular interest for water harvesting studies; the sustained runoff yield plateau. The washed-out layer, if present, will be eroded by this runoff water, exposing the underlying layer to further raindrop impact and hence crust formation, by way of crust coalescence. In some cases a thin, secondary washed-out layer will develop, with loss of fines. These crusts are very flat, with a depositional crust covering most of the surface, together with a thin, oriented clay seal after the end of the rain event if there is sufficient clay in suspension.

Farres (1978) introduced the term 'equilibrium crust', which has not been taken up by other authors, and is not probably valid in its original context (crusts 'filling up' from the bottom of the crusting zone until the protection it offers prevents further aggregate breakdown and hence the release of material for further infilling; but see seal erosion issues below), and yet it could be used to describe a crust as a function of various forces, as proposed above, as long as the term equilibrium is acknowledged to be a temporary equilibrium. If this perspective on crusting is valid, can we then move on to a systematisation of our knowledge of crust types and mechanisms of their formation by explicitly classifying them with respect to their position in time and space?

(3.13)

Temporal dynamics of crusting and implications for mapping crusting soils
Few studies were identified which explicitly examine the effects of subsequent storms on runoff; rather, they are implicit in studies which reuse the same plot by allowing drainage to prescribed levels of moisture in order to study the effects of antecedent moisture, or studies which evaluated crust formation by monitoring micromorphology or hydraulic properties after every given interval of rain depth. Such an experimental protocol does not distinguish between the effects of antecedent moisture with the effects of progressive crust formation. Most of the crusts observed in the study area are subject to cracking. Oostwoud (1992) found for the study area that cracking depth corresponds to crust depth, and hence crust depth might thus be used as a means of monitoring of crust development, however this was beyond the scope of the present study, which is focussed on the effects on infiltration over time.

As has been seen above, there are typically changes in the soil surface over the course of the rainstorm which will influence infiltration behaviour in a subsequent storm, such as the development of an overlying depositional layer as the velocity of the runoff water subsides. Conversely, the removal of fine particles can lead to an erosion or pavement crust (Valentin and Bresson 1992), also called an armour or stone mulch, which also impedes future infiltration. Hence, one would expect a decreasing time to runoff in subsequent storms. Le Bissonnais and Singer (1992), using a series of forty minute storms, found that subsequent storms, onto soil which was still wet (but not saturated), resulted in lower sediment concentration than the first storm event, indicating crust formation. Rainfall energy normally induces reduced microtopography of the soil surface (Onstad 1984) and hence more energetic flows (Hairsine et al. 1992), which themselves alter the surface in a number of possible ways depending on flow velocity and soil erodibility. Thus each subsequent rain event interacts with a different soil surface. Falayi and Bouma (1975) found substantial morphological differences between crust formed under laboratory and field conditions.

Of particular interest to this discussion is the finding that natural crusts were much more highly striated, indicating cycles of sedimentation due to a series of rainstorms of different intensities. The implication of this, in terms of mapping runoff potential, is the possible increase in runoff potential over the course of a rainy season (counteracted by the effects of vegetation growth), to a peak which is then broken by livestock and human trampling over the dry season, exposing the soil to massive soil erosion at the commencement of the next rainy season, with implications for the rapid sedimentation of water harvesting structures. If this is the case, then water harvesting systems would need to provide an economic return at least as great as that provided by the
opportunity cost of labour, taking into account the lifespan of the structures. Oustwood and Bryan (1994), who constructed low cost low labour unfenced V shaped microcatchments in the study area found that they provided a significant increase in biomass over the control areas and survived the effects of trampling and sedimentation for at least two rainy seasons. A financial analysis, however, was not carried out.

This sort of ‘action-research’ is a very promising research path, and fits the current trend towards on-farm experimentation under ‘real world’ conditions. Such research, however, can also result in the loss of valuable instruments, as the University of Toronto project found with a recording rain gauge. Kings College London installed a recording rain gauge securely at the RAE water harvesting project residence, but no-one locally, apparently, knows how to download the data, which has since overwritten itself and was therefore, unfortunately, unavailable for this research.

(3.13.1)

Ability to assess crust evolution under simulated conditions

The effect of wetting and drying cycles does not seem to have received as much attention as this phenomenon may deserve as a longer term factor in crust evolution. Differences in hydrological behaviour between an experimentally produced seal and seal which forms during a subsequent rain event in a pre-existing crust is not well covered in the literature (Bristow et al. 1994). On sandy soils, which predominate in the Sahel, crusts strength was found to be augmented by wetting and drying cycles (Gifford and Thran 1974), whereas on clay soils, which more predominate in the study area, it causes increasing fracturing of the surface (cracking) during each drying phase (Lemos and Lutz 1957, Sharma and Agrawal 1980), with a commensurate infiltration cost from a runoff yield perspective.

Patrick and Berliner (1993) found that under natural rainfall on loams in an arid environment, that crusted surfaces would suddenly break, as indicated by runoff rates, above a threshold rainfall intensity. Furthermore, the present study found that rainfall simulation with low (1.5 m drop height, 35 - 50 %) reproduction of instantaneous kinetic energy of natural rainstorms (depending on rainfall intensity) onto crusted soils resulted in far higher time to runoff than natural storms, indicating that crust formation occurs during each storm, even on undisturbed crust which are the product of many wetting and drying cycles. Examination of hydrological parameters with those of 3.5 m simulation results at the same sites, however, found that, when compared on the basis of
cumulative energy, that the low (instantaneous) energy simulator, which is more practical in terms of handling, gave reasonable results. The time requirements of the simulation to reach key infiltration parameters such as steady state infiltration, however, is proportion to the relative reduction in energy, and hence there is a trade-off between manageability with the 3.5 m simulator (implying a greater number of field assistants) and time requirements with the 1.5 m simulator (reducing the number of simulations possible, and therefore the replication of results and the ability to attach a statistical significance to apparent differences in runoff potential).

Such factors need to be considered on a case-by-case basis when considering survey strategies for runoff assessment using rainfall simulation. It was noted, however, that with the 1.5 m drip-type simulator, especially when compared with the 5 m spray-type simulator used by the University of Toronto projects (which had also earlier used the 1.5 m design; see Methods section for a discussion of their experience with ‘simple tests’) that the steady state infiltration rate was considerably higher, providing a misleading basis for runoff yield calculations for comparison with crop water requirements under a particular rainfall regime. Thus it is perhaps best to use a high kinetic energy reproduction simulator such as the 3.5 m design at sites which, on the basis of simpler tests, have been ascertained to be promising; in other words, to move from qualitative to quantitative assessment as and where justified.

In the case of the study area, there is very rarely more than one rain event per day, typically in the early evening, and hence with a full day’s solar irradiation to dry the surface before the next storm (Rowntree 1988). Antecedent moisture changes after natural storm events were monitored at various locations, which confirm the supposition of rainfall onto a dry surface. Hence, in this study, the interest is on antecedent dry conditions and an examination of the effects of cumulative crust formation after a full drying cycle. Although drying periods may also of course occur within a rainstorm, the simulations carried out in the present study used continuous rainfall for the sake of easing data analysis. During natural continuous rainfall variations in rainfall intensity of course occur, but this is not the typical protocol in rainfall simulations for reasons of simplifying the analysis, nor has it been attempted in this study except on validation plots. At all sites the crust was removed in order to determine a) whether and to what degree it would re-form within a single storm event, by comparing the infiltration behaviour to that of a crusted control, and b) for a set of validation plots, to help determine the relative importance of within and between storm contributions to crust development by comparing the results with those of the one surface type monitored over multiple storms.
There has been very little work carried out in the area of the evolution of crusted surfaces over a multi-season time scale, and neither was this carried out in this present study for various logistical reasons. Nonetheless, this is a very most promising areas of research for the future. From the point-of-view of water harvesting assessment, there are important implications for the validity of environmental surveys of runoff surfaces based on a snapshot in time, which has long been recognised in soil science by mapping soils on the basis of relatively stable subsurface properties (which is of questionable value, however, if all the processes of interest occur at the surface). Even if just a snapshot survey is undertaken, however, an understanding of the evolution of crusting surfaces gives insight into the dominant processes operating at a particular location and the 'stage' in which a particular surface is mapped, which aids in the prediction of the infiltration and hence runoff trajectory of that unit.

(3.14)
Conceiving crusts as transient entities over time and space

A major breakthrough in the study of crusted soils came with the thesis of C Valentin (Valentin 1981), working on arid unutilised soils, which introduced the possibility that one crust type could be transformed into another over time. This relationship was then formalised in the thesis of Boiffin (1984), working in a completely different environment, on loamy cultivated fields in a temperate climate. Although Boiffin's work is less relevant to this current study because he was primarily concerned with the influence of the initial moisture condition on crusting - whilst the soil surface is almost always dry in the study area - his logic of evolutionary stages, which may take place within and across a series of rain events, is still valid and relevant for semi-arid environments.

Boiffin (1984) proposed a generalised temporal sequence for structural crusts: an initial stage, followed by an 'altered fragmented' stage, and finally 'continuous' (flat, dense) stage. This schema allowed the establishment of systematic relationships between the rapidity of crusting, the conditions under which it occurs, and the dominant processes involved; crusting soils with different treatment histories could be compared in terms of their progress along a common continuum. Although rather simplistic, and made feasible by the fact that only soil type was studied (albeit of a range of textures), it is a significant study in so far as it recognised the
transient nature of the crust and developed a general framework within which cause and effect could be examined across a wide range of variables.

Furthermore, and of central importance to this current study, which is focussed on field-scale environmental assessment, micromorphological studies of Boiffin's (1984) crusts showed that the stages observed in the field were a macroscale reflection of an evolution occurring at a microscopic process level. The 'altered fragmented' stage referred to above was found to correspond to processes involved in the formation of a structural crust, whilst the 'continuous' stage corresponded to the processes involved in the formation of a depositional crust (Boiffin and Bresson 1987). Hence, not only was the idea of crust evolution introduced, but also the possibility of a transformation from one crust type to another, as the dominant processes operating on the surface change in response to changes in the surface. This reformulation of and movement between Chen et al.'s (1980) dichotomy structural and depositional crusts, a dichotomy which formed the basis of much of the more recent work reviewed, was a significant step forward in crusting studies.

Such a transformation between crusts was also suggested by Valentin's (1981) work, later formally developed in a classic series of publications. Bresson and Boiffin (1990) further substantiated the structural to depositional transformation trajectory with a systematic study of forty two parcels on a loamy soil with widely varying properties, including sodic soils (due to different management histories), which all followed this same trajectory. Their work is particularly relevant to the present study as they found that the principal control on the transformation rate was the infiltration rate of the structural crust, as the depositional crust forms under conditions of runoff (low velocity) produced by structural crusts upslope. In short, there are a number of possible rates of transformation in a crusted landscape, and which may involve a complex variety of feedback mechanisms, all of which serves as caveat in the environmental survey of such landscapes in terms of the temporal validity of the classification of runoff units as a basis for assessing water harvesting suitability.

(3.15)

Crust transformations and implications for mapping runoff potential over time and space
The are few systematic long term studies of changes in crusting surfaces which have been noted in the literature, the most relevant of which have been carried out by the Orstom group in the Sahel (Figure 3.4). Both natural and anthropogenic factors can induce a sequence of changes in the surface and hence infiltration characteristics. Drilling a well often results, for example, in changes in livestock movements, which in turn triggers a sequence of changes in the infiltration characteristics of the soil, in parallel to changes in the nature of the surface. In the case of Ferlo in Senegal, a number of transects were undertaken in a radial fashion away from a well, corresponding to declining cattle densities (Casenave and Valentin 1989). Such an approach is very relevant to this current work, as a high proportion of the study area subject to trampling. In the immediate vicinity of the well was found that, in general, trampling destroys the hummocks (1) and thus induces the same crust transformation as that found when mapping crusts along a gradient of decreasing rainfall, namely the transformation from a fine ‘Drying’ type crust to ‘Structural’ type, through to an ‘Erosion’ and then, ultimately, a ‘Gravel’ or ‘Pavement’ type crust. As a function of the distance from the well, however, a different series of transformations were apparent; due to the breaking up of the surface crust under trampling and the incorporation of manure, infiltration increasing as one approaches the well, up until a threshold distance of about 2 km from the well, after which the reverse occurs. In addition to these temporal and spatial vectors of change, one must also add the differences in these sequences according to whether the crusts have developed on sandy or lateritic surfaces (in this example from Senegal).

In short, the evidence of the existence and complexity of crust transformations from field investigations implies that the inherent variability of the state of the surface, and the associated infiltration and runoff parameters, would ideally be incorporated into both a classification system and associated survey system.

An appropriate classification system, that of Casenave and Valentin (1989), is presented in a summarised form in Chapter 5, together with efforts based on it to upscale to the resolution amenable to detection and mapping of these elementary hydrological response units. If and to the degree that this can be accomplished, and calibrated to runoff values, the temporal frequency of global coverage earth observing systems (such as Spot and TM), is such that changes in runoff potential could be mapped and then updated as required, and on a broad enough scale, given the size of a single scene, to make this economic for project interventions, so long as the cost of current satellite imagery, which has increased dramatically in the case of the (originally heavily subsidised) Landsat series, is not beyond the reach of the particular projects. Given, however,
that water harvesting is normally carried out for subsistence purposes in areas of inherently low economic potential and by a population normally with little political import (Baringo being an exception on the latter score), it is unlikely to ever be an approach which could operate on a cost-recovery basis unless lucrative cash crops (such as qat) were ‘irrigated’ thus.

(3.16)
General conclusions and implications for this study

In this chapter it has been argued that crusting soils, particularly those resulting from physico-chemical degradation, are widespread and very important for the surface hydrology of semi-arid areas. As water harvesting is potentially very attractive in these same areas, it is very relevant to the overall goal of assessing suitability for water harvesting to develop a methodolog(ies) by which to determine the runoff potential of these soils. This objective, however, is complicated by a number of considerations raised in this review of the literature on the phenomena of crusting and sealing. First of all, the method dependence of assessing crusting should be apparent from this review of the literature. Secondly, in a similar manner, the definition dependence of crusts means that two studies may actually be referring to two different phenomenon when reporting results of work on ‘crusted’ soils. Finally, and particularly significant for this study, crusting and sealing phenomena vary at a relatively fine scale over space and time. Together, these complications revealed by the literature review imply the necessity of establishing a consistent classification system, the inventoring of those crusts occurring in a study area, and a mapping of the distribution of their occurrence over the entire study area. These issues will be addressed in Chapter 5 in the context of methodological options for achieving these objectives.
Chapter 4

Methods (Part one)

Hydrological Investigations

- Determining runoff yield in Baringo; research design and methodology
  ('point' measurements / hydrological investigations)
- Simple, rapid, very low energy tests of runoff potential
- Issues in rainfall simulation
- Rainfall simulators employed; designs, protocols, treatments
- Calibration of simulators
- Validation of simulations

Chapter Overview

(4.1)
Overview of chapter

(4.2)
Research design: General approach taken

(4.3)
Diagnostic properties and simple tests employed;
indirect measures of infiltration

(4.4)
Crust stability upon wetting: details of tests employed in this study
(4.5)  
Diagnostic properties and simple tests employed;  
direct measures of infiltration

(4.6)  
Conclusion: value of ‘simple’ tests

(4.7)  
Rainfall simulation

(4.8)  
Rainfall properties to be simulated

(4.9)  
Complications in the accurate simultaneous simulation of various parameters of 
natural rainfall and trade-offs involved; ‘Drip type’ versus ‘Spray type’ simulators

(4.10)  
Trade-offs and complications with the drip-type simulator design

(4.11)  
Simulator design chosen as best satisfying the criteria established for the purposes of 
ranking relative runoff potential

(4.12)  
Ideal requirements for rainfall simulator for the present study and actual characteristics 
of simulator chosen
(4.13) Design and use of the simulators employed in this study

(4.14) Calibration of simulators and simulator boards #1 and #2

(4.15) Calibrations carried out

(4.16) Relationships between differences in capillaries and rainfall intensity; changes in calibration over time

(4.17) Conclusion; implications of results of calibrations

(4.18) Protocol used in the rainfall simulation

(4.19) Validation and ‘upscaling’ of rainfall simulation results

(4.20) Conclusions

(4.21) Implications for mapping runoff potential
(4.1)

Overview of chapter

This chapter presents the approach taken and details of the methodology employed in determining runoff potential in the study area. In particular, it details the nature of the hydrological investigations, particularly issues related to the simulation of rainfall. What is known about characteristics of natural rainfall in the study area are presented in Chapter 6 together with other details about the study area. Methods related to the possibilities of 'upscaling' point measurements of runoff potential by systematically classifying and mapping crusting soils and by linking them to spectral areal coverage of the landscape - in the form of optical remote sensing - is reserved for the subsequent chapter, Chapter 5. This chapter covers the 'philosophy' of attempting to substitute rapid, low cost indicators of runoff potential in a suitability assessment context for the quantitative but time consuming rainfall simulations, as well as the details of these 'simple' tests. The results of the rainfall simulations carried out are presented in Chapter 7, and the results of the alternative measures of runoff potential in Chapter 8, together with a comparison between the two in terms of the relative runoff potential of the study sites. Details of the study sites themselves are presented in Chapter 6.

This chapter, on a chronological basis, starts with an introduction to the research design, then turns to the role of simple tests as tests of the wetting effects on sealing in crusting soils, before addressing the question of rainfall simulation in some detail. Relevant properties of rainfall to be simulated are discussed, the design options for doing so compared and their advantages and disadvantages noted and then the design chosen described and its shortcomings noted with respect to an hypothetical 'ideal' design. The calibrations carried out on this design before putting it to use in the field are detailed and the implications of the findings discussed. The protocol employed with each of the two simulator designs used are outlined and then questions of how to validate the results addressed. Finally, general conclusions are drawn about the approach taken and the instruments employed and the implications for mapping runoff potential highlighted. This leads naturally to the subsequent chapter, where various attempts to map runoff from point measurements of infiltration are reviewed and the approach favoured in this study explained.
(4.2)

Research design: General approach taken

The general approach taken is illustrated by a number of figures, which will be referred to here below. The approach taken is essentially comparative and data driven. It is based on the principle that to build up an accurate picture of the environment in general, and the spatial (and temporal) distribution of runoff potential in particular, it is necessary to employ a range of techniques, each of which may reveal a different aspect of the phenomenon under study.

This idea is underlain by the principal of the principle of weight of evidence, on the premise that a range of data sets collected with a range of instruments and protocols, when combined, are more likely to highlight possible errors, in the form of deviations from the rest of the datasets, and that, as a statistical principle, errors will to some degree cancel each other out. On the other hand, it is recognised that such an approach can prove difficult for the same reasons; the range of data types, measurement scales, explicit and implicit definitions and class limits employed, temporal disparities, georeferencing errors etc. create a problem of data integration, data reduction and error assessment, and a GIS analysis was therefore utilised for the final assessment of suitability for water harvesting, as this is an analytical tool well suited for this type of problem.

An inexpensive raster open-architecture GIS widely used in developing countries (Eastman 1995), Idrisi, was chosen for this purpose, and analysis restricted to this software for GIS and image processing purposes, in spite of some limitations. It is much quicker to carry out some routines in other, more expensive software, but it is not considered that such expensive software is likely to be widely available in developing countries.

With a GIS, however, the old adage ‘garbage in, garbage out’ very much holds true, and therefore buttressed by systematic calibration of the instruments employed and a critical awareness of the limitation of the protocols and data sets employed and of any contradictions between them in terms of dates, scale, definitions etc. Such contradictions, however, are a real world situation, and the contradictions between the surveys carried out by the various agencies which have worked in Baringo soon became readily apparent. A transect was chosen down a shallow catena towards Lake Baringo, collecting infiltration and ancillary data over a short sample interval (50 m blocks
every 100 m, over some 3 km), and the picture painted by this data collection exercise contrasted with those presented by a number of secondary data sets / thematic maps.

**Figure 4.1** illustrates the principal data sets collected and possible relationships between them. This is predicated on the logic that the 3.5 m rainfall simulation results (carried out in the second field season) would be the most accurate / reliable measure of runoff potential, and its central position reflects its status as the reference value (comparison will also be made with the 'ultimate' reference value, runoff under natural rainfall, as described in the validation section below). The figure is a quadrat set out along the axes 'direct / indirect measures of reflection / absorption' in an left-right dichotomy and 'direct / indirect measures of infiltration / runoff' opposed in a top-bottom orientation. This figure provides an overview of the types of data collected and the modes of collection, as well as the nature of the data in terms of qualitative or quantitative and the comparisons possible and envisioned between the data sets generated using these instruments / measures and associated protocols. These will be described below for the more important measures.

**Figure 4.2** provides an overview of some possible approaches which one could take in mapping runoff potential, and the comparisons which could be made between the resulting data sets for the purpose of improving the accuracy of the final output, as well as to determine the advantages and disadvantages of each approach. This figure also establishes the relationship between and roles of primary and secondary data sets in the approach chosen for the present study.

**Figure 4.3** presents the operational approaches possible for assessing runoff potential integrating ground truth and earth observation imagery. The central role of a GIS in converting between ‘point’ data (ground measurements, which can effectively be considered to be points, given the resolution of a satellite pixel (20 or 30 m but taken to about one ha to account for georeferencing errors)) and area data. The latter are normally represented cartographically as choropleth maps; which imply that all points within a given polygon are of equal value, which is rarely the case.

A similar assumption underlies image classification: to put it crudely, if two areas look similar on an image, then they are probably similar on the ground. Applied to the objectives of the present study, this principle would be translated as: if the demarcation of the study area into homogeneous zones, on the basis of the spectral characteristics of the landscape, corresponds to the classification of the landscape into runoff response units, then one can map runoff potential from remote
Figure 4.1
Possible relationships between data sets

DIRECT MEASURES OF INFILTRATION / RUNOFF

RAINFALL SIMULATION:
ONE METER DRIP TYPE
FIVE METER SPRAY TYPE (secondary data)

SPRAYERS:
HAND, BACKPACK
RINGS: LARGE, SMALL

DIRECT MEASURES OF REFLECTANCE:
CONCURRENT FIELD SPECTRO-RADIOMETRY

3.5 METER RAINFALL SIMULATION RESULTS REFERENCE VALUES

'INDIRECT' MEASURES OF REFLECTANCE:
POST &/OR ANTE REMOTE SENSING

QUALITATIVE MEASURES
(for example, crust colour)

QUANTITATIVE MEASURES
(for example, soil strength using penetrometer)

INDIRECT MEASURES OF INFILTRATION / RUNOFF
Figure 4.2
Assessing alternative approaches to mapping runoff potential and validation through cross referencing

'REFERENCE VALUES'
(Rainfall simulation)
RUNOFF FOR VARIOUS LOCATIONS (and implicitly for various surface units in the region)

ENVIRONMENTAL PROPERTIES
(Indirectly measured and/or deduced from what measured) correlated to runoff potential

ALTERNATIVE DIRECT MEASURES OF RUNOFF VALUES
(Sprayers, rings, low energy rainfall simulation, plus secondary data)

Compare results of generalised rankings from own data with others' data for the area, ie:

Point data (Bowyer Bower and Scoging), Factor maps / Areal data (UNEP and GTZ studies)
Figure 4.3
Possible approaches to assessing runoff potential
(And iterative circular process a third option)

START FROM

THE GROUND

END AT

POINT
MEASUREMENTS
OF RUNOFF; Rainfall
simulation &/or proxies

CONVERT

POINTS

GIS ↔ GIS

AREAS

GENERALISE POINT
MEASUREMENTS
TO AREAS; For
example, interpolation

DEFINED SAMPLE
LOCATIONS
CONSIDERED
REPRESENTATIVE

CORRELATE
RUNOFF UNIT
CLASSIFICATION
TO IMAGE UNITS

DEMARcate IMAGE
INTO UNITS OF
HOMOGENEOUS
REFLECTANCE

END AT

'THE SKY'

START FROM
sensing; which would be much more efficient than attempting to map a large area from the ground. This is particularly true of areas such as lowland Baringo, which is heavily dissected by gullies, greatly reducing accessibility by vehicle; indeed, the Bowyer-Bower / Scoging survey (1992), which used a systematic sampling scheme without reference to imagery, ended up being carried out almost entirely by foot due to problems of access.

A UNEP study carried out in Baringo which was, like the present study, essentially the development of a methodology for defining, measuring and mapping a spatially distributed environmental phenomenon, concluded that the stipulation to map soil crusting (as a parameter in the wind erosion factor in their desertification hazard rating) was impossible, at least on the basis of a classic soil survey and principally field based approach (Kamar 1987). UNEP reports (Ottichilo 1990) that image processing did not prove to be useful, but the soil surveyor, M. Kamar (1996 pers. Comm.) reveals that this was never, in fact, attempted. The mapping units in this study, however, were based on a September 1986 SPOT hardcopy image at 1:100,000 for field use, such that the mapping units closely correspond to homogenous zones on the image. The film from which this image was printed was obtained, with some difficulty, for the present study and an enlargement to 1:50,000 (the maximum with SPOT before pixelation occurs), which proved to be exceedingly useful for fieldwork.

Compared to carrying out survey work without reference to imagery, the advantages of remote sensing are clear, and especially in the case of rainfall simulation, which realistically requires a vehicle for transporting the water supply. Thus, if one can characterise by way of rainfall simulation sites with vehicle access which, on the basis of image inspection and an unsupervised classification of satellite imagery (homogenous zones in terms of spectral characteristics), can be considered to be representative of other areas in the study zone, then only a very small percentage of the total study area need be subject to the time consuming application of rainfall simulation and the valuable quantitative data it provides in the form potential runoff yield. This is the principle of stratified sampling, with stratification, in this case, being based on imagery. Survey work was also carried out on foot as part of this study, using simple alternatives to rainfall simulation such as the handsprayer (crust water acceptance by maintaining incipient ponding, described below).

Table 4.1 summarises the comparison of the characterisation of the landscape on the basis of spectral and hydrological characteristics, compared across a range of spatial scales (really a proxy
Table 4.1 Characterisation of soil surfaces in the study area

<table>
<thead>
<tr>
<th>SURFACE CHARACTERISTICS</th>
<th>SPECTRAL</th>
<th>HYDROLOGICAL</th>
<th>OTHER</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>SPATIAL LEVEL</strong></td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Elemental runoff unit</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(minimum 100 cm²)</td>
<td>Spectroradiometer</td>
<td>Hand sprayer</td>
<td>Description of relative position in runoff system; description of composition of surface</td>
</tr>
<tr>
<td>Elemental unit:</td>
<td>Spectroradiometer; From crust sample; for each aggregate size class, and each when wet and dry</td>
<td>For suitability as runoff zone, rainfall simulation (see below); for suitability as runoff zone, infiltration rings</td>
<td>For each aggregate size class; from crust sample: Emerson drop test, spray test, clay test; all using both well and rain water</td>
</tr>
<tr>
<td>predominant unit type</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Runoff plot</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(dominant units only)</td>
<td>Aerial photographs, Digital aerial photographs, Satellite imagery</td>
<td>Rainfall simulation; 1m and 3.5m drop heights.</td>
<td>Crust: thickness, strength, layering, porosity, macro photograph, colour, type (ORSTOM)</td>
</tr>
<tr>
<td>(0.25-0.5 m²)</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Site</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>(1 ha)</td>
<td>Aerial photographs, Digital aerial photographs, Satellite imagery</td>
<td>Infiltration rings and hand sprayer, for estimate of spatial heterogeneity of infiltration</td>
<td>Various, including: topography, slope, runoff features (gullies, rills, sheetwash; % area, dimensions, vegetation cover etc)</td>
</tr>
<tr>
<td>(Ground truth for imagery)</td>
<td></td>
<td></td>
<td></td>
</tr>
</tbody>
</table>
for resolution) at which data are collected, and the instruments and protocols applied at each scale and the types of data measured.

An important issue should be apparent simply from the description of these data sets; the unbiased comparison of imagery across a range of temporal, spatial and spectral 'scales'. For the classification of areas which had not be visited, however, an automated procedure was utilised and one standard image data set, a March 1st (end of dry season; surface free from basal annual vegetation) 1989 (most recent available) Landsat TM (highest spectral resolution available) image was selected to be used with various ground verification data sets and classification routines.

Table 4.2 reviews the data sets collected to satisfy the objective of characterising the study area in both hydrological and spectral terms. Note that, whilst a complete list of data collected is given here, only those results considered to be of interest will be reported. Details of those tests are described below. Table 4.3 expands upon Table 4.2 in that, for the principal measurement devices, key parameters measured, the mode of measurement, estimated precision and the relevance to study are detailed here.

(4.3)
Diagnostic properties and simple tests employed;
indirect measures of infiltration

(4.3.1)
Crust stability upon wetting and relationship to runoff potential

The soil science literature is rich in papers reviewing soil stability tests. With respect to crusting soils, however, these tests suffer from a lack of raindrop impact energy; there is usually a mode of energy application, such as shaking, ultrasonic waves, remoulding or applying single drops, these still are a poor reproduction of natural conditions (Valentin 1994). Wet sieving of aggregates from nine sites around lowland Baringo by Bryan and Sutherland (1989) allowed separation of highly erodible and non-erodible soils, but the relationship with measures of hydraulic properties (hydraulic conductivity; time to 100% ponding and percentage ponding after fifteen minutes under a 1.5 m rainfall simulator and discharge under a 4 m laboratory rainfall simulator) show no significant relationships when these data were reanalysed as part of the present study.
Table 4.2  
Data sets to be analysed

1) HYDROLOGICAL

   a) Assessing suitability as a runon zone

**Infiltration Rings**  
Simulating conditions of ponded water behind a bund of a water harvesting structure

**Large rings:**
- Single ring
- Spatial heterogeneity of site: three to five rings, 25 or 50m apart
- Single vs double rings

**Small rings:**
- Small versus large rings
- Spatial variability over short distances
- On rainfall simulation sites at the end of simulation, as a 'shortcut' to final infiltration rate (exploratory)

b) Assessing suitability as a runoff zone

   i) Direct measures

   a) Wetting soil without applying energy

**Hand Sprayer**  
For rapid assessment of runoff potential

Onto surfaces in natural state and with surface / crust removed

b) Wetting soil while applying energy

**Rainfall Simulators**

Two heights / levels of kinetic energy

Onto surfaces in natural state and with surface / crust removed
Table 4.2 (cont.)
Data sets to be analysed

ii) Indirect measures

a) Field based

1) Crust characteristics

Characteristics assumed to influence infiltration and hence runoff potential

- General appearance: macro photographs (plane and profile)
- Layering
- Thickness
- Strength (three depths)
- Porosity (visual description; particularly vesicular porosity, indicating air entrapment, and estimate of average pore size)
- Type (where fits ORSTOM typology)
- General description

2) Site characteristics

Characteristics assumed to influence infiltration and hence runoff potential

Evidence of runoff

- Topography
- Slope
- Runoff features: gullies, rills, sheetwash; area affected and dimensions of
- Soil texture (estimate by hand, using standardised system)
- Stone cover (size classes and area affected by each class)
- Cracking (average intercrack dimensions, average crack width and depth)
- Munsell colour
- Basal vegetation
- Salinity (if any readily apparent salt efflorescence)
- General description
b) Field 'laboratory' based

For dry sieved aggregate classes of sampled crust;

- Weight as a proportion of total by class

and comparing results using rain water and (as used in rain simulators) with well water;

- Emerson drop test; aggregate stability upon wetting by immersion
- Hand spray test; aggregate stability; upon wetting by gradual water application
- Swelling test; presence of clay
Table 4.3

Principal Environmental Data Sets Collected or Elaborated

1) Quantitative measurements of runoff and/or runon behaviour

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Key parameters measured</th>
<th>Mode of measurement</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patrick, field assistants Suter and Chebii spring 1996 spring 1997</td>
<td>Runoff response</td>
<td>Rainfall simulation</td>
<td>Taken to be reference values for runoff potential</td>
</tr>
<tr>
<td></td>
<td>• at 1.5 meter drop height</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• at 3.5 meter drop height</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• at a low and high intensity</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>• with and without crusted surface</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>Infiltration under a hydraulic head; simulating behind bund conditions</td>
<td></td>
<td></td>
</tr>
<tr>
<td></td>
<td>at a standard ring size at a pilot size for rapid assessment</td>
<td></td>
<td></td>
</tr>
<tr>
<td>As above</td>
<td>Runon behaviour</td>
<td>Single infiltration rings</td>
<td>Taken to be reference values for runon potential</td>
</tr>
<tr>
<td></td>
<td>Infiltration under zero kinetic energy</td>
<td>+/- 1mm reading ruler; water height; Volume error depends on ring size</td>
<td></td>
</tr>
</tbody>
</table>

2) Semi-quantitative measurements of runoff potential

<table>
<thead>
<tr>
<th>Author(s)</th>
<th>Key parameters measured</th>
<th>Mode of measurement</th>
<th>Comments</th>
</tr>
</thead>
<tbody>
<tr>
<td>Patrick, Rebello</td>
<td>Infiltration under zero kinetic energy</td>
<td>Backpack sprayer Hand sprayer</td>
<td>Note: technical problems with the ‘backpack sprayer’</td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hand sprayer;</td>
<td></td>
</tr>
<tr>
<td></td>
<td></td>
<td>Hand sprayer</td>
<td></td>
</tr>
</tbody>
</table>
3) **Visual and simple semi-quantitative measures** of runoff potential and/or factors potentially influencing reflectance properties of the soil, such as evidence of water movement, soil colour, texture assessment by hand, penetrometer, crust depth, crust type (‘Valentin system’), physical sampling of crust for dry sieving, clay absorption test, Emerson drop test, aggregate spray test.

(Patrick, Patrick and Rebello; also secondary data courtesy of Bowyer-Bower and Scoging 1992); all over an area of a few m² but considered representative of a larger surface).

4) **Quantitative measurement of reflectance of soil surface**

<table>
<thead>
<tr>
<th>Spectral values of approx 400 cm² (height dependent) soil surfaces in wavelengths equivalent to first four bands of TM</th>
<th>Milton Multi Band Radiometer</th>
<th>Allows comparison to be made between surface units in terms of reflectance characteristics at a fine scale; that of ESE’s</th>
</tr>
</thead>
</table>

5) **Measurement of factors influencing reflectance properties at satellite resolution**

<table>
<thead>
<tr>
<th>Patrick, Patrick and Rebello</th>
<th>Tree cover</th>
<th>To bridge the scale gap between the resolution at which crust properties vary and the 30 x 30 m TM pixel / area over which crust reflectance integrated</th>
</tr>
</thead>
<tbody>
<tr>
<td>Bowyer-Bower and Scoging 1992</td>
<td>Bush cover Erosion status</td>
<td>(2500 m² for Patrick) (20 to 25 m radius for Bowyer-Bower)</td>
</tr>
</tbody>
</table>
Valentin (1994) states categorically that there is no substitute for the monitoring of structural degradation in situ (p. 60). In this study rainfall simulation is the preferred mode of investigation, however for the purposes of rapid runoff assessment over large areas this is an expensive and time consuming procedure without the resources of a long term Orstom Sahel politically enabling funding environment, which is atypical, and thus a priority has been placed on establishing whether and to what degree alternative measures are useful and on determining for which scale and stage of survey (reconnaissance to detailed) where they would be most appropriate. In the case of the simple tests, it is anticipated that they would be used at the reconnaissance end of this spectrum / sequence, and rainfall simulation at the other, when hard numbers are required for the purpose of soil and water conservation engineering the system types deemed most suitable to the local social and physical environment.

(4.3.2)

Wetting and energy; the relative roles of simple tests and rainfall simulation in a runoff assessment procedure

Metelerkamp (1974) argues that aggregate stability should be assessed at the scale of a meter square surface in order to be more representative of the surface, and for kinetic energy to ponding to be the measure of preference rather than observation of aggregate breakdown. Whilst such an approach is clearly preferable, there is still an interest in this present study in determining whether and to what degree rainfall simulation results can be correlated to quicker and cheaper qualitative and semi-quantitative tests.

In this study simple tests of kinetic-energy-free wetting were undertaken (Plates 4 and 5), for comparison with rainfall simulation results. As the latter combines wetting and energy effects, whilst the former the effect of wetting alone, a comparison between the two is one way of addressing the research question: 'What is the relative importance of the wetting effects and energy effects of rainfall on runoff?', which will also be addressed by comparing low and high energy (drop height) rainfall simulations at the same rainfall intensity. This, in turn, may assist in answering one of the research hypotheses originating from the review of the crusting literature; is kinetic energy the key control on crusting and, in particular, seal formation in the study area? This question is also addressed in the present study by assessing the results, in terms of effects on
Plate 4  Hand Sprayer (clockwise from upper left); a) Cemented aggregates before and (b) after spraying c) Hand sprayer and windshield and (d) in use on a crusted surface; note spray pattern, with increasing ponding at centre
Plate 5
Crust sampled and simple tests carried out on samples
(clockwise from upper left):
a) Crust sampler designed. Standard depth marks etched on side
b) Crust samples dry sieved into aggregate classes; here variations
in colour and reflectance are assessed between class sizes and sites
c) Finest portion after sieving are mixed with rain and well (source of
rainfall simulator water) water as two treatments; clay expansion
compared between sites and as a function of water type
d) Emerson test; sudden immersion of aggregates for aggregate
stability; both immediate and longer term effects can be recorded
infiltration and runoff, of various degrees of crust degradation ('trampling' and puncturing; see Plate 6).

The particularity of crust formation, where rainfall is assumed to be the principal agent responsible, is the delivery of energy in a co-quanta together with a given volume of water - a raindrop - ideally, therefore, both wetting and energy effects should be examined in unison. As these two are linked for a given drop height, comparison must be made at different drop heights for a given wetting rate if their respective effects are to be isolated, effectively altering the wetting unit : energy unit (instantaneous kinetic energy) ratio, and comparing the resultant seal formation by way of infiltration and runoff, measured on a common scale, in this case cumulative energy. Crust formation can be assessed, amongst other possibilities, by the change in surface porosity, as has been done here by the use of hand spraying (Plate 4), before and 24 hours after rainfall simulation. Monitoring of changes in surface characteristics (in terms of rate of water acceptance) under natural rainfall over the rainy season, after drying, again by means of a handsprayer (Plate 7) is another approach to assessing the effects of rainfall on the surface, albeit in this case without being able to separate the wetting and energy effects. The results of these various approaches will be reported in chapters 7 and 8.

(4.4)
Crust stability upon wetting: details of tests employed in this study

(4.4.1)
Stability upon sudden wetting (immersion) and issues of soil and water chemistry

In terms of simple tests of crust response to sudden wetting, the most appropriate model was considered to be a version of the classic Emerson Dispersion Index (Emerson, 1967), which classifies a soil aggregate response to sudden immersion into eight classes depending on the degree of cloudiness of the water. This cloudiness is taken to indicate the degree of dispersion caused by the clay in the aggregate. The advantage of this test is that it measures a property which has been shown to be an important mechanism in seal formation (pore clogging with fine material dispersed under the impact of rainfall) and which is quick, cheap and easy to carry out. The index used in this present study is a modification of the Emerson Index, which been simplified to only
Plate 6

Surface treatments used in rainfall simulations

a) (top) ‘Nail board’ used to puncture and to roughen crusted surface
b) (middle) removing crust (Marigat)
c) (bottom) crust removed and control (Marigat)
Plate 7
Preparations related to rainfall simulation campaign (clockwise from top):

a) Preparing reserve plots in case of rains (Lameluk)

b) Plots of soil removed from Lameluk to residence; Plots under natural rainfall, crust and crust removed, all replicated, and one set of plots under a rainfall simulator screen at 3.5m, the same height as the simulator, to assess the effect of reduced kinetic energy under natural rainfall.

c) Hand sprayer being used to monitor crust development on the plots
four classes and has been used specifically with respect to crusting rangeland soils (in Australia), but not specifically for indicating runoff potential (Tongway 1994).

With all these tests, the high clay content at many of the sites implies that the chemistry, as indicated from the review in Chapter 3, of the water used could have a significant effect on apparent dispersibility and hence sealing/relative runoff ranking. Ideally, therefore, rainfall simulations would be carried out either with water of a standardised chemistry (distilled) or with natural rainwater. The latter was attempted, having set up a rooftop collection system, but the volumes collected were too small or infrequent, and thus this was reserved for the validation tests (see below) and for water efficient simple tests. In the case of simple tests, samples are immersed in both rainwater and the source water used for the rainfall simulation and the same repeated for the clay dispersion test and handspraying of crust aggregate classes. It is believed that this will give an indication of the practical consequences of any chemical differences between natural rainfall and the water used in the simulations.

(4.4.2)

Stability upon 'gradual' wetting; swelling index and relevance to cracking crusts and runoff

An alternative to the Emerson test was devised for this study, as the disaggregation of air dry aggregates is a response to pressure of air trapped in pore spaces, which in turn is a function of multiple factors, not just clay properties. Clay content is of particular interest, due to the evidence of clay enrichment of the surface and to the high clay content of many of the soils in the study area. In this study, therefore, the crust aggregates were first partially 'destroyed' by means of gentle dry sieving over a standard interval and the finest fraction (< 0.5 mm) then poured into a clear bottle up to a standard depth and water slowly added up to another mark. The bottle was vigorously shaken for 30 seconds and then left to settle for 12 hours. The increase in volume (height in the bottle) of the soil (Plate 5, c) was used as a 'swelling index', which was taken to be an indication of the combined effects of clay content and mineralogy. As with the other 'simple' tests, these data were then compared to those of rainfall simulation at the same sites from which the crusts were sampled, on the hypotheses that runoff ranking will be the same for both, and where runoff potential, in the case of this particular test, is assumed to be positively correlated to the swelling index. This assumption is based on the observation that many of the soils in the study
area manifest cracking in the dry season, and the hydrological implication of this was confirmed during fieldwork; runoff would not occur under rainfall simulation until these cracks had sealed.

(4.5)

Diagnostic properties and simple tests employed;
direct measures of infiltration

A nondestructive test for investigating changes in crust properties induced by rainfall, the handsprayer (Plate 4, c and d), which covers a far larger area than a penetrometer was developed. This has multiple applications, particularly the direct assessment in situ of infiltration, as well as a measure of changes in the porosity of the upper 5 mm of pre to post rainfall simulation surfaces. The protocol adopted for the handsprayer was the following; as many sprays as possible, recorded every 15 second interval, such that ponding occurs and, once it just appears, to maintain an incipient ponding by spraying when the surface moisture (readily apparent from the glistening in the bright sun) starts to disappear. In effect, one is maintaining a surface controlled wetting procedure, reflecting a natural process, and for this reason the test is considered to be promising. As wind diffuses the spray, it is important to use a wind shield, and a lightweight wind shield was designed and constructed for this purpose (Plate 4 c).

Wetting depth, is up to about 1 cm for the central 5 cm area after 90 seconds (depending on the number of sprays over that period, which is the basis of the test), and then decreasing asymptotically towards the edge of the wetted area. This made it difficult to calculate the infiltration rate, as one must decide upon an ‘effective’ area as a basis for calculation, and therefore the total volume infiltrated was also used as a measure with this test.

The results with this apparatus were very promising, and this is attributed to the naturalistic manner of water application and the undisturbed state of the surface exposed to the spray. An insecticide backpack mounted pump operated sprayer with much higher spray volumes was also tested, but as the pressure of the spray declined as the volume in the liquid container declined, this test was considered to be unreliable. Nonetheless, it revealed the effect of crusting when crusts were removed.
The hand sprayer uses less water, is more portable, and can be used with a higher degree of precision and standardisation, but integrates the soil surface infiltration response over a smaller area; hence more replication is required. The variability between replicates between ESE’s ('elementary' homogenous surface units in terms of morphology, which are assumed to be uniform hydrological response units, normally on the order of a minimum of 10 cm diameter; note that the concept of 'ESE' used here is applied at a finer resolution than that envisioned in the original Casenave and Valentin (1989) methodology, which is predicated on a 'pixel' or homogenous hydrological response unit of 1 m²) for the key sites selected will be reported in the Results chapter. This will determine whether the range of values, or 'error bars' around each mean infiltration curve for each ESE can be separated from other ESE’s, and thus whether they can be expected to have, within the limitations of an energy-free test, real differences in hydrological behaviour. These same ESE’s were then characterised in terms of their reflectance in the first four TM bands using a simple and robust Milton Multiband Radiometer, to assess the correlation between hydrological and spectral classifications of the surface, one of the principal objectives of this study. The results of this comparison are presented in Chapter 8.

‘Calibration’ of the handsprayer was carried out in order to determine the inherent variability of the apparatus in terms of spray volume and the change in spray volume delivered in response to accidental rotation of the spray head (changing wetted area and thus infiltration rate) (see Figure 4.4). On both counts this was considered to be within a reasonable range. The change in wetted area (= change in spray area) and hence the rate of spraying (and volume) required to maintain a constant incipient ponding was also measured in terms of sensitivity to rotation of the spray nozzle. The inherent variability is relatively low on this measure, and the wetted area inelastic to nozzle rotation up until a threshold (5 x 1/8 rotations), when the spray becomes a stream; but this is readily apparent to the user.

In short, the inherent variability can be said to be low, and the precision high. In addition, monitoring over the field season found virtually no change in calibration. Therefore, the reliability of this simple instrument can be considered to be high, and is seen as a possible alternative to rainfall simulation for indicating relative runoff rankings between sites and between ESE’s at each site. The results of comparisons between the ranking of runoff potential of the key sites based on hand spraying (and the other simple tests described) and rainfall simulation will be presented in Chapter 8.
Figure 4.4 Calibrations of hand sprayer

(a) Calibration by volume: each point represents the average of three replicates. Virtually no inherent variability, increasing volume as spray nozzle opened.
(b) Calibration by wetted area; relatively low inherent variability; when nozzle opened far enough a stream-like spray causes wetted area to be reduced, but this should be apparent to user.
Conclusion: the value of ‘simple’ tests

In conclusion, it should be apparent from the discussions above that, whether or not in the final analysis the interpretations of any single simple test is 'correct', that which might be called 'triangulation' or cross-checking between various qualitative and semi-quantitative simple tests can 'cancel out' some of the misleading impressions given by just one or two such tests taken on their own. The assumption is made that the greater the number of tests the greater the accuracy of the interpretation. This is a statistical principle which, when coupled with some knowledge of the strengths and limitations of the tests and the principal processes involved in crusting and infiltration, can lead to a reasonable characterisation of different surface units in terms of runoff potential without resorting to rainfall simulation. To establish the validity of such a characterisation, however, one must naturally provide a benchmark against which the interpretations can be tested, and in the case of this study this benchmark will be taken to be rainfall simulations where there is at least 70% kinetic energy reproduction and, of course, natural rain events themselves, to the degree that it is practical to monitor this highly unpredictable phenomenon given the non-availability of instrumented plots. The relationship between the types of tests employed in this study, organised conceptually in a hierarchical fashion according to the trade-off between the degree of user control, is represented as Figure 4.5

Rainfall simulation

Even with all the problems and limitations that rainfall simulators bring to research programs, many of us probably would be amazed at the high percentage of useful erosion, runoff and infiltration knowledge that has been obtained during the past 20 years from simulated rainfall studies. While simulated rainfall is not a magic method for satisfying all research needs, it often is the only way that research can feasibly be conducted. Many research studies could never even be considered if they could not be conducted using simulated rainfall

Figure 4.5
'Hierarchy' of Runoff Assessment Techniques
Comparing techniques in terms of degree of similarity to natural rainfall and degree of experimental control over water application and soil response

More realistic

- Runoff plots in the field under natural rainfall; static rainfall and runoff data (totals)

Runoff plots disturbed (removed to residence for observation); natural and altered surfaces under natural rainfall; dynamic rainfall and runoff data

Rainfall simulation; natural plots, natural and altered surfaces, artificial rainfall; dynamic rainfall and runoff data

Hand sprayer and infiltration rings; natural and altered surfaces, unrealistic wetting procedures (but rings are for runon area, behind bund; adequate); dynamic infiltration data (qualitative for sprayer)

Evidence of runoff in the field: sheetwash, rills, gullies; associated indicators of runoff / reduced infiltration capacity: crusting, crust characteristics such as thickness and strength; crust type as per ORSTOM system

'Field Laboratory' indicators of infiltration capacity of crust sampled from field; aggregate stability upon wetting, infiltration capacity of aggregate classes, clay content

Less realistic

Less control
(4.7.1)
Scope of rainfall simulation carried out in this study

A wide range of rainfall simulators designs have been used for a large number of applications in a variety of physical environments and under a spectrum of economic and logistical constraints. The present study is focussed on a particular intersection of these variables. This specific intersection of variables consists of:

- field rather than laboratory usage
- operation in a semi-arid environment in a developing country on a limited budget
- the objective of characterising relative and absolute runoff values of surface units for assessing water harvesting potential
- the use of this information as a decision support tool for project interventions.

(4.8)
Rainfall properties to be simulated

The importance of rainfall characteristics on crust formation and hence runoff is apparent form the review of crusting. In order to understand the complexities of accurately reproducing rainfall characteristics, the trade-offs in practice when attempting to reproducing multiple characteristics simultaneously, and the likely implications of such trade-offs on apparent runoff potential, it is necessary to briefly review at this point the physical aspects of the principal rain characteristics shown to influence crust formation.

(4.8.1)
Rainfall energy and drop size distribution

...until some parameter is proved to be adequate for comparison, this analysis suggests a) that both the drop-size distribution and drop-fall velocity of natural rainfall should be simulated as closely as possible and b) that an appreciable sacrifice of either for the other is unwise. One of the parameters may be chosen as a guide, but its influence should be secondary to a comparison with actual raindrop characteristics."

Meyer (1965), in a classic study of the effects of drop characteristics in rainfall simulation
From the review of crusting, rainfall energy emerged as the one of the most important parameter of rainfall with respect to crust formation. The term energy, however, can be defined, calculated and measured in a number of ways, and in the case of the present study, ultimately related to the infiltration and runoff response. As the objective of the present study is to characterise the (hypothesised) surface controlled runoff response to rain events in the study area, and as rainfall impact energy (whatever the definition and units) is hypothesised to be the genesis of surface control in devegetated tropical environments, the question of the reproduction or non reproduction of energy in rainfall simulation will be discussed at some length below. As was seen in Chapter 3, kinetic energy was found to be the most explanatory measure of measure with respect to crusting. Momentum, however, has also been used by some authors in explaining crust formation. Both kinetic energy (KE) and momentum (Mom) are a function of mass and velocity:

\[
KE = 0.5 m v^2 \quad (4.1)
\]

\[
Mom = m v \quad (4.2)
\]

where \( m \) is the mass of the individual raindrop

\( v \) is the velocity of the raindrop (normally at terminal velocity)

Note that momentum refers to the pressure effected upon the impact surface.

As can be seen from equations 4.1 and 4.2, the calculation of both kinetic energy and momentum is predicated on a knowledge of raindrop mass, which is a function of raindrop size, and raindrop velocity. The first documented studies of raindrop size date back to Lowe (1892), but it was not until the US Soil Conservation Service commissioned studies of Laws (1941) and Laws and Parsons (1943) that the systematic relationships between raindrop size and fall velocity, and between drop size distribution and intensity were established. Drop size distribution as a function of rainfall intensity, based on Laws (1941), has been graphically represented as Figure 4.6, together with a comparison with the drop size distribution of the simulator utilised. Note that the median drop size of natural rainfall (and therefore the drop size distribution) is positively correlated to the rainfall intensity, whereas for this rainfall simulator design, the drop size distribution is intensity invariate.
Figure 4.6
Intensity dependence of drop size distribution, natural and simulated rainfall

- Drop size distribution at 13 mm/hr
- Drop size distribution at 100 mm/hr
- Cumulative frequency of drop size distribution at 13 mm/hr
- Cumulative frequency of drop size distribution at 100 mm/hr

Simulated vs. Natural Rainfall; Drop size distribution

- 13 mm/hr
- 25 mm/hr
- 50 mm/hr
- 100 mm/hr

Simulated rainfall
As such, the discrepancy between the two will vary with intensity, and as drop energy is related to drop mass, so also the proportion of rainfall energy reproduced by the rainfall simulation will be intensity independent. The implication of this, for a drip-type simulator, the chosen design, is that there can be only one ‘design’ intensity providing 100% kinetic energy reproduction, away from which this will deviate from that of natural rainfall. With spray-type simulators, on the other hand, as used by Bryan (1994) and his research students in the Baringo area, drop size distribution varies with intensity, but not necessarily in accordance with the pattern found with natural rainfall; but rather as a function of the nozzle type and variations in pressure (a motorised pump drives the system) (Bowyer-Bower and Burt 1989).

The fall velocity of raindrops as a function of raindrop size, over the fall heights used in the simulations carried out in the present study, are represented in Figure 4.7. Note the disproportionate increase in velocity for changes in drop size at the larger end of the drop size distribution. This is due to the fact that drop mass increases as a cubic function of drop radius, the volume of a sphere being:

$$\text{Volume} = \frac{4}{3} \pi r^3$$

and where mass is proportional to volume.

In response to a gravitational force, the raindrop, upon release from a cloud or dropformer under a simulator board, will initially accelerate, but will eventually reach an equilibrium with an opposing dynamic force, which could be termed air friction, which corresponds to a drop size dependent terminal velocity. As friction operates on the surface area of the drop but gravity on the mass, and as mass increases disproportionately with respect to surface area (equation 4.3), the change in terminal velocity with drop size decreases with drop size. For the purposes here, and given that the physical principals under discussion are well known, it is not considered necessary to illustrate the mathematical derivations of this phenomenon, the results of which are illustrated in Figure 4.7 (upper diagram) over the range of board heights used in the present study.

As terminal velocity is not achieved with drip type simulators used under field conditions, as the drop commences at zero velocity, attaining terminal velocity is not of interest due to the logistics of raising the simulator to a sufficient height. In Figure 4.7 (lower diagram), the relationship between drop energy over the drop size range produced by the simulator board and the number of
Figure 4.7
Velocity as a function of drop height and the relationship between drop size and kinetic energy
drops per unit volume simulated rainfall and the resultant kinetic energy delivered to the soil surface for each unit volume of water consisting solely of drops of the specified size confirms the important implication of drop size distribution in terms of changes in the energy available for the reorganisation of the soil surface.

As a general principal, effective terminal velocity is achieved for all drop sizes across the rainfall intensity range simulated in this study - about 5 to 75 mm/hr, but centred on the 15 to 30 mm/hr range - at a height of about 13 meters, based on tabular and graphical data from Laws (1941) and Epema and Riezebos (1983). The maximum simulator height used in the present study, for logistical reasons, was 3.5 meters. Kinetic energy as a function of drop size and drop height, over the range of drop size and drop height used in the present study, is presented as Figure 4.8 (lower diagram). Note an increase in kinetic energy of approximately 66% between the lowest and highest rainfall simulator position. From Figure 4.8, drop energy as a function of drop size and height is presented (upper diagram) and (lower diagram) the kinetic energy per mm rainfall imparted to a m2 plot area, as a function of board height. Due to the greater proportion of rain volume delivered at drop sizes around the median value, the greatest contribution to total energy delivered to the soil comes from this segment of the drop size distribution, and not from the largest drops.

Laws and Parson (1943), in a classic paper, determined the relationship between raindrop size and rainfall intensity. The general relationship can be expressed as:

\[ D_{50} = 2.23 \text{ RI}^{0.182} \]  \hspace{1cm} (4.4)

where \( D_{50} \) is the median drop size

\( \text{RI} \) is (average) rainfall intensity

It is important to note that, unlike nozzle type rainfall simulators, drip type simulator designs typically produce an intensity invariant drop size distribution. This is a source of dissimilarity with respect to natural rainfall, and has implications in terms of energy reproduction and hence ability to induce crust formation and thus the apparent runoff potential. In other words, an apparent rainfall intensity dependence of infiltration and runoff under natural rainfall may in fact be an energy dependent response, which would not be as marked with an intensity invariate dropsize distribution drip-type simulator. Deviations from the kinetic energy of natural rainfall,
Figure 4.8
Kinetic energy as a function of drop size and height and drop size distribution

Energy as a function of drop size and drop height

Kinetic energy at drop heights between 1.5 and 3.5 m; contribution of each drop size class to the kinetic energy per mm simulated rainfall, where total kinetic energy/mm rainfall = the area under each curve.
due solely to deviations in drop size distribution under the simulator from that of natural rainfall, over the range of rainfall intensities used for the majority of simulations carried out in the present work, is presented in Figure 4.9.

Natural rainfall in this Figure Group is postulated to fall from heights of 1.5 and 3.5 m for the sake of comparison. The actual deviations from the kinetic energy delivered to the soil surface by natural rainfall at terminal velocity is presented as Figure 4.9, and indicating the proportion energy contributed by each drop size class; and in Figure 4.10 the range of energy reproduction achieved by the rainfall simulators at each height, as function of rainfall intensity is presented, together with the height required at each intensity to achieve 100% kinetic energy reproduction. The height required to achieve 100% kinetic energy reproduction is somewhat lower than that required to achieve effective terminal velocity, as the median drop size of the simulated rainfall is somewhat greater (Figure 4.9) than that of natural rainfall.

This is one possible strategy for compensating for a lower-than-terminal-velocity drop height, but if this principle is pushed too far, as, it is argued, has been the case with a number of portable simulator designs presented in the literature, there are a number of complications. Cases of this can be found from the earlier drip-type designs, such as those of McQueen (1963), with a drop size of 5.6 mm, and Osborn (1950), at 5 mm, both working in the United States. But even more modern drip-type designs exhibit such a strategy, such as Hoogmoed (1987), using 5.6 mm for experiments in Mali and Israel and Bhardwaj and Singh (1992), working in India with a portable simulator with a 5.75 mm average drop size. The median drop size used with 23 drip-type simulators over a 32 year period in the U.S, Israel, Australia, New Zealand and Belgium is represented in Figure 4.11, a. The studies from which this figure is derived consist of seven examining runoff, but a larger number investigated the clearly related phenomenon of infiltration.

(4.9)

Complications in the accurate simultaneous simulation of various parameters of natural rainfall and trade-offs involved; ‘Drip type’ versus ‘Spray type’ simulators

From the preceding discussion, it is apparent that there are a number of interacting factors which must be considered when attempting to simulate natural rainfall, some of which are mutually
Figure 4.9
Kinetic energy of simulated and natural rainfall at the simulator drop heights

Kinetic energy for natural rainfall at 1.5 and 3.5 m drop height; such that differences in energy due purely to differences in drop size distribution (a function of intensity)
Figure 4.10 Kinetic energy of the simulators used and the drop heights at the median drop size of natural rainfall required for 100% kinetic energy reproduction at various rainfall intensities

Over the rainfall intensity range typical of the study area, the simulator drop heights reproduce, for the 1.5 m simulator, between 44 and 53% and for the 3.5 m simulator, between 70 and 84% of the kinetic energy of natural rainfall, assuming that the drop size distribution of the simulated rainfall were the same, and at each intensity, as that of natural rainfall. An ideal drip-type simulator would need to be almost six metres high for 100% energy reproduction.
Figure 4.11
Median drop size of simulators and water use requirements

Median drop size of drip-type simulators, 1957 - 1979
(based on data from Bubenzer, 1979)

Comparative water requirements of spray-type and drip-type simulators per unit plot area to achieve steady state infiltration
(based on data from Bowyer-Bower and Burt, 1989, semi-arid Swaziland)

\[ y = 1100.3x^{-1.9257} \]
\[ R^2 = 0.9701 \]
incompatible, such as having a practical drop height for field use and achieving terminal velocity. Whilst this latter problem can be overcome with spray-type simulators, with which drops exit the nozzle at velocity, there are considerable difficulties controlling drop size distribution with this design, due to variability in the pressure in the system. Note that the changes in drop size distribution with changes in intensity / pressure does not necessarily correspond to the changes in drop size distribution with changes in rainfall intensity of natural rainfall. Even if there were no variability in pressure, however, there is often poor spatial uniformity of rain depth with the spray-type design due to the greater density of drops at the centre of the plot, and the aforementioned problem of achieving low intensity without leaving the plot dry for relatively long intermittent periods between spraying (Bowyer-Bower 1992).

At high intensities, the proportional change in intensity for a given change in intensity is lower and therefore less serious, and the question of accuracy at lower intensities is not so important for erosion studies, which is the principal application of rainfall simulation from the literature reviewed, where there is greater interest on the high intensity events which produce a disproportional amount (Oostwoud 1992) of annual water erosion, as has been shown for the study area. For the purpose of assessing runoff potential, however, it is very important to know the threshold intensity for runoff production, and thus accurate reproduction of lower intensities is a key criteria when selecting a simulator design. Figure Group 4.12 (lower figure) indicates that above 75 mm/hr one drop size distribution is acceptable for rainfall simulation, but below this intensity threshold the value should range between one and 3 mm, as a function of intensity.

The drip-type design is attractive in the sense that the intensity variability at low intensities is much less pronounced than with the spray-type alternative, although as noted above, such simulators typically produce a single drop size, which can however be varied by placing a screen under the drop formers to cause dispersion and coalescence into a reasonable drop size distribution. This distribution, on the other hand, generally cannot be altered as a function of intensity unless the screen height and mesh size and density were altered for each intensity, which would involve a considerable time in calibration, which was beyond the scope of the present study. Another problem with the drip-type simulators is the fact that drops leave the drop forming capillaries at zero velocity, meaning that drop formers usually have very sub-optimal kinetic energy reproduction when they are less that seven metres tall, which would be an impracticable height for field operations, although such designs are used at full height in the laboratory (cf. Bryan and de Ploey 1983).
Intensity and drop size characteristics of rainfall relevant to rainfall simulation for assessing runoff potential

(upper) Drop size distribution associated with rainfall intensity classes, the lower graph measured data for Zimbabwe; note variability between this distribution and the classic reference work based on data from the US Midwest, above (Hudson, 1981).

(lower) As applied to rainfall simulation (Bubenzer 1979).

**Drop Size Distributions at Low, Medium and High Intensities**

1. 1-12.7mm/hr
2. 12.7-40mm/hr
3. 40-65mm/hr
4. 65-115mm/hr

(from Laws & Parsons, 1943)
Some of the key differences between drip and spray type simulators with respect to both accurate reproduction of rainfall characteristics and the logistics of doing so under field conditions are summarised in Table 4.4. Note, however, that in table (b) the area exposed to rainfall under the drip-type is only 0.5 m², whereas the diameter of the area exposed under the spray type ranges from 2.5 m² at 120 mm/hr to 8 m² at 10 mm/hr. To compare water use efficiency per unit area (an area of 2.5 m² is assumed for all intensities), refer to Figure 4.11, b. Both Table 4.1, a, and Figure 4.11, b, reveal a great advantage at the lower intensity range in terms of water use with the drip-type simulator, the range of interest for the present study. Only at about 90 mm/hr is there no longer an advantage to be gained in this respect to by using a drip-type design. A lower intensity range is of interest because of the rainfall characteristics of the study area (Rowntree 1988); the fact that greatest number of events fall into the lower intensity categories, and because these are the events which may prove critical in periods which would otherwise effectively be dry spells from an agronomic point-of-view.

The variability in spray area with the spray-type simulator is due to the fact that this design typically regulates intensity by changing water pressure, with resultant changes the spray area. Thus the water use efficiency per unit area is considerably less unattractive with the spray-type simulator design that would at first appear from Table 4.1, b. However, in practice only the central area of a plot is used under spray-type simulators due to the substantial change in intensity from the centre of the nozzle to the edges. Taking a figure of 2.5 m² as a standard plot area for all intensities under the spray-type simulator, the relative water use efficiency vis a vis the drip type can be seen from Figure 4.11, b, to range from 10% at 10 mm/hr to parity at 120 mm/hr. Thus the advantages of using a drip-type simulator are most evident at low intensities, and in the study area where the majority of rainfall (Rowntree 1988) is delivered at intensities below 30 mm/hr.

Note also that the logistics of transporting large volumes of water in areas of difficult terrain can be insurmountable, particularly in landscapes highly dissected by gullies as is the case of the study area. For example, the University of Toronto research carried out in the study area using a 5 metre simulator was restricted to sites where a 2000 litre water trailer could be towed and necessitated the use of salt rich water from several rivers in the area (Bryan 1994).

Given the importance of the chemistry of the soil-water solution on crust and seal behaviour, the consequences of using such a water source may be great. In addition, the chemistry of surface water from such sources is likely to be rather variable over time, depending on rainfall. As many
### Table 4.4(a) Advantages and disadvantages of spray-type and drip-type simulators

<table>
<thead>
<tr>
<th>Attribute</th>
<th>'Spray type'</th>
<th>'Drip type'</th>
</tr>
</thead>
<tbody>
<tr>
<td>Drop size distribution with respect to intensity</td>
<td>More flexible but less control over</td>
<td>Less flexible but more control over</td>
</tr>
<tr>
<td>Terminal velocity of raindrops</td>
<td>Obtainable due to water being under pressure</td>
<td>Large drop height impracticable in field situation</td>
</tr>
<tr>
<td>Experimental error</td>
<td>Difficult to control adequately</td>
<td>Relatively easy to control under field conditions</td>
</tr>
<tr>
<td>Versatility</td>
<td>Good; eg over trees</td>
<td>Less versatile</td>
</tr>
<tr>
<td>Economy of water use</td>
<td>Very high consumption; see Table 4.3 b</td>
<td>Very economical</td>
</tr>
<tr>
<td>Protection from wind</td>
<td>Difficult due to width of spray area</td>
<td>Complete protection unproblematic if not excessively tall</td>
</tr>
</tbody>
</table>

Adapted from Bowyer-Bower and Burt, 1989

### Table 4.4(b)

**Water consumption under drip and spray type simulators at various intensities; an example based on runoff responses on degraded surfaces in Swaziland**

<table>
<thead>
<tr>
<th>Rain intensity mm/hr</th>
<th>Average time to steady state runoff minutes</th>
<th>Water consumption, Spray-type litres</th>
<th>Water consumption, Drip-type litres</th>
</tr>
</thead>
<tbody>
<tr>
<td>10</td>
<td>600</td>
<td>5250</td>
<td>52.2</td>
</tr>
<tr>
<td>20</td>
<td>120</td>
<td>1260</td>
<td>22.5</td>
</tr>
<tr>
<td>30</td>
<td>90</td>
<td>980</td>
<td>25.0</td>
</tr>
<tr>
<td>60</td>
<td>30</td>
<td>288</td>
<td>17.5</td>
</tr>
<tr>
<td>90</td>
<td>25</td>
<td>242</td>
<td>21.0</td>
</tr>
<tr>
<td>120</td>
<td>15</td>
<td>171</td>
<td>17.5</td>
</tr>
</tbody>
</table>

Adapted from Bowyer-Bower and Burt, 1989
of the soils studied are relatively clay rich, the validity of comparisons between them is highly questionable using this water source, and yet this water source (and others, such as irrigation channels; Oostwoud 1992) were the exclusive source of water for the University of Toronto research programme in Baringo. Thus, in short, the advantages of the potential accuracy of high kinetic energy reproduction, as with this 5 metre spray-type simulator, may be outweighed by the lower replicability / comparability due to water source chemistry as well as intensity variations due to pressure changes and wind, and the associated changes in drop size distribution, wetted area and temporary drying, and the implications for the apparent infiltration values and thus runoff rankings of sites being compared.

(4.10)
Trade-offs and complications with the drip-type simulator design

From the above discussion, it can be seen that from a logistical perspective the drip-type simulator is clearly preferable under field conditions in developing countries because of the water use efficiency at low intensities, which is precisely the rainfall intensity range of interest in determining runoff generation for water harvesting suitability assessment, as well as the potentially greater replicability of the protocol employed. The drip-type design, however, in field use, has the inherently problematic characteristic, as discussed above, of suboptimal drop velocity (due to the restricted drop height possible and the lack of velocity imparted by the drop forming capillaries). Attempts to overcome this dilemma by increasing drop size, however, have been shown above to introduce a large number of unknowns and complexities with respect to the calculation of energy equivalency with respect to natural rainfall, not to mention the effects on crust formation and runoff. In terms of plot size, spray-type simulation is able to integrate the soil response to rainfall over larger areas, particularly if some non uniformity of spray depth is accepted. The question of the degree of 'upscaleability' from small plots to 'natural' runoff producing units involving a higher variability in source and sink areas will thus need to be examined in the case of (small area, portable) drip-type designs. In short, each design has a variety of advantages and disadvantages, and those most relevant to the research question being addressed must be identified with care.
Simulator design chosen as best satisfying the criteria established for the purposes of ranking relative runoff potential

The simulator design chosen (and later modified for the second field season) for the present study is based on the 'Amsterdam' model, developed by the Dept of Physical Geography at the University of Amsterdam, initially for studies of soil splash on forest soils in Luxembourg (Imeson 1977) (see Figure 4.13 and Plates 5 and 6), and later applied to semi-arid areas of southern Spain and mountainous semi-arid areas of Morroco (Imeson 1983, Imeson and Verstraten 1986) and Kenya (Bryan and Sutherland 1989). A similar design used more recently has also been applied in southern Spain (Obando J, pers. Comm. 1996). A full list of research groups using various versions of this design and the locations of use are presently being compiled for the BGRG Rainfall Simulation Electronic Database at the University of Leicester (Cammeraat, pers. Comm. 1999), to which the revised version developed as part of this research will also be added. The present design stems from evolutionary developments in use in association with the Agricultural Research Station Zaidin Granada (Bowyer-Bower and Burt 1989) (Figure 4.14).

This same simulator has been used in the Baringo study area (Bryan and Sutherland 1989) under the auspices of the University of Toronto erosion research programme in the area. These simulations, however, were principally carried out on the Tugen hills surrounding and transition piedmont zones to the Njemps flats, the Njemps flats being the heart of the study zone delimited for the present study. The 'heart' of a drip-type simulator is the drop forming board, developed by Prof. J. de Ploey of the Laboratory of Experimental Geomorphology, Leuven, Belgium. The Leuven group has used the drop forming board under laboratory conditions, converting a church tower (!) (Jungerius, pers. Comm. 1996) in order to accommodate the drop height of 7 meters, allowing 90% kinetic energy reproduction (Bryan and de Ploey 1983). For field use, clearly, a compromise needed to be made in terms of drop height for logistical reasons. The current design allows a drop height of between 1.3 to a maximum of 2.0 meters from the mesh screen, depending on the particular version. The mesh screen was introduced in order to improve drop size distribution.

The design criteria used by Imeson (1977) were:
Figure 4.13 Origin of the rainfall simulator used

The original rainfall simulator (left) upon which the design employed is based. Kinetic energy (lower right) was varied by adjusting the height of the board on the ladder and drop size distribution (upper right) with the interwire spacing of a mesh and the distance below the board. (Imeson 1977)
Figure 4.14 Drop former mechanism of the rainfall simulator used

The ‘heart’ of the rainfall simulator; a system for producing drops of the desired size and at the the desired rate: the drop former and rainfall simulator board. Drop size is a function of the diameter of the tygon tubing and fishing line, rate of the pressure head inside the sealed board.

(Bowyer-Bower and Burt 1989)
- Inexpensive
- Able to be used in a remote, hilly area, having few access roads and limited water supply
- Allow for *in situ* comparisons (of soil erodibility)
- Consistently reproducible results
- Approximate natural rainfall as much as possible
- Simple and light enough for one person to set up, use, and dismantle

The basic Amsterdam design was further elaborated by Bowyer-Bower and Burt (1989) for use in the semi-arid lowveld of Swaziland. More specific criteria stipulated by Bowyer-Bower (1989) with respect to the reproduction of the characteristics of natural rainfall are, for an intensity range of 10 to 120 mm/hr and a plot area of at least 0.5 m², the accurate reproduction of:

- Raindrop size
- Height of fall
- Number of drops per unit time

Curiously, however, no indication is given in either Bowyer-Bower and Burt (1989) or Bowyer-Bower (1993), of the rainfall characteristics of the study area, nor of the characteristics of the rainfall produced by the simulator used. Furthermore, the height of fall (at 2 m) in no way accurately reproduces that of natural rainfall.

(4.12)

**Ideal requirements for rainfall simulator for the present study and actual characteristics of simulator chosen**

Following logically from the design ‘terms of reference’ for the present study, the simulator (and any alternative or complementary environmental survey tools and techniques), should ideally be low cost, feasible to construct in-country, relatively simple to operate, portable and quick to generate results. The results should be reliable for the purpose of comparison between treatments and between sites, in other words deliver a consistent rain event, in terms of the calibrated intensity and the spatial and temporal distribution of the rainfall, both within storm and between storm over the course of the field season. The results should of course also be accurate, which
means reasonable reproduction of the characteristics of natural rainfall in the study area and particularly those characteristics shown to be important controls on crust formation. Hence median drop size and drop size distribution as well as kinetic energy should be within critical limits of local natural rainfall.

Due to the complexities of the interactions between these variables, the consequences of deviations from natural rainfall characteristics on crusting is poorly understood. This is more true for the implications for runoff than for erosion, as much greater emphasis has been placed on the former in studies using rainfall simulation (deduced from an inventory of 61 studies using rainfall simulation, Bubenzer (1979)), though the processes are of course interrelated.

Unfortunately, none of the characteristics of the natural rainfall to be simulated for the present study are known apart from depth and intensity patterns. Therefore, the representativity of the chosen depth-intensity design rainfalls simulated is not known. In the study area there was one recording rain gauge in an area, but these records have disappeared. Fortunately, the records were first written up by Rowntree (1988) and the principal characteristics of the rainfall in the study area of relevance to mapping runoff potential and assessing water harvesting suitability outlined in Chapter 7. However, due to the low temporal resolution of the rain gauge, the minimum intensity increment that can be calculated is 30 minutes. Informal rainfall collection carried out by the present author shows substantially higher intensity peaks measured over shorter intervals, as might be expected, and it is reasonable to assume that these bursts, which normally occur at the beginning of the storms and thus onto dry soils, are particularly important in determining runoff response.

(4.13)

Design and use of the simulators employed in this study

Plates 8, 9, 10, and 11 present an introduction to the design, calibration, set up and operation of the 3.5 m (the final design) and 1.5 m simulators (the original design) used (respectively) in the second and field seasons. As mentioned earlier, Table 4.4 outlines the advantages of this type of design. The drop size distribution of the board employed and the kinetic energy reproduction,
Plate 8
Testing 3.5m simulator

Clockwise from lower left;

a) Testing monitor funnel design
b) Testing rainfall spatial distribution under board
c) 3.5m simulator assembled, showing monitor funnels and board
Plate 9  Raising 3.5m simulator

a) (top) Raising 3.5m rainfall simulator
b) (bottom) Simulator in use at Lameluk field station
Plate 10
Setting up 1m simulator

Clockwise from upper left; 
a) Manometer board  
b) Difference in height in tubes, proportional to rainfall intensity  
c) Setting up rainfall components of 1m simulator  
d) Setting up runoff plot component of 1m simulator
Plate 11 Testing lm simulator

a) (top) Initial rainfall spatial distribution under simulator board used by Rorke Bryan / Moi University
b) lm simulator being tested, after cleaning board
compared to a reference natural rainfall value at different intensities and different heights and across the range of drop size classes.

From these data we may summarise by noting that the rainfall characteristic believed to be the most important in terms of crust formation, kinetic energy, is reproduced (with respect to the Laws and Parsons (1943) drop size distribution and Eperna and Riezebos (1983) drop height-energy calculations, which are taken to be the values for a natural rainstorm), for the 1.5 m simulator, at between 45 and 53% of that of natural rainfall over the intensity range of 13 to 50 mm/hr; and for the 3.5 m simulator, between 71 and 84%. Whether or not these levels of kinetic energy reproduction will be ascertained, in part, by comparing the infiltration and runoff values, where there are common sites, with the results of the 5 m spray-type simulator of Bryan (1994), bearing in mind the various caveats raised above regarding both the spray-type design in general and the specific manner of implementation as per the University of Toronto research programme, particularly the possible effects of water chemistry.

The operation of the simulator design chosen is fairly straightforward, which is one of the reasons for employing this design. Referring to Plate 10, the novel aspect of this design is the manner of setting rainfall intensity, which is based on the Mariotte principle and capillary principle. The heart of the design, apart from the drop forming mechanism, which is presented in Figure 4.14, is the manometer board (Plate 10, a). Water runs from a reservoir (20 litre semi-translucent jerry can; in this case two were employed to increase the length of simulation possible and a Y connector added; translucent in order to monitor water levels). Water flows through the hose from the jerry can which is open (taps were added to the jerry cans with some difficulties sealing them) and into the manometer board. The volume of flow in the original design is by way of a ‘thumbscrew’ which squeezes the hose, but in this case we substituted a high precision in-line valve for greater control over the rate of flow.

The water allowed through this valve then rises up first capillary (b) against the pressure of the air in the capillary, whilst the rest of the flow continues across a restriction, a changeable aperture separating the two capillaries. Part of this flow then rises up the second capillary, which is the same diameter as the first one, and the difference in height between them is proportional to the rate of flow / hydraulic head / rainfall intensity. Even as the level of water drops in the jerry can, the hydraulic head remains the same, in theory, due to the Mariotte effect, which is achieved by
placing a capillary through a bung sealing the hole in the top of the jerry can, which connects the atmosphere to the system, under the water level.

Upon entering the simulator board (Plate 11), the water then fills up the board against the pressure of the air ‘trapped’ in the board, the latter being released by way of a bunged aperture at the opposite corner of the board from the water entry point. Drops then form at the end of the fishing line at the centre of the drop formers (Figure 4.14, a) and fall 30 cm onto a wire mesh suspended below. Here the drops break up and coalesce into larger drops and then fall with a given drop size distribution described above onto the soil 1.5 m below. As can be seen from Plate 11, a, a board inherited from the University of Toronto programme, the spatial distribution of the rainfall is not necessarily uniform. This is a problem with the drip-type design, depending on the source water, but it is inevitable that the board will require cleaning, which is a time consuming operation and had to be done several times during the fieldwork.

A risk, however, is that, if the board is opened up, it may be difficult away from the laboratory to reseal it. Hence the option was taken to completely strip out the drop formers and insert new ones, which takes about three days including drying time. Two 1.5 m simulators were employed simultaneously in the first field season, using, ‘board # 1’ (used previously by the University of Toronto and Moi University) and ‘board # 2’, kindly provided by Prof. Jungerius of the University of Amsterdam.

By the end of the first field season there was some dissatisfaction with the results from the 1.5 m simulator, due to much longer times / raindepths to runoff and higher infiltration rates than with the 5 m simulator ‘reference values’ at the sites where both were carried out; Lameluk (site of the University of Toronto / Moi University field station) and Eldume. Thus in the second field season a new type of simulator was designed and built which aimed to retain the advantages of the original design, but raising the board to a target kinetic energy reproduction of 70% of (Laws and Parsons’) natural rainfall for a 25 mm/hr design storm.

From Figure 4.10 it can be seen that this gives a theoretical kinetic energy reproduction of 75% of natural rainfall so defined, which was assumed to be sufficient to give a good approximation of the runoff behaviour under real storm events in the study area. 1.5 m simulations were also carried out in the second field season at the main reference site of Lameluk for the purpose of comparison with the 3.5 m simulator. The results of the first season were not explicitly compared
with those of the second season due to the likelihood of changes in the soil surface in the year interim (Spring 1996 to Spring 1997) and because of the expansion of irrigated fields which forced a change of exact locations at Lameluk and Ongata Mara between the first and second seasons.

The 3.5 m simulator was built under supervision in the Engineering laboratory of Moi University, Eldoret, the host nation counterpart institution for this research, which required about ten days of work, including some modification en course, as this was an experimental design. Plates 8 and 9 illustrate the new design, including the spatial distribution of rainfall, which was affected by periodic cleaning of this new board from the University of Amsterdam over the course of the field season. The three principle innovations with this design compared with the original are:

1) The addition of ‘monitoring funnels’, which allow for a continuous simultaneous measurement of (pre-calibrated) rainfall intensity and runoff, as well as the real time spatial variations between the two sides (each over a different plot) of the simulator board. Each funnel, which samples about 12% of the rainfall from one half of the board, sends the sample down a tube along a folding arm to a tipping graduated cylinder marked in ml depth, which is recorded every five minutes and then drained (Plate 8, a). Although graduated cylinders could be placed on the ground, this would directly affect the soil surface and be difficult to monitor by the person(s) busy collecting runoff. As the drops still had about 3 m to fall after passing the funnels, there was opportunity for mixing due to friction, reducing the probability of lesser rainfall underneath the funnels, although this was still the case, visible in the first few minutes of the simulation.

2) The principle that, as a vehicle is anyway realistically required to transport water etc., that this can as well be used as a source of physically stabilising the board at a greater height. As such, a non self-supporting ‘ladder’ construction was chosen as the basic framework, which can be assembled using nuts and bolts in a few minutes from the constituent sections using no special tools. The ladder height is approx. 4.2 m. The process of raising the simulator is demonstrated in Plate 9; throwing two ropes over the truck and pulling it up, board suspended, with a third person assisting from underneath the ladder. As such, it is recommended that the person under the ladder be on good terms with the two others. In contrast to the terms-of-reference of the original design, which specifies one person use, this requires more workers, however it is judged that, due to the water requirements, it is unlikely
in practice that rainfall simulation would be carried out by a lone worker, much less without a vehicle.

A later revision saw the ladder mounted directly on the roof, allowing one to drive short distances from site to site without reassembling the simulator. The roof rack can be adjusted for these purposes otherwise the third person mentioned above can stand on the roof clinging desperately to the simulator while the vehicle is being driven along, as was first attempted, much to the entertainment of the local people. The advantage of using the vehicle to stabilise the simulator is that a larger structure is not required, such as the square pyramid or rectangular frame typically used with both drip and spray-type designs, saving time in setting up and dismantling the frame, which allows for more simulations to be carried out.

3) The design of a rapid and effective system of shielding the rainfall from the wind, which is essential in semi-arid environments due to the lengthy inter-tree fetch. This consisted of iron sections to which are attached heavy plastic sheets, which are bolted rapidly onto either side of the ladder and kept taut and away from the path of the raindrops with ropes secured with pegs from the top of the simulator.

(4.14)

Calibration of simulators and simulator boards #1 and #2

- Experimental design and Results
- Implication for this study and others using the same simulator

In light of the manifold sources of variability reviewed above, both in terms of the reference value being simulating (natural rainfall), and the variability inherent in the simulation process itself (a function of the design chosen), it can be concluded that the key criteria for the success of rainfall simulation, for a meaningful comparison between simulations results, will be consistency between simulations. This consistency will be defined in terms of temporal and spatial variability of simulated rainfall so that, at the least, one is able to compare the response of the soil (surfaces), between sites, and for a given treatment (the treatment being either a change in the rainfall characteristics or a change in the surface, for example, removing the crust).
This is particularly important in the case of the present work, where threshold time/depth has significant implications in terms of runoff yield (in the case of short rain events, or a short burst above the threshold runoff producing rainfall intensity followed by very low intensity rainfall, as appears to be the case in the study area). If, for example, one end of the rainfall simulator board delivers rainfall at a greater intensity than the other end, then the orientation of the board might give very different threshold time/depth to runoff if the plot length is sufficiently long and smooth (1 m in the case of the first field season).

In the second field season the rainfall simulator board was turned sideways and two plots (one control and one crust removed) subjected to the ‘same’ rainfall intensity, in response to the findings of the first field season of variability between simulation runs in measured rainfall intensity at the same apparent / calibrated / target intensity (more on the calibration of this simulator design below), which made comparison difficult. If, in the case of turning the board sideways, however, there is considerable variability in intensity between the two halves of the board, then the results will a) be inaccurate if this difference is not measured and b) even if it is monitored, in this case using the funnels described above, the comparison between treatment and control will be no less complicated than with two separate simulations.

Detailed calibrations were carried out on both simulators and both boards, with particular attention was paid to the issue of the spatial variability of rainfall, for the reasons discussed above. Several weeks were invested in calibrations at the beginning of the first field season and one week at the beginning of the second. A very thorough and systematic approach was taken to calibration because of the centrality of rainfall simulation to this study, the fact that it was being considered the reference value against which simpler tests would be compared (both as a part of the experimental design and given the difficulty of measuring simultaneous rainfall and runoff under natural rainfall, due to the lack of instrumentation), and because of the relative complexity compared to the simple tests, of rainfall simulation, which implies a greater number of possible sources of error. In addition, the ultimate objective of this work has to do with comparisons; between sites, between treatments, between instruments, and thus it is important to know the degree of inherent variability characteristic of this instrument in order to know whether apparent differences between sites or treatments or instruments can be considered to be real differences.

This was particularly important as it was too time consuming to carry out a sufficient number of replications at all sites for all treatments to allow for a statistical analysis of significance of
difference. The treatments in this case involved at least 10 sites (differences between sites), at least one treatment at each site (crust removed) and at least two rainfall intensities (treatments) and in the second field season two drop heights at some sites (treatments). Indeed there are few instances (apart from some laboratory studies) of systematic replication using rainfall simulation uncovered in the literature. As such, one must choose between ascertaining the statistical validity of apparent differences between a control and a treatment at a given level of confidence, or ascertaining patterns of apparent differences across a larger number of treatments.

As the objective here is to develop a survey methodology, in which case the former strategy is likely of little interest to the user, the latter option was favoured. Having chosen this route, it was then important to establish the precision of the instrument used, particularly as so little had, surprisingly, been reported on this aspect of this widely used design. This was generally found to be true of rainfall simulation studies. The reason for this is not know, except perhaps that it is so time consuming, precisely because it involves, or should involve, replication (and is not as exciting as something one can actually do with the simulator).

It is believed that the findings from these efforts made to systematically assess the various possible sources of error with this widely used design, particularly in terms of discoveries about the error bars around target intensities, to be discussed below, constitutes a contribution to knowledge of application to erosion, infiltration, crusting and runoff studies. These error bars greatly reduce the effective precision of the instrument, such that only qualitative classes such as 'low', 'medium' and 'high' intensity can be realistically discriminated between; and with a good deal of separation between the highest target intensity in the lower class and the lowest target intensity in the next, to ensure a non-overlap of error bars.

(4.15)

Calibrations carried out

Systematic calibration of the drop former board, which is the 'heart' of the rainfall simulator design chosen, was carried out over a period of several weeks at the beginning of each of the two principal field seasons. It is not possible to report all of the results; instead only those tests which are considered to be of interest (whether or not the results were as anticipated) will be examined
here. A number of problems in terms of variability in measured values, in particular in the spatial
distribution of the rainfall, which has implications as described above, has emerged from this
work.

More fundamentally, the discrepancy between intensity as calibrated in the field and as monitored
under field conditions, both over the course of an individual run and over the field season, has
been brought to light and calls into question the basic design of this widely used simulator. This is
very significant in that the effect of intensity on sealing, runoff and erosion cannot be accurately
ascertained if rainfall intensity is not known with a reasonable degree of precision. Similarly,
intensity as an explicit treatment, as used in Bowyer-Bower (1992), may be dubious at relatively
small differences in intensity if there are large error bars in actual (as opposed to calibrated)
rainfall intensity in field use, as appears to be indicated by this present work.

As has been outlined earlier, the simulator design chosen has been widely used in semi-arid areas
of the Mediterranean, as well as in some areas of northern Europe, since the late 1970's. Interest
remains strong, and there have been many requests from the former area in particular, and as far as
Israel, for the Amsterdam type design (Cammeraat, pers. Comm. 1999). None of the papers
reviewed report any data about calibration under field conditions. It would appear that the
assumption has been made that an initial calibration at the start of the simulation campaign, or
perhaps the calibrations made by Amsterdam group, are valid over time. If so, then this
assumption does not hold true for the present study, and it is suspected that the same is also true of
many of the other studies using this (and similar) drip-type designs. If this is correct, then a more
rigorous monitoring protocol is required in future and some of the results of earlier work may
need to be re-examined. Indeed, it may be necessary to re-examine the concepts behind the
manometer board, or even the whole hydraulic system, sound as it would appear to be on the basis
of the principles of physics on which it is predicated.

It is also important to point out that calibrations between a) the difference in height between the
two capillaries of the manometer board and b) measured rainfall intensity under the board are
impressively tight between replicates on one day at the field station at the start of the rainfall
simulation campaign. Actual behaviour under field conditions and over the course of the field
season, however, revealed a dramatic increase in variability in the calibration, to the point that
large differences in hydraulic head / differences between the capillaries / rainfall intensity would
be required to ensure that the error bars for two target intensities do not overlap. This
The phenomenon would not be apparent to the user unless a) a sufficient number of ‘replicates’ (simulations at the same intensity, even if at different sites) were carried out and b) intensity measured for all simulations and c) preferable, continuously, as opposed to relying on the calibration upon which the design is predicated.

**(4.16)**

**Relationships between differences in capillaries and rainfall intensity; changes in calibration over time**

The range of intensities over which the rainfall simulations would be carried out were anticipated to be from approx. 7 mm/hr, in order to determine threshold intensity for runoff generation, up to approx. 70 mm/hr, to examine whether crusting could be induced once the crust was removed, requiring a high rate of energy input in order not to spend excessive time on such runs. Thus it was necessary to determine the range of intensities which could be produced using various diameter inserts, from a 5 mm aperture, down to 1 mm. The objective of the calibration was to determine which aperture(s) produce the desired range of intensity for each board and which have a low gradient graph of difference in capillaries (independent variable) *versus* intensity (dependent variable), which equates to a lower relative error in terms of intensity for any operator error reading the hydraulic head off of the manometer board. Finally, the difference in height between the capillaries must be a readable distance without leading to errors due to parallax, for the height of the operators (two 5 foot 2 and one 6 foot 4!).

**(4.16.1)**

**Calibrations of board # 1**

Calibration of simulator board # 1 involved the use primarily of 2, 3 and 4 mm apertures in the inter-capillary ‘bridge’ of the manometer board. One and five mm apertures were also tested but did not fully cover the rainfall intensity range required. The results of the initial (field station) calibrations, presented in Figure 4.15, indicate little variability, with the calibration on 15/3/96, using three replicates, confirming this impression. The calibration of 23/2/96, with the same insert, however, shows some considerable difference from that of three weeks later, which could
Figure 4.15 The calibration of simulator board #1 for insert apertures 2 – 4 mm
(clockwise from upper left)
NB: (b) two replicates at each hydraulic head (max +/- 5mm/hr) and (c) three replicates at each hydraulic head (max +/- 3mm/hr); otherwise one.
possibly be due to cleaning of the board in the interim, of up to 8 mm/hr difference at a difference of 40 mm between capillaries; this has potentially serious consequences if it were not discovered through monitoring changes in calibration throughout the field season.

Even more serious a problem slowly became apparent as represented in Figure 4.16, the variability in calibrations over the course of the field season, for actual simulations carried out under field conditions. This is not apparent in (a), calibrations with the 2 mm insert, probably because of the few simulations carried out with this aperture. However, with (b) the 3 mm insert, the results reveal substantial overlap in error bars in the rainfall intensity supposedly corresponding uniquely to differences in manometer readings which are widely separated. As a result, for example, one can barely separate, with confidence, the actual intensities of the target intensities of 33 and 53 mm/hr, due to a variability of +/- approx. 8 mm/hr for the former and +/- 10 mm/hr for the latter. Whilst the statistical probability of the lower target intensity erring on the 'positive' side of the average intensity whilst the higher target intensity errs on the negative, such that the error bars overlap, is only 0.25 on the basis of this data, it is still a major cause for concern.

(4.16.2)
Calibrations of board # 2

The calibrations with the 3 and 4 mm insert (which provided the necessary range of intensities while providing a low graphing gradient; this demonstrates the individual hydraulics of each board; for board # 1 the 2 and 3 mm inserts were preferable) are presented in Figure 4.17. With both inserts the line of best fit is logarithmic, whilst with both inserts for board # 1 it is linear, which confirms the point above about the individuality of each board / system and hence the importance of re-calibration for any change in the system (for example, changing the water datum in the form of the height of the jerry cans above the board), which can be time consuming (one day). The fit is tight around the mean even with three replicates (4 mm insert).

Figure 4.18, the calibrations under field conditions, reveals, as with board # 1, little variability in the case of only a few replicates per target intensity / difference in capillaries, but, again as with board # 1, with more replicates, the variability becomes much greater. For example, at a difference in capillary of 15 or 16 mm, the corresponding rainfall intensities in the scatterbox
a) Simulations carried out in the field over the course of the first field season, using the 2 mm insert reveals little difference in intensity for a large change in hydraulic head.

b) Using the 3 mm insert, with which more runs were carried, due to variability in intensity between multiple simulations at a given difference in hydraulic head, it is not possible to unambiguously discriminate, for example, between a 10 and a 25 mm difference in hydraulic head, due to the overlap in corresponding intensities. This is in stark contrast to the tight clustering around the line of best fit achieved for the calibrations carried out at the field station.
Figure 4.17 Field station calibrations of board #2, 3 and 4 mm inserts

a) 3 mm insert. Best fit ($r^2 = 0.98$), is logarithmic curve, unlike board #1, in which case the best fit is linear. The reason for this difference is not known.

b) 4 mm insert. Same comments as for (a). Allows a wider range of intensities (here to 80 mm/hr)
a) Using 3 mm insert, a tight relationship is apparent ($r^2 = 0.965$)

b) Using 4 mm insert, a much greater variability in measured rainfall intensity for any given hydraulic head setting on the manometer is evident. This is likely partly due to the greater number of 'replicates' at each setting, and the larger change in intensity for a given change in head with a larger aperture insert.

- **Figure 4.18** Relationship between rainfall intensity and hydraulic head for board #2 for all simulations in field season #1, for 3 and 4 mm inserts

### Relationship between hydraulic head and intensity, board #2, 3 mm insert

- **Equation:** $y = 0.9664x + 7.6589$
- **$R^2$:** 0.965

### Relationship between hydraulic head and intensity, board #2, 4 mm insert

- **Equation:** $y = 2.7854x + 12.262$
- **$R^2$:** 0.7732
range from 44 to 69 mm/hr! In order, therefore, to separate actual intensities without ambiguity, one would have to, for example, set a target intensity of 55 mm/hr and accept a window of about 35 mm/hr – 55 mm/hr – 85 mm/hr within which another target intensity (where intensity is a treatment) is not permitted. The greater intensity ‘buffer’ at the higher end is the result of greater variability in intensity, although this may be the result of one (out of four replicates) outlier.

Figure 4.19, a comparison of the lines of best fit though the field station and field season calibrations respectively reveals the consequences of the difference in fit between these two data sets. The logarithmic response of declining marginal increase in intensity for every unit increase in hydraulic head, which characterises the field station calibration, is not true of the field season results. The reason for this is not known, but the consequence would be large errors (in addition to the intensity variability around the line of best fit within each data set) in the apparent intensity of the field season simulations at the low and high target intensities, as illustrated in (a). This effect has not been reported, to one’s knowledge, in the literature, leading one to suspect that the calibrations whenever the simulator was first set up were assumed by others to hold true over time, which is manifestly not the case at least in this experience, and with serious implication in terms of the apparent effects of rainfall intensity on erosion or crusting or infiltration. The design of this widely used simulator should be modified to allow for continuous monitoring of the relationship between hydraulic head and intensity.

(4.17)

Conclusion; implications of results of calibrations

To summarise briefly, it is believed that the investment in time of some four weeks of calibrations over the two field seasons plus ongoing calibrations over the course of the field seasons yielded very significant findings about the variability in the calibration between a) the difference in the height of the water in the two capillaries of the manometer board and b) the intensity of the rainfall produced under the simulator board, the central principle around which this simulator is designed. As apparent from the amount of time required to identify this phenomenon, it is tempting to calibrate once, at the beginning of the field season, or to rely on calibrations from another user, and spend one’s time instead actually using the simulator. This, however, would be a false economy; it is known from the literature review that rainfall characteristics have a major,
With both the 3 and 4 mm inserts the line of best fit through the field data is a straight line, whereas for the field station calibrations the line of best fit is logarithmic. Whatever the reasons for this, an important implication of this is that a calibration established at the beginning of the fieldwork cannot be relied upon uncritically during fieldwork. This discrepancy is greatest at the lowest and highest settings of hydraulic head / intensity; at low intensities (see (a)), the resulting error in apparent intensity can be well over 100%, and at high intensities the difference, for example, between 53 and 68 mm/hr.
if not dominant influence on erosion, crusting, sealing, infiltration and runoff, and rainfall intensity is explicitly used as a treatment in many rainfall simulation studies. In addition, the widespread use of this design over the past two decades mean that the findings of the present research, if accurate, imply the necessity of re-examining many of the results of studies relying on this simulator design.

In terms of the impact on the present study, this problem has been mitigated by the fact that the actual intensity of each simulation was measured, in the first field season, over the first five minutes (after allowing five minutes for the system to stabilise, as indicated from the calibrations) preceding the simulation and the last five minutes after termination of the experiment. In response to the findings over the first field season, the target intensity continued to be set by way of the manometer board, but the actual intensity was monitored on a continuous, real-time and spatially distributed manner as described with respect to the design of the 3.5 m simulator and which, it is argued, resolves the problem of errors of analysis but does not alleviate complications in comparability between treatments resulting from deviations from a target intensity. Furthermore, if rainfall intensity is to be used as a treatment, then the target intensities specified must be separated by an amount greater than the potential overlap of error bars of actual intensity around these target intensities. Rough values of these error bars have been provided by the present research, but must be determined on a system-by-system basis due to differences in board and system hydraulics, as indicated by other calibrations carried out in this study.

(4.18)

Protocol used in the rainfall simulation

Table 4.5 details the parameters chosen for assessing hydrological characteristics and the bases on which comparisons between simulation runs will be made.

The issue of the multiplicity of possible parameters with which to characterise the hydrological behaviour of the surfaces assessed is returned to in the results of the simulations from the first field season, and the parameter-dependence of the apparent relative runoff potential of the simulation sites will be evident. Figure 4.20 presents the principal ‘treatments’ (changes in surface or rainfall or both) forming the basis of the research design, although antecedent moisture
Table 4.5

Possible analyses of rainfall simulation data
For each run, where 'run' = a particular set of treatments
(rainfall treatments + surface treatments)

**Representation of the general characteristics of runoff response to simulated rainfall**

Integrated response: response over all points in time

- **Dynamic**: Runoff response over time; time series
- **Static**: Horton's alpha coefficient for infiltration curve

Discrete response: a portion of and/or a point on the response curve

- Time to Runoff
- Final Runoff
- Coefficient
- Final (empirical) Infiltration Rate
- Sediment Loss, per unit surface area

**Comparing runoff responses: Standardising the comparisons**

Assessing the effects of treatments by parameterisation of the rainfall simulation treatments and/or soil responses
Comparisons made on the following bases:

A) **EMPIRICAL**

1) 'Naturalistic'
Based on the shape of the runoff curve

<table>
<thead>
<tr>
<th>Measure at</th>
<th>Measure (some or all)</th>
</tr>
</thead>
<tbody>
<tr>
<td>'Breakpoint' between rising limb and equilibrium sections of curve</td>
<td>Runoff coefficient</td>
</tr>
<tr>
<td>Last fragment of curve</td>
<td>Infiltration rate</td>
</tr>
<tr>
<td></td>
<td>Time elapsed</td>
</tr>
<tr>
<td></td>
<td>Cumulative kinetic energy</td>
</tr>
<tr>
<td></td>
<td>Cumulative rain depth</td>
</tr>
</tbody>
</table>
2) Pragmatic

Based on *practical considerations* of relevance to soil and water conservation engineering for designing water harvesting structures and a knowledge of the characteristics of rain events in the study area. Parameters should be measured at realistic values for the nature of the rainstorms under consideration.

i) With reference to characteristics of simulated rain

<table>
<thead>
<tr>
<th>Measure at</th>
<th>Measure (some or all)</th>
</tr>
</thead>
<tbody>
<tr>
<td>For a given drop size and spatial arrangement (drop forming board); In order to equate runs using different Drop height (energy) treatments:</td>
<td>• Runoff coefficient • Runoff yield • Infiltration rate • Time elapsed • Cumulative rain depth • Cumulative kinetic energy</td>
</tr>
<tr>
<td>• Cumulative kinetic energy corresponding to that of natural rainfall after 5, 10, 15, 30 (normally the maximum period of high intensity rainfall in the study area), and 45 minutes rainfall</td>
<td></td>
</tr>
<tr>
<td>In order to equate runs using different Drop rate (intensity) treatments:</td>
<td></td>
</tr>
<tr>
<td>• Cumulative depth; 10 and 15 mm (considered to be lower and upper threshold depths for runoff in the study area) 20, 30 and (where available) 45 mm rainfall</td>
<td></td>
</tr>
</tbody>
</table>
**B) THEORETICAL**

Based on principally theoretical considerations of interest in the study of infiltration
For selected (considered representative) runs

<table>
<thead>
<tr>
<th>Measure at</th>
<th>Measure (some or all)</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Finite time</strong> on theoretical infiltration curve</td>
<td>Infiltration rate</td>
</tr>
<tr>
<td>(Approaching) <strong>infinite time</strong> on theoretical infiltration curve</td>
<td></td>
</tr>
<tr>
<td>Where curve =</td>
<td></td>
</tr>
<tr>
<td><strong>Phillips curve</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Green and Ampt curve</strong></td>
<td></td>
</tr>
<tr>
<td><strong>Kostiakov curve</strong></td>
<td></td>
</tr>
<tr>
<td>Other possible (<em>ie</em> best fit)</td>
<td></td>
</tr>
</tbody>
</table>
Figure 4.20

Possible interactions to be analysed between surface treatments and rainfall treatments

<table>
<thead>
<tr>
<th>Surface Treatments</th>
<th>Rainfall Treatments</th>
</tr>
</thead>
<tbody>
<tr>
<td><strong>Surface</strong></td>
<td></td>
</tr>
<tr>
<td>Crusted</td>
<td>Non Crusted</td>
</tr>
<tr>
<td><strong>Surface Treatment</strong></td>
<td></td>
</tr>
<tr>
<td>Natural</td>
<td>Crust removed</td>
</tr>
<tr>
<td><strong>Antecedent Moisture Status</strong></td>
<td></td>
</tr>
<tr>
<td>Dry</td>
<td>Wet</td>
</tr>
<tr>
<td>Dry</td>
<td>Wet</td>
</tr>
<tr>
<td>Dry</td>
<td>Wet</td>
</tr>
<tr>
<td><strong>Surface Type</strong></td>
<td></td>
</tr>
<tr>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>A</td>
<td>B</td>
</tr>
<tr>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>A</td>
<td>A</td>
</tr>
<tr>
<td>A</td>
<td>B</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Energy</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>x x x x x x x x x</td>
</tr>
<tr>
<td>Low</td>
<td>x x x x x x x x x</td>
</tr>
</tbody>
</table>

<table>
<thead>
<tr>
<th>Intensity</th>
<th></th>
</tr>
</thead>
<tbody>
<tr>
<td>High</td>
<td>x x x x x x x x x</td>
</tr>
<tr>
<td>Low</td>
<td>x x x x x x x x x</td>
</tr>
</tbody>
</table>
wet was only true at a few sites due to the fact that rain normally falls onto a dry surface in the study area.

a) the replication required for achieving statistical 'certainty' (at a given confidence level) and
b) the characterisation of a sufficient number of sites to reasonably represent the expected variability in runoff potential within the study area

The sampling strategy and rationale for the strategy will be outlined in Chapter 7

(4.18.1)

1.5 m Rainfall simulator

Table 4.6 lists intensity and duration rainfall treatments at the principal sites (= surface treatment) where the 1.5 m simulator (first field season) was used, together with the spatial distribution of rainfall for each board for each simulation and a range of response parameters for each simulation. Photographs and details of each site are presented in Chapter 7. The response parameters are organised according to a hierarchy, first, of 'related to runoff' and 'related to infiltration'; then, for each of these highest level classifiers, responses at measured at initiation and equilibrium thresholds, and the interval in between. Finally, at the bottom of the hierarchy, each of the second level classifiers is divided into a 'time to', 'depth to' and 'energy to' measure. The definition of each parameter is given in the table.

(4.18.2)

3.5 m Rainfall simulator

The protocol employed for the 3.5 m simulator was similar to that of the 1.5 m version, however there were a number of important differences related to the differences in design. First of all, as the drop height is much greater the time for set up and dismantling was substantially increased, which meant decreasing either the number of sites (= surface 'treatments') or number of rainfall intensities tested (rainfall treatments) or the number of replicates or a combination thereof. Furthermore, between the first and second field season agricultural fields had expanded considerably, rendering some of the sites from the first season (using the 1.5 m simulator) inaccessible. For these reasons it was difficult to make direct comparisons between the results of the two simulators, even though patterns emerged which will be discussed in Chapter 7.
Table 4.6 Details of rainfall simulations, 1.5 m simulator

<table>
<thead>
<tr>
<th>Site</th>
<th>Code</th>
<th>Date</th>
<th>Treatment</th>
<th>Intensity</th>
<th>Int Class</th>
<th>Duration</th>
<th>Board</th>
<th>Spatial distribution</th>
</tr>
</thead>
<tbody>
<tr>
<td>Lam</td>
<td>L</td>
<td>20-Feb</td>
<td>L</td>
<td>103</td>
<td>D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eldume, Site 1</td>
<td>E</td>
<td>22-Feb</td>
<td>M</td>
<td>103</td>
<td>D</td>
<td></td>
<td></td>
<td></td>
</tr>
<tr>
<td>Eldume, Site 1</td>
<td>E</td>
<td>22-Feb</td>
<td>M</td>
<td>92</td>
<td>T</td>
<td>0.32</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Logumukum</td>
<td>Lo</td>
<td>14-Mar</td>
<td>M</td>
<td>28</td>
<td>T</td>
<td>0.31</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Logumukum</td>
<td>Lo</td>
<td>14-Mar</td>
<td>H</td>
<td>15</td>
<td>T</td>
<td>0.06</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marigat</td>
<td>M</td>
<td>8-Apr</td>
<td>H</td>
<td>28</td>
<td>D</td>
<td>0.09</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marigat</td>
<td>M</td>
<td>27-Mar</td>
<td>M</td>
<td>34</td>
<td>D</td>
<td>0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marigat</td>
<td>M</td>
<td>27-Mar</td>
<td>M</td>
<td>36</td>
<td>D</td>
<td>0.19</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marigat</td>
<td>M</td>
<td>27-Mar</td>
<td>L</td>
<td>28</td>
<td>T</td>
<td>0.23</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Marigat</td>
<td>M</td>
<td>27-Mar</td>
<td>M</td>
<td>45</td>
<td>T</td>
<td>0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meisori</td>
<td>Me</td>
<td>22-Mar</td>
<td>H</td>
<td>70</td>
<td>D</td>
<td>0.04</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Meisori</td>
<td>Me</td>
<td>22-Mar</td>
<td>M</td>
<td>65</td>
<td>T</td>
<td>0.33</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ong Mara</td>
<td>OM</td>
<td>25-Mar</td>
<td>M</td>
<td>66</td>
<td>D</td>
<td>0.14</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ong Mara</td>
<td>OM</td>
<td>25-Mar</td>
<td>H</td>
<td>66</td>
<td>D</td>
<td>0.15</td>
<td></td>
<td></td>
</tr>
<tr>
<td>Ong Mara</td>
<td>OM</td>
<td>25-Mar</td>
<td>M</td>
<td>77</td>
<td>T</td>
<td>0.16</td>
<td></td>
<td></td>
</tr>
</tbody>
</table>

Intensity = mm/hr Int Class = Intensity class; 'low' / 'medium' / 'high'
Duration = minutes
Board = (D) Simulator board, University of Amsterdam design, current; (T) older design (essentially the same key parameters)
Spatial distribution = standard deviation of intensity between funnels (4 or 8) as a proportion of intensity
Nevertheless many of the same sites used for the 1.5 m simulations were used with the 3.5 m simulator.

The strategy employed with the 3.5 m simulator to simultaneously assess the spatial variability of runoff potential in the study area while also investigating the surface control on runoff was to split the board into two, reducing the plot size from 1 m x 0.5 m to two plots of 0.5 x 0.5 m. This allowed for a control (crusted, in the case of the presence of a crust at a site) and crust removed treatments at every site. One of the main findings of the work with the 1.5 m simulator was the rainfall intensity dependency of runoff, which made comparison between sites difficult across a range of intensities. This was further complicated by another major finding with the 1.5 m simulator, that of the substantial overlap between error bars around target intensities, which made it difficult to separate the effects of rainfall intensities which are not widely separated (i.e. at least 15 - 20 mm/hr different in target intensity). These findings and their implications are discussed in detail in Chapter 7. Therefore with the 3.5 m simulator only one target intensity was employed at every site, essentially eliminating the effect of rainfall from the experimental design. This choice was made because the intensity dependence of runoff was clearly established with the 1.5 m simulator and because the primary objective of the research is to develop ways of determining the spatial variability in runoff potential across a study area.

In terms of simulator design and experimental protocol, an improvement was made to the 3.5 m simulator to compensate for the variability in actual intensity from the target intensity calibrated at the beginning of the field season by constantly monitoring intensity on each side of the board using funnels taking a constant sample from the centre of each half of the board. Because the funnels were placed a short distance underneath the drop formers there was a minimum loss of effective plot area because the drops scattered over the course of their trajectory such that even the area of the plots under the funnels received some rainfall.

The sampling strategy with the 3.5 m simulator differed from that of the campaign with the 1.5 m simulator. With the former a reference site was chosen, Lameluk, because it is an area fenced in by the University of Toronto (no longer used) research project, which eliminated disturbance such as goat trampling. This allowed for a greater number of replicates and for a number of treatments not possible at the other sites, where only a day or two could be allocated. Note that the results from some sites had to be discarded, as with the 1.5 m simulator, for various reasons, including lack of runoff (normally when using a very low intensity in order to directly determine the
threshold intensity for runoff generation instead of extrapolating with curve fitting) or because of board leakage. Some two weeks of simulations were allocated to the reference site, which was also the location of the overland plots of various lengths under natural rainfall used to determine conveyance losses for ‘upscaleing’ the results of the rainfall simulations. The rest of the time the 3.5 m simulator was transported to various sites, including to the researchers’ residence to compare the results with natural rainfall on simulator plots of soil taken from Lameluk such that real time rainfall – runoff relations under natural rainfall could be monitored whenever it happened to rain, and to compare these results to the simulation results. These comparisons, a kind of validation of the simulations, are explained below and the results presented in Chapter 7.

(4.19)
Validation and ‘upscaleing’ of rainfall simulation results

(4.19.1)
Comparison of rainfall simulation results with rainfall – runoff patterns under natural rainfall

As an inherent part of the experimental design, the issues of validation and spatial ‘upscaleability’ of the results were considered from the outset of this work. Given the relative infrequency and unpredictability of natural rain events in such environments, which is one of the reasons for using rainfall simulation, and the lack of instrumentation for rainfall-runoff plots for budgetary reasons, the question of validating the rainfall simulations was not straightforward. The strategy taken, accordingly, was two-pronged; to set up runoff plots at a location where rainfall and runoff could be simultaneously monitored when rains were most likely, which was known from Rowntree (1988) to be the evening, adjacent to the field residence; and overland plots at a site where they would not be disturbed, in the fenced field station.

The validation plots consisted of soil carefully removed from the field station (Lameluk) site and placed in specially designed 50 x 50 x 15 cm depth metal trays which have holes punched in the bottom to allow free drainage (see Plate 7). In order to minimise disturbance to the crust, an area 50 x 50 cm was demarcated and then the soil around it dug away, allowing the ‘tray’, which is open in the front and whose facing edges are sharpened, and using the handles welded onto the
sides, to be slid into the soil sample, requiring however some force and therefore likely causing some smearing along the bottom and thus possibly a drainage impediment.

These trays were then placed on sand and levelled and a fenced enclosure constructed at the field residence to keep goats away (the only external disturbance which had been anticipated) and, after allowing several events to occur so as to counteract any disturbance effect, removed the crust from 3 of the 6 plots and subsequently monitored crust development on the basis of water acceptance, using a handsprayer. A wire mesh the same as used under the simulator was placed over two of the trays (one crusted and one removed) at a height of 3.5 m, in order to break the energy of natural rainfall at this height, such that natural rainfall was used to 'simulate' the simulated rainfall, in order to isolate the effects of the reduction of kinetic energy due to the reduced drop height, with all other variables held constant. For the sake of precise comparison, rainfall simulations using rainwater directed from the residence roof to a tank and mimicking the observed intensity patterns of natural rainfall events recorded were carried out on the ‘natural-rainfall-simulating-simulated-rainfall’ plots.

Unfortunately, baboons ended up jumping on the wire mesh over these plots, which had to be repaired and may have influenced the results. Surprisingly, no cases of this phenomenon were noted in the literature, but it is strongly suspected that, along with deviations from design intensity and variations in water chemistry, baboon attacks on the simulator screen would explain much of the unaccounted-for-error in rainfall simulation experiments.

(4.19.2)

Assessing the validity of extrapolating the results of small rainfall simulation plots to the short slope scale

In order to determine the validity of spatially ‘upscaling’ the results from small rainfall simulation plots (0.5 x 1.0 m in the first season, 0.5 x 0.5 m in the second season, under the 3.5 m simulator) to the scale of small external catchment water harvesting systems (a target slope length of 10 m) and to assess the conveyance cost of increasing the catchment area, a series of slope lengths were demarcated at the field station, Lameluk, using iron sheeting to create overland plots of 0.5 m width and 0.5, 1.5, 4.5, and 13.5 m (Plate 10). Jerry cans were dug into the end of the plot area
Counterclockwise, from upper left; a) Constructing overland flow plots b) Simulated rainfall c) Crack sealing necessary before flow can continue d) Rill pattern
and, due partly to the great usefulness of these containers, reburied, which made runoff yield measurements after each rain event time consuming.

The longest plot had two Gerlach troughs because of the difficulties of setting up a leak proof system of overflow from one jerry can to another, but this caused back-eddying and some undermining of the soil and in consequence some loss of runoff from the system. Maintenance of the plots was required on a regular basis, especially at the contact area between the Gerlach troughs and the soil, where some leakage occurred due to the apparently high velocity of flow on these smooth and rapidly sealing slopes of approx. 2°. It is recommended that future studies of this sort employ plaster of paris to ensure an effective seal at the lip. Rainfall simulation without energy application (0.3 m drop height) (Plate 10, b), in order to examine the basic infiltration capacity of the soil due simply to wetting, was also carried out on the plots to ascertain the conveyance cost of overland flow on non prewetted soil (at this reference site). These results would then be contrasted (see Chapter 7) with runoff under natural rainfall on a ‘pre’ (i.e. along the flowpath, before overland flow occurs) wetted and impact energy sealed surface.

The infiltration capacity under the wetting experiments proved to be very high; in the case of the 13.5 m plot, after 90 minutes at approx. 160 mm/hr from a rain area 1 m long at the top of the plot, the maximum distance travelled (from the lower end of the board) by the overland flow was 6.1 m, giving an average infiltration rate of 26.5 mm/hr over the entire wetted area for a total infiltration of 120 litres. Once wetted, one hour into the experiment tracer dye was added to the top of the plot and the flow pattern and velocity observed. Nine seconds were required to travel the first metre, but 72 seconds to travel the last. Microrilling was noted from approx. 0.8 m from the end of the board, and a serpentine pattern followed by the flowpath around islands of vegetation (Plate 10, d). The maximum depth at the top of the plot was approx. 10 mm (rulers were placed at regular intervals along the plots).

These experiments were carried out the day after a major storm (41 mm depth) the previous evening and yet, after allowing the soil to dry until 2 PM, when this experiment commenced, the soil was dry to 5 cm. This confirms the results of samples taken at intervals over the days following the large storms at various sites, which almost universally noted a drying out of the top few cm by the afternoon. From these results, and considering the fact that storms normally occur in the early evening and rarely more than one per day (Rowntree 1988), it can be concluded that
rain falls onto dry surfaces and that, at the edges of rain cells, there would a high conveyance loss, but within the storm area much less so (see Results chapter).

Given the much lower conveyance cost under natural rain events in the area than with the kinetic energy free overland plot experiments, one can confirm the importance of kinetic energy in reducing infiltration. As the intensity of the natural storms is not known, this precludes quantitative deductions, but a 3.5 m rainfall simulation at this same site revealed steady state infiltration rates of about 12 mm/hr with rains of 70% kinetic energy reproduction at 27 mm/hr, as opposed to an average infiltration of 26 mm/hr for the wetting experiment, and ring infiltration values of 45 - 65 mm/hr; indicating that the effects of wetting alone would not explain more than about 50% of the infiltration value on this soil under natural rainfall. Regarding the effect of wetting, it was noted that flow would not proceed on the overland plots until crack sealing had occurred (Plate 10, c), and the same phenomenon was observed under the rainfall simulation; in other words, with or without impact energy, the wetting demand of these common shrink-swell clays must be satisfied before runoff can occur.

Furthermore, given the general relationship established at this site between the ‘energy effect’ and ‘wetting effect’ of rainfall, and seeing as a raindrop is a co-quanta of moisture and energy, it is anticipated that the runoff yield implications for water harvesting of a high intensity short duration storm delivering the same raindepth as a low intensity storm of longer duration will be very different, due both to the rapidity of surface sealing of the former and the time required for crack sealing of the latter. Just such two events did in fact occur on these plots (two 41 mm events, measured at the site of the plots), and although the intensity was not recorded at this site, it was recorded at the field residence, some 8 km away, which indicates one high and one low intensity storm, and which resulted in very different runoff yields from the overland plots. The comparison of these two events (together with the rest of the storms) will be presented in Chapter 7.

In terms of implications of these various findings for runoff assessment, it can be concluded that kinetic energy would appear to be, as hypothesised, the dominant factor in inducing sealing and therefore runoff generation, but that the absorptive capacity of the shrink-swell clays in the upper part of the soil (which is likely subject to clay enrichment in these sedimentary crusts) is also very important, and thus that water chemistry can be expected to induce a possible error in rainfall simulation results with these soils. This possibility was indirectly investigated using the ‘gradual wetting’ tests described at the start of this chapter, and by comparing the effects of using rain and
well (the latter being the source of the rainfall simulation water) tests, the results of which will be reported in Chapters 7 and 8.

(4.20) Conclusions

Based on an analysis of previous studies in the study area employing simple tests and rainfall simulation, the results of a) a comparison between simple tests and b) between all tests and rainfall simulator results indicate that:

a) The use of rainfall simulation results as reference values against which to interpret or calibrate simple tests, the basic strategy proposed by the research design, may be misleading in so far as the relationship appears to be dependent on the type of simulator chosen as the reference value. This confirms the analysis of the rainfall simulation section, which demonstrates the multiple factors of error and variability inherent in the various attempts to replicate different aspects of rainfall and to combine these with other considerations such as logistics in the field. Therefore, it is acceptable to compare the results of the simple tests to those of a simulator, however only one design should be selected for this purpose, which will be assigned the role of a standard reference value. It should not be assumed, however, that this reference value represents the ‘real’ values under natural rainfall, but subject to an awareness of the degree to which the characteristics of natural rainfall known to influence the response of interest have been mimicked in the simulator design, the simulator will be taken to be more accurate than the simple tests, in so far as they lack a reasonable kinetic energy reproduction, amongst other limitations.

b) A research approach based on the triangulation between simple tests appears to be promising, or at least much more promising than relying on just one or two such tests. Laboratory data, where available, are a useful but not essential aid in the interpretation of the runoff potential of the surfaces assessed.

c) Amongst the tests previously employed and newly developed, the handsprayer appears most promising, as it replicates the in situ response controlled natural process, that of infiltration
of the top 5 mm of crusted soil, albeit without energy application. As such, the ‘final infiltration rate’ obtained using this tool (which is predicated upon assumptions about the effective wetted area) should be close to the saturated hydraulic conductivity of the crust and represents the wetting effects of rainfall on sealing.

The systematic calibrations and error assessments carried out on the primary instrument employed, used to provide reference runoff values, the rainfall simulator, lead to a number of discoveries about the design chosen, amongst which are:

a) Considerable variability over the field season in the calibrated apparent intensities, in spite of very little variability between replicates during calibrations at the beginning of the season, which would otherwise inspire confidence about the precision of this instrument. The reason for this variability is not known, but on the basis of other calibrations and the monitoring of behaviour over the field seasons, could include:

- Temperature effects
- Changes in air pressure
- The intensity dependence of the spatial distribution of rainfall
- Clogging of the drop formers
- Differences in parallax between users of different height
- A failure to seal the system
- Differences in the hydraulics of two boards/simulators
- The board not being properly levelled (though carefully checked)

b) The implication of this variability is the necessity of discounting differences in runoff response as a function of differences in (apparent) intensity of, say, less than 15 - 20 mm/hr, if the intensity has not actually been measured in a study for every simulation. If at least three replicates have been carried out for each treatment, however, then the results may be considered to be reliable.

The use of overland plots, under both rainfall simulation and natural rainfall, indicates that the hypothesis of a surface control on runoff, and one which is primarily a function of rainfall impact energy, is a valid basis for the research design, but that the wetting effects of rainfall are also
important. These two factors can potentially be separated according to the nature of the experimental design employing rainfall simulation. Given the high clay content and probable surface enrichment in clay, water chemistry is an issue worth investigating in the study area. The runoff yield to be expected under water harvesting with catchment lengths ranging from 1.5 to 13.5 m will be strongly influenced by the intensity-duration of the storms; hence it is important to ascertain, from what data are available, the local rainfall characteristics to be simulated. This knowledge should then be incorporated into the protocol for the rainfall simulation campaign.

(4.21)

Implications for mapping runoff potential

The choice of the rainfall simulator as the most reliable tool for characterising infiltration (as it reproduces the kinetic energy believed to be responsible for sealing) introduces a fundamental dilemma. As only a few rainfall simulations can be carried out per day as a practical matter in the field, the opportunity to develop statistically meaningful relationships is unlikely in most cases. Therefore, the results of a long campaign of rainfall simulations such as summarised in the inventory of Casenave and Valentin (1989) for the Sahel, are a rich and rare resource, but it was found that the direct application of these relationships to another semi-arid area (Baringo) has not been unproblematic. Many of the surfaces inventoried in lowland Baringo could not be identified precisely in the inventory, and of those which could, many of the listed infiltration values proved to be unreliable. The implications of this are critical to the theme of the study: for any given area, a new set of relationships needs to be developed, and then related to the spectral characteristics of that same area. As a starting point for such an investigation, however, the multiband ratioing indices which proved to be useful in the Sahel and southern Tunisia for discriminating between surfaces of distinct hydrological characteristics were extrapolated to the study area.
Chapter 5
Methods (Part two)

The classification of crusting soils in terms of runoff potential and possible uses of remote sensing and GIS for mapping runoff potential

- The development of a crust classification system in the Sahel and runoff models and values identified for these soils
- Efforts to map crusts, particularly using remote sensing
- Implications for and attempts to assess water harvesting suitability, particularly using GIS
- Approach chosen in this study
- Image indices chosen for this study

Chapter Overview

(5.1)
Overview of chapter

(5.2)
The development of a crust classification system in the Sahel and the subsequent efforts to map crusts from remote sensing

(5.3)
Parallel investigations and synergy (1): the Orstom Tunisia work

(5.4)
Parallel investigations and synergy (2): the INRA group
(5.5) The identification of suitable areas for water harvesting using a crust classification system and remote sensing data

(5.6) Karlsruhe University approach to mapping runoff potential for assessing water harvesting suitability and implementation on a model catchment

(5.7) From mapping crusted surfaces to runoff yield prediction and water harvesting suitability assessment

(5.8) Summary of options for ‘upscale’ point measurements of runoff potential

(5.9) Approaches taken in this study

(5.10) Conclusions
Overview of chapter

This chapter is a combination of (a) a review of relevant attempts to 'upscale' point measures of infiltration in semi-arid and arid environments to spectral 'maps' of the landscape, in the form of optical remote sensing, together with (b) an explanation of the approach(es) attempted in this study. As a necessary background to this topic, however, one must first examine how surface controls on runoff, in the form of crust types, can be identified, classified and their distribution in the landscape mapped, as an 'intermediary' scale or bridge between a 0.5 or 1 m² rainfall simulation plot and the pixel size of the remote sensing imagery used (400 to 900 m²).

That background work takes two forms in this chapter; first a discussion of a systematic crust classification system developed by French researchers for the West African Sahel, followed by a description of attempts by French research groups in Tunisia, the Sahel and in France to link infiltration and spectral properties in the landscape, either directly or indirectly. Similar attempts by other researchers, principally those using the French crust classification system, are also examined. Some of these attempts use spectroradiometers, others various means of grouping crusts into 'crust associations' large enough to be visible to satellite sensors. Spectral unmixing was attempted by a group from Wageningen University, but not much work has been done in this area to date with physically degraded (as opposed to chemical and biological) crusting soils. In the present study spectral and hydrological measures were taken simultaneously, using a simple measure of infiltration in order to allow for sufficient replication to assess the separability between fine distinctions in crusted surfaces at each rainfall simulation sites and between sites. The few attempts to date to map runoff potential specifically for water harvesting suitability assessment, using the French crust classification system, are described and the relevance to the present study discussed. Finally, from amongst the various options presented, those considered most relevant and practical to the present study are highlighted; the results of the application of which to the study area are presented in Chapter 9.

The development of a crust classification system in the Sahel and the subsequent efforts to map crusts from remote sensing
An Orstom hydrologist working in the southern Sahel, Rodier recognised the potential of *les mares* or *lacs colinaires*, large enclosed basins similar to dambos, depressions which naturally harvest water from the surrounding shallow slopes, and developed a research interest in their hydrology. Rodier became well connected within the Orstom structure and knew how to maintain funding (Lamachere pers. Comm., 1998) for what developed into a major, sustained research effort in Rodier’s area of interest, resulting in the instrumentation of *les mares* throughout sahelian francophone Africa (Rodier 1992, FAO 1996).

### (5.2.1)
The work of Christian Valentin

In the late 1970's a doctoral student of pedology named Christian Valentin joined the Orstom group (working, however, outside their main zone, in the more arid soils in northern Niger (near Agadez)). Although a soil scientist and focused on the vertical micro organisation of the soil surface, Valentin’s interests in the implications for infiltration was stimulated by other pedologists and hydrologists in the Orstom research programme, most particularly by the meeting of minds with J. Collinet (Collinet and Valentin 1979), who had worked in Upper Volta on the factors controlling infiltration in the Sahelien environment, as well as by collaboration with J. Asseline, with whom Valentin developed a portable rainfall simulator to replace the excellent (Asseline Pers. comm, 1998) but massive and impractical Swanson ‘boom irrigation’ design (Asseline and Valentin 1978). Other important collaborators included J. Albergel, working in Burkina Faso, who was particularly interested in the effect of scale change on hydrology in these environments, the subject of his doctoral thesis (Albergel 1988).

In the course of his work, Valentin recognised the ubiquity and importance of crusting of soils in this region. His thesis (Valentin 1981) identified a number of distinctive crust types which *regularly recurred* in the same types of microenvironments in the study area, and established a genetic relationship between them. The importance of these findings was not immediately recognised, in part no doubt to the fact that it was not published in English (nor even in French until 1985).

In the Sahel, C. Puech started working with the disciples of Rodier on *les mares*, by way of the essentially French funded (and recently defunct, due to cutbacks) Comite Inter Etatique d’ Hydrologie (CIEH). His statistical approach to the variability between *les mares* soon turned to
an interest in mapping the crusted catchment areas from Spot imagery when funding was made available through Spot by way of J.M. Lamachere, who had been working on a particular reference mare in Burkina for over a decade, Mare d'Oursi. The pioneering work of Lamachere and Puech is of particular relevance to this current study.

Valentin, working together with an Orstom hydrologist, A. Casenave, who had been working with Asseline and Valentin's portable simulator, carried out a very detailed but comprehensive classification of the crust surfaces believed to be representative of much of the Sahel (Casenave and Valentin 1989). This was the first systematic classification of crust types ever compiled, for which, together with the methodology employed, Valentin would soon become very well known internationally.

(5.2.2)

Orstom Sahel crust classification system and associated infiltration values: ‘the catalogue’

Valentin's (1981) groundbreaking work on crusts in an arid environment showed that process-level organisation of the soil surface is manifest in distinctive morphology, observable in the field, albeit requiring a magnifying glass in order to make a definitive identification, which is based on microlayers in the top few millimetres of the soil, but also generally recognisable from its appearance in the horizontal plane with the aid of a ‘catalogue’ of photographs and descriptors. It is this latter feature of the classification system which allows us to potentially rapidly identify the crust type in another study area, such as Baringo, and then link it a runoff value, or to calibrate to a local rainfall simulation value or simple infiltration test.

Crust typologies such as that represented by this catalogue could be based on a multitude of criteria, but have mainly been organised on a genetic basis, which in turn reflects an author's understanding of the processes involved. The manner in which these processes are investigated influences an understanding of the processes involved, and this would naturally influence any crust typology as well, as argued in Chapter 3, where it was referred to as 'method dependence'. The same will be true of any locally developed adaptation of or alternative to the Valentin system, as with the simple tests utilised in the present study to rapidly characterise the effects of sealing each surface unit of distinctive morphology.
As implied from Figure 5.1, the genesis of crusted surfaces according to Escadafal's (who developed the concept of the Etats de Surface Elémentaire while working in arid Tunisia) and Valentin's conception is essentially the work of water:

1) *in situ*, in the form of the kinetic energy of raindrops, sorting the surface by various mechanisms such as packing and sieving (Figure 5.2), and

2) *in motion*, resulting in the formation of Erosion, Runoff and Sedimentary crusts, respectively, down a 'microcatena' each with distinct process(es) dominating (a catena which exhibits self-similarity, producing a fractal landscape across any scale/resolution of observation, as will be seen in Baringo, and potentially the key to upscaling (as with Ben-Asher and Humborg's (1992), albeit somewhat arbitrary, assignment of PAC ESE's to areas around the drainage network)).

Note in Figure 5.2 that different processes are involved in the transformation to a similar, structural, crust type due to different particle size composition of the soils, but the driving force in both cases is the kinetic energy of rainfall, but which is much more intense but shortlived in the Sahel. As a corollary, the soils in France are more often wet at the time of rainfall, making slaking a key process. Runoff over a structural crust then results in a number of new crust types as a function of their position along a microcatena, as principally sources or sinks of entrained material.

The work of Escadafal in arid Tunisia reveals a very strong relationship between the surface as demarcated into ESE's and the position of these surfaces in a geological/topographic schema made up of 'morpho-pedological' units. Note that vegetation is included in the classification of ESE's, as it is strongly linked to surface edaphic genetic processes, for example forming an anchor for sand accumulation, with a particular crust type forming on these stabilised sands. It was found that the morpho-pedological units could be clearly distinguished on the basis of the *proportion* of constituents ESE's, even if the same ESE's are found across units. Those with similar proportions of similar ESE's are typically found to have developed on similar geological materials or on windblown sands masking underlying variability. In fact, even when soil types vary, the ESE's at two locations in a similar topographic position in the landscape show similar properties. It is this predictability in the relationship between morpho-pedological units and their
Figure 5.1 Relationship between ESE’s and larger landscape units

The work of Escadafal in arid Tunisia reveals a very strong relationship between the surface as demarcated into ESE’s (defined here primarily in terms of their grain size) and the position of these surfaces in a geological/topographic schema made up of ‘morpho-pedological’ units.

(Escadafal 1989)

c = rocky; gr = gravel; sg = large sand; s = sand; sf = fine sand; sn = bare soil; vg = vegetated

The definition of the abbreviations of the Etats de Surface Elementaires making up this landscape are provided in the caption, above.
F 5.2 Towards an ‘universal’ crust classification

Equivalent degradation sequences for loam and sandy soils and processes involved (initial states = cultivated loam soil in France and sandy, agricultural soil in the Sahel). Note that different processes are involved in the transformation to a similar, structural, crust type due to different particle size composition of the soils, but the driving force in both cases is the kinetic energy of rainfall, but which is much more intense but shortlived in the Sahel. (Bresson 1995)
corresponding ESE’s which furnishes the key to mapping ESE’s from satellite imagery (Escadafal 1989).

Similarly, Valentin found a strong relationship between landscape position and dominant surface type. Generally, one finds coarse ESE’s (gravel) at the top; drying, runoff and erosion crusts midslope; erosion, structural and especially sedimentation crusts near the bottom. These patterns can then repeat themselves at microcatenas within catenas. A similarly ‘fractal’ landscape structure is found in the classic dendritic drainage networks in Baringo (Casenave and Valentin 1989).

A major contribution to our understanding of crusting soils by the Orstom Sahel research programme is the recognition that they represent, in effect, a self-scaling (without using that language) and transient system and a sensitive indicator of dominant processes at a particular place and time. It is precisely this self-scaling characteristic, as hinted at above, which may make it feasible to traverse scale thresholds and hence resolve the upscaling quandry, although the present work makes no claim to have managed to achieve this; rather it is raised as a logical extension of the research reviewed and an area of future work; but this fascinating and important theme is returned to when discussing the fieldwork results, as the phenomenon of drainage-driven self-similarity across scales is so readily apparent in lowland Baringo.

Figure 5.2 represents this idealised temporal degradation sequence for both sandy (Valentin’s work / Sahel) and loamy (Bresson’s) soils from a structural and then, along a catena, depositional crusts. The equivalencies between the most common terminologies, typologies, mechanisms and processes proposed in the francophone and anglophone literatures and how they would fit into this ‘universal’ time-space classification has been audaciously attempted by Bresson (1995), basically dividing all crusts into either ‘structural’ (drop impact dependent) or ‘depositional’ (genesis related to a depth of water, which may be moving).

Figure 5.3a and b presents the decision trees employed in the Valentin crust typology, whilst Table 5.1 lists the physical characteristics of the principal crust types and the infiltration and runoff values and their range or ‘error bars’. The most widespread of these crusts in lowland Baringo is the ‘Sedimentation’ crust. The various parameters with which the hydrological behaviour of the surface units are characterised are listed across the top of Figure 5.3 (b). The issue of the plethora of possible parameters and of those most useful to the particular purpose will
Figure 5.3 a
The Casenave and Valentin classification system of surface units (Part a)

Higher level classification of ‘elementary surface states’ (ESE’s) or soil surface units, found in the Sahel. Basic distinction between cultivated and uncultivated, with the latter then bifurcated between surface units evidencing faunal activities and those without. The latter are then discriminated on the basis of % stone content, and finally by crust presence or absence. (Translation of Casenave and Valentin 1989)
The Casenave and Valentin classification system of surface units
(Part b)
Continues the classification specifically for crusted surfaces, determining crust type first on the basis of the texture of the uppermost layer of the crust, being either sandy of 'plasmic' (fine, clay-like). The former group is then further differentiated by the number of layers and their order (ie sandy over plasmic). The latter is further defined on the basis of 'structure', which might also be called surface roughness.
(Casenave and Valentin 1992)
Table 5.1
Infiltration and runoff values of ‘Valentin-type’ surfaces units
(from left to right)

a) Characteristics of crusts, on the basis of thickness, strength and porosity, the latter two by qualitative class. Erosion crusts in Baringo are an order of magnitude thicker than described here, unless the crust component is technically defined as only the upper most layer of a cemented mass.

b) Infiltration values for surface units. $K_i =$ average infiltration from $t = 0$; $K_{io}$ = infiltration for a storm of 50 mm onto a dry soil; $l_i =$ threshold rainfall intensity for runoff initiation on a saturated soil, which will be a very similar value to the saturated hydraulic conductivity of the crust; $P_{rd}$ = threshold infiltration (rainfall depth for our purposes) for runoff initiation given dry antecedent conditions, and $P_{w}$ saturated.

(both tables Casenave and Valentin 1992)

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<th>Main features and properties of the different types of surface crust in the semi-arid zone of West Africa</th>
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<td><strong>Type</strong></td>
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<td>Runoff depositional</td>
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<td>Gravel</td>
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<th>Infiltration values for the different types of unit surfaces</th>
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become apparent when examining the results of the first season of rainfall simulation in Chapter 7.

In the case of the present research, the ideal parameter would be runoff yield for a storm of a given intensity pattern and duration, as well as recurrence frequency at a given confidence level, if such data were available, as they rarely are, as discussed above. Available data on the meteorology of the study area will be presented in Chapter 6 and then applied in the water harvesting suitability assessment procedure developed (a simplistic GIS overlay model, for illustrative purposes) in Chapter 9. It will be seen that water harvesting in this concrete example (given a number of assumptions) can potentially greatly mitigate the drought stress effect of unusually low rainfall months. The example of April 1993 is used, as April is normally the highest annual rainfall month, but a pattern skewed to January in that year, as will be seen in Chapter 6, results in an annual rainfall no lower than average, but considerably less rain during the normal planting season (starting mid March).

If one wanted to utilise the ‘Valentin’ catalogue directly, and had identified a surface / crust type from the photographs and description therein, which parameter would be most relevant in terms of summarising the hydrological behaviour? This dilemma has already been broached when comparing values of the ‘same’ surface in the Sahel and Baringo using different rainfall simulation protocols. If one wanted to compare the values of local rainfall simulation with that of the catalogue, for example for the purpose of calibrating a few ESE’s and then applying a correction to the rest of them, one could use $K_1$ ($\%$), which is the ‘average’ infiltration, but this is across many simulations, the details of which are not known.

Alternatively, $K_{io}$, average infiltration rate over a rainstorm of 50 mm depth and from antecedent dry conditions, would allow one to replicate these experiments locally, but as discussed above there are many variables involved in rainfall simulation, and particularly between the spray-type simulator used by Orstom and the drip-type used in Baringo. In addition, one would have to emulate the intensity pattern used by Orstom, which is based on natural storm events in the Sahel, which have much higher rainfall intensities, comparing available data, than in Baringo, and hence would be unrealistic for local runoff assessment for water harvesting purposes, which is more focussed on making the most of small events which can ‘bridge’ between large storms. $K_{i20}$ has been dismissed for our purposes, as this is for antecedent moist conditions, which is rare in the
study area. It is useful; threshold intensity, as is Prd, runoff depth (runoff yield), for their storm and experimental protocol.

The original equation for runoff for the ESE's is:

\[ L_r = A \cdot P + B \cdot IK + C \cdot P \cdot IK + D \]  \hspace{1cm} (5.1)

Where:

- \( L_r \) = surface runoff (mm)
- \( P \) = rainfall depth (mm)
- \( IK \) = antecedent precipitation index (mm)
- \( A - D \) = coefficients (dimensionless)

Due to the minimal effects of antecedent moisture, this can be simplified to:

\[ L_r = A \cdot P + D \]  \hspace{1cm} (5.2)

In other words, runoff yield is a function of rainfall, with the coefficients derived from regressions on rainfall simulation data sets for each surface type. To what degree the term \( P \) dominates the coefficients, which are presumably characteristics of the particular surface concerned, or more exactly describes the interaction between rainfall and surface characteristics. The debate about the relative importance of rainfall and surface characteristics in determining infiltration (and runoff), though not the principal question asked in the present study, is clearly related and has practical implications. This question, accordingly, will be addressed by holding either rainfall (intensity) or surface type constant and varying the other. Whilst the experimental design, as discussed above, cannot manage both multisite comparisons and sufficient replication of any such treatments at each site for statistical analysis, it is still possible to gain an impression in this area.

Ideally, in another semi-environment with widespread crusting soils or other surface types similar to those in ‘the catalogue’, one would be able to determine these coefficients from this reference source. It is suspected that, in practice, some local rainfall simulation or other indicators of the propensity for sealing, which controls runoff, will have to carried out. In order to ascertain this, a rainfall simulation campaign was carried out in the study area, together with the simple
alternative indicators of crust stability and water acceptance and clay expansion etc. which relate to processes involved in soil sealing, described above, to be interpreted according the model of triangulation the rationale for and an example of which in the study area have already been presented.

(5.3)

Parallel investigations and synergy (1): the Orstom Tunisia work

Working in southern Tunisia, R. Escadafal, doing soil survey in this arid zone, soon realised the importance of the very surface of the soil in mediating the soil-atmosphere relationships, including infiltration and absorption / reflection. Borrowing a term coined by Bruneau and Killian (1984) when developing a survey methodology in the humid tropics, états de surface, literally 'surface state', Escadafal now applied it to an arid environment. A similar term in English has been used in climatology, that of a 'land-surface' (Becker et al, 1988), whilst Andrew (1954) (in Rallison and Miller 1982) coined the term 'surface-cover complex', which later became incorporated in the U.S. Soil Conservation Service system of determining runoff from curve numbers (Tauer and Humborg 1992), and as such the SCS system is a promising approach (albeit on a coarser scale than required for water harvesting planning purposes). Nonetheless, Tauer and Humborg (1992) caution that the Curve Number system is not directly relevant for the Sahel because it is calibrated for extreme events in the USA and generates virtually no runoff below 40mm rainfall, which is larger than most rain events in the Sahel, and indeed in lowland Baringo (Rowntree 1988).

A complementary term had been used by Escadafal (1984), that of l'organisation superficielle', or 'the organisation of the surface'. This latter concept was explored simultaneously by Valentin (1981,) in his thesis and subsequent work. It would be fair to say that Valentin recognised the importance of and developed to a very high state of knowledge the structure of the top few millimetres of the soil in arid and semi-arid environments, as well as the relationship between the micro and macro morphology of the surface, whereas Escadafal developed the most sophisticated ideas about the structure of the landscape in these same environments, built up from various types of constituent 'elementary surface units'. In addition, Escadafal is an experienced and well known remote sensing specialist, working on the remote sensing of arid soils from the late 1970's in Tunisia (cf. Escadafal 1980).
Escadafal introduced his 'New method for the description of the soil surface in arid regions' (in French) in 1981 (Escadafal 1981), though further developments over the 1980's were not published as his doctoral thesis until 1989 (Escadafal 1989). An intellectual cross-pollination within Orstom got underway from the early to mid 1980's (the 'West African' portable rainfall simulator was used in Tunisia from 1984), culminating in the development of a 'catalogue' of elementary surface (effectively crust) units in the Sahel, published by Casenave and Valentin in 1989 (unfortunately in French only).

Whereas the research of Valentin and his associates in the Sahel has been more practical in so far as the implications for infiltration have been thoroughly examined, the work of Escadafal (1989) has been a more basic concern with the surface composition of the landscape of an arid region and the reflectance characteristics thereof, however more recently (Escadafal, et al. 1994) the emphasis has shifted to runoff implication and (Escadafal and Bacha 1996) to desertification monitoring; in all these cases carried out in Tunisia. The particularity of Escadafal's work is the conceptualisation of the landscape in terms of homogenous surface units, where homogenous is defined at a pragmatic scale corresponding to observation during the field survey. The smallest elemental unit in this system is about 800 cm², but can vary up to several square metres or more.

An 'états de surface' (ES) or surface state is defined by Escadafal (1989) as:

*The composition and organisation of the land surface at a particular moment in time*

Whilst an **elementary surface state** (ESE) is defined as:

*A (internally homogeneous) constituent of a surface state which can be individually identified and characterised at macroscopic scale*

The principle of demarcating ESE's within a landscape provides an idea of the power, but resolution dependence, of mapping them from remote platforms. The question then presents itself as to how to make sense of the patterns of ESE's in the landscape at a smaller scale (i.e. over a greater area and, implicitly, a coarser resolution). This problem is addressed within the conceptual and practical approach developed by Escadafal by establishing a hierarchy (landscape
composed of ES’s composed of ESE’s) and ascertaining the statistical relationships between them.

This was carried out systematically over about a decade and presented as Escadafal (1989). These relationships are represented diagrammatically in Figure 5.1, a. The key which links the ESE’s and the landscape is topography, as a statistical relationship, was found between the position in the landscape and the organisation (for Escadafal, principally the proportions of class sizes of the constituent materials (sand-silt-clay but also much coarse material, which is widespread in that study area)) of the surface. The parallel with the concept of a catena, which is central to the understanding of both soil formation and therefore distribution and mapping (Brady 1984, Dent and Young 1981), is readily apparent, and implies a system organised by flows of energy (mass movement or water) down a gravitational gradient.

The key role of topographic position is also evident from the work of the Orstom Sahel group (Figure 5.4, a), working mainly at a finer resolution and with less coarse surfaces in a less arid environment than Orstom Tunisia, and for whom the structure of the class sizes in terms of their vertical (and, in later work, horizontal) distribution is the focus. The ordering of the layers of particle size classes was revealed by this research to be the key to understanding crust formation, sealing, and the implications thereof on infiltration, runoff and erosion. Once again, the parallel with classic soil science, which is less concerned with the very surface of the soil, is apparent: the principle of horizon development and the classification of soils (partly) in terms of these horizons.

The main difference from traditional concepts of soil is the fact that these surface horizons are not buffered by an overlying layer, unlike the subsoil, from changes in the atmosphere (rain, wind, overland flow, etc) or from man or animal or vegetation, and hence they are highly dynamic, which poses problems in terms of the temporal validity of any mapping effort, but presents an opportunity in so far that it is a sensitive indicator of precisely such changes, and can be monitored, particularly in areas of low vegetation cover such as semi-arid environments, with remote sensing.

In short, it should be evident that the definition and therefore classification, as well as distribution and genetic factors of the soil surface in arid and semi-arid areas, logically, mirrors in many ways the same aspects of the soil science of the entire pedon. Indeed, if one defines a soil strictly in
Figure 5.4 Mapping ‘Valentin-type’ crusts from remote sensing

a) A map of ‘Associations of ESE’s’, analogous to a soil association, a composite mapping unit; the proportion of constituent ESE’s in each mapping unit are given in the legend. The demarcation of these composite units – Etats de Surfaces – which are essentially soil-vegetation associations or natural physiognomic units, has been done on the basis of the visual interpretation of aerial photographs. Ground verification then established the proportion of constituent ESE’s. Note the way in which the ESE’s ‘radiate’ out around the drainage system; indicating a topographic control on their distribution. (Casenave and Valentin 1989)

b) The reflectance characteristics of ‘Valentin-type’ crusts, in three SPOT bands (upper graph), and their corresponding infiltration values (lower graph). Multispectral analysis clearly required to distinguish between crust types, due to the overlap in spectral range between many crust types in any one band. (Courault et al 1991)
terms of horizon development, it could be argued (for the sake of rhetorical purposes) that there is no 'soil' beneath the top few centimeters in semi-arid environments. Shallow pits dug as part of the present work indicate virtually no horizon development on the plains around Lake Baringo.

(5.4)
Parallel investigations and synergy (2): the INRA group

Again starting in the late 1970's another investigation into crusting which would eventually lead to the development of a parallel system of crust classification was commencing in the well laboured plots of the L'Institut National de Recherche Agronomique (INRA) in Grignon, near Versailles. J. Boiffin was working on a doctoral thesis entitled 'The structural degradation of the upper layers of soil under the action of rainfall' (in French) (Boiffin 1984), which formalised the spatial and temporal relationships between crust types, as will be discussed. At the same institution, one of the elite Grandes Ecoles, was a micromorphologist named L.M. Bresson, who was asked by Boiffin in 1982 during the course of his thesis to lend his technical expertise to the study of crusting, which was to launch Bresson on a new research trajectory. Another micromorphologist, N. Fedoroff, requested Bresson to produce a synthetic work on crusts for The 14th World Congress of Soil Science in Kyoto in 1990, as result of which Bresson contacted Valentin in order to make an explicit comparison of crusting typologies they had developed, respectively, for sandy intertropical and loamy temperate soils. Fedoroff had earlier worked with Escadafal (Escadafal and Fedoroff 1987) on the micromorphology of crusts in Tunisia.

In the end they compared some 500 crusts from arid through to temperate zones (Bresson and Valentin 1990, Valentin and Bresson 1992), and in doing so made the first attempt at a universal synthesis of the morphology, genesis and classification of crusts. (Figure 5.2) Later Bresson would take his sabbatical in Australia at CSIRO Canberra (Chartres et al, 1994, Bresson and Moran 1995), which further stimulated his interests in the systematic comparison of crusts across varied environments. Presently, in an attempt to make the classification system more operational, they are working on a statistical analysis of crusts developed on some 150 different materials in order to create a diagnostic system, based on the accessible property of crust texture.

(5.4.1)
Mapping crusting soils from satellite imagery
At the National Agronomic Institute near Paris, Prof. Girard was supervising the Spot funded Ph.D. research of D Courault, on scale changes in spectroradiometric measurements of Boiffin's crusted fields (Courault 1989, 1993). These are the most detailed, thorough studies of the spectral properties of crusted soils of which one is aware. Courault subsequently worked in Niger with Orstom, contributing to the ‘Valentin research agenda’, working with J.M. D'Herbes, who together produced the first large area map of crusted surfaces from remote sensing, at a scale of 1:200,000, for the area around Niamey (Courault et al, 1991) based on the ‘Valentin’ crust classification system (Figure 5.4, b).

This study demonstrated the possibilities of mapping crust / surface types by way of the vegetation with which they are associated, as the ESE’s themselves vary on too fine a scale to be directly accessible to satellite sensors. Tromp and Steenis (1996) use spectral unmixing to identify the constituent spectral endmembers (‘pure’ or spectrally homogeneous constituent reflection / absorption units within one satellite pixel) within a Landsat TM image on crusting Sahelian soils.

The endmember reflectance characteristics are very similar to that revealed using a simple field spectroradiometer (a Milton Multiband Radiometer) in the present study; a set of parallel curves, generally increasing in % reflection towards the near infrared. It should be noted that the spectral unmixing procedure used by Tromp and Steenis (1996) involved the use of very specialised software (CSES 1993) which would not normally be available in developing countries, and found that, in spite of using these algorithms, they could rarely identify truly spectrally ‘pure’ endmembers because of the scale of variability of the surfaces in semi-arid environments and the subtlety of the spectral differences even between pure endmembers. A similar subtlety was observed in lowland Baringo.

Important spectroradiometric work on crusted soils has also been carried out by Hill et al. (1997) in the semi-arid Mediterranean basin in the context of the De-Mon I and II, and particularly by de Jong (1994), which demonstrated the difficulty of distinguishing between crusts formed from physical (structural) degradation, using hyperspectral resolution airborne sensors, but with less detailed work at the field scale and without examining the temporal dimensions of crusting, as compared to Courault’s work in France. In contrast to the subtle spectral distinctions between crusts of physio-chemical origin in the Sahel, which frustrated the attempts of Tromp (pers. Comm., 1996) to establish clear distinctions between crusted surfaces on spectral criteria using field spectroradiometry, Epema (1992), working on chemical ‘lithic’ crusts in southern Tunisia,
found spectral classification of surface units to be effective, as did Pinker and Karneli (1995) on
cryptogamitic crusts in the Negev and Sinai and Epema and Bom (1994) on physico-chemical
crusts along a transect in Niger (Figure 5.5), as part of HAPEX-Sahel.

With this last, apparently promising study, spectral variability using a simple field
spectroradiometer similar to that used in the present work revealed that the primary sources of
variation were stones, vegetation and crusts, respectively, within three separate sites, depending
on the dominant surface feature. As the vast majority of the principal study area of the present
research (the ‘Njemps Flats’) has no basal vegetation cover for about 9 months per year and a low
stone cover, the hypothesis made is that variations in crusting will control crusting at this
resolution (some 100 cm², depending on the height of the MMR), however the distinction
between crusts will be more subtle than between crusts, stones and vegetation. Epema and Bom
(1994) also found, however, that the semivariograms of reflectance at these sites, or the distance
beyond which reflectance has a spatial dependence, is 6 to 15 m, or less than a satellite pixel
resolution (for Spot or TM).

Thus, if similar for Baringo, one could not expect to map elementary (‘homogenous’) surface
units (ESE’s) directly from satellite remote sensing, yet these ESE’s have been found to be
hydrologically distinct from each other, the classification criteria of interest, in the work of both
Orstom Sahel and Tunisia at this resolution, and there is no reason to believe that this will be
different in Baringo. In short, there is a fundamental disjuncture between the scale or resolution
at which runoff generation varies in arid and semi-arid environments and the resolution of the
satellite imagery most readily available.

(5.5)
The identification of suitable areas for water harvesting using a crust classification
system and remote sensing data

The focus of this chapter now turns to the question of assessing the environmental suitability of
water harvesting, the principal task of which is to determine the relative (and ideally absolute)
runoff potential of the various areas comprising a possible water harvesting site under
consideration. There are only two studies, to one’s knowledge, which have attempted to use
remote sensing to map runoff potential for the explicit purposes of assessing water harvesting
Figure 5.5
Wageningen University research into the spectral discrimination of crusted surfaces in the Sahel

a) The correspondence between TM bands and wavelength characteristics of surface types as measured by field spectroradiometry. In contrast to the findings of Orstom, the middle infrared appears to be the most promising in terms of separating between crusts.

b) A classification of satellite imagery using the classes from (a), where the constituent endmembers of mixed (non pure) pixels are disaggregated. This is only feasible where there are 'pure' examples of the endmembers on which to train, where these signals can be discriminated the one from the others, and where atmospheric conditions and any temporal lags between acquiring ground and remote values can be resolved

(both figures Tomp and Steenis 1996)
suitability, but a considerably larger body of work of possible relevance using remote sensing for hydrological applications can be drawn upon. Of this literature, only that which is focused on arid or semi-arid areas, and particularly on the soils rather than vegetation, and on the surface of the soil, and preferably in the African context, will be considered to be directly relevant and adapted to the environment of the case study area.

Regarding the methodologies employing remote sensing specifically for assessing water harvesting suitability, both have come out of Karlsruhe University Institut fur Wasserbau und Kulturtechnik, the first project beginning in 1985, there has been a continued interest in this topic at this institution, making it the centre for such work and engendering a visit as part of this study. The research on European Community funded University of Karlsruhe project was carried out at a test site in northern Burkina Faso and then (the principal site) in western Mali.

(5.6)

**Karlsruhe University approach to mapping runoff potential for assessing water harvesting suitability and implementation on a model catchment**

Of the various approaches discussed, some of which had not yet been developed at the time, the Karlsruhe University researchers utilised a flow accumulation model based on a mapping of the infiltration loss occurring on a surface of surface units with various values derived from the unique and very important ‘catalogue’ (Casenave and Valentin 1989) linking the appearance of (mainly crusted) surfaces from a wide range of sites in the Sahel to their hydrological characteristics, as ascertained from rainfall simulation. In theory, armed with this catalogue, it is not necessary to measure infiltration and runoff oneself, but rather to simply identify the surface type (‘*états de surface* ’ (ES) or surface state, meaning a distinctive surface cover complex made of parameterised constituent hydrological response units, *états de surface elementaires* (ESE’s) on the order of a few square metres.

The general approach taken by this group to site selection will be briefly described before moving on to the details of the use of the Orstom Sahel ‘catalogue’ to map runoff potential from remote sensing. The final output in their GIS based analysis is a stratification of physiognomic units into ‘unsuitable’, ‘possible’ and ‘favourable’ for micro or macro water harvesting. This is essentially an ‘FAO-style’ land suitability by class assessment schema, based on multiple criteria and
subjective judgments of suitability together with specific class boundaries at steps along the
decision tree. In this case, due to the topography of the study area, slope is an important
determinant. This is much less true of Baringo. The social implications of macro water
harvesting, with its requirements for a high degree of social cooperation, is not addressed within
this schema. Distance (of any point from a population centre) does however incorporate a human
dimension, a factor also employed in the present study (Chapter 9).

In practise, the constituent units (ESE’s) were too small to be assessed from remote sensing, but
the larger complexes, analogous to soil associations, or typical combinations of constituents, such
as ‘bare rock and soils with a high amount of stones’, consisting in this case of at least two ESE, could be used, an ES. Even at this level of generalisation up from the ESE’s for which runoff
values are known, however, the project found that pixels (Spot and TM used) rarely, if ever,
consisted purely of one type of ES.

A classification of the catchment on the basis of these ES’s and their associated hydrological
values (by way of assigning the ‘Valentin catalogue’ values to a map of the catchment derived
from satellite imagery) overestimated runoff yield by a factor of about 5.5 to 6 times (Figure 5.6,
a). This was due, upon investigation, to the assumption that all areas of the catchment were
contributing to the runoff which was measured at the outlet. In fact, deducing from the measured
runoff and assigning runoff to the ES’s in an interative routine (Ben-Asher and Humborg 1992)
out from the main drainage system, starting at the outlet and working up the Strahler stream order
hierarchy (for an assumed contributing ‘band’ around each branch, based in turn on an assumed
flow velocity) (Figure 5.6, b), it was concluded that the contributing area, in fact, was only about
21-24 % (maximum) of the catchment area, depending of course also on the characteristics of the
particular rain event.

Above a threshold raindepth, only marginal increases in contributing area were generated with
this model. In short, the combination of the Casenave-Valentin ESE approach of linking the
appearance of elementary hydrological response units to their behaviour, allowing for the
mapping of runoff from satellite imagery, combined with the concept of Partial Area Contribution
phenomenon (to account for the infiltration cost of travel from more remote areas of the
catchment to the drainage system, particularly during the short but intense rain events
characterising this area), allowed for ex ante mapping of the runoff potential of a catchment for
the purposes of assessing suitability for (macro scale) water harvesting.
Figure 5.6 Karlsruhe University approach to water harvesting site selection using remote sensing and ‘Valentin-type’ surface unit classification

a) The results of runoff volumes predicted from satellite classifications of the surface of the study area in terms of ‘Valentin-type’ ESE’s and using the published runoff values for each surface type (upper lines) and observed runoff (lower).

b) The discrepancy in (a) is explained by invoking the Partial Area Contribution phenomenon, here ‘allocating’ a drainage reach and thus contributing ESE’s, *a posteriori*, iteratively until the all the observed runoff at the catchment outlet is accounted for (both figures Tauer and Humborg, 1992).
From mapping crusted surfaces to runoff yield prediction and water harvesting suitability assessment

The University of Karlsruhe study in Mali (Tauer and Humborg 1992), referred to above, developed a methodology for assessing the suitability for water harvesting on environmental criteria. The major focus of the research effort was on mapping runoff potential from remote sensing, however other factors are obviously also important in determining suitability for water harvesting. In this case, the key criteria are crop water requirements (derived from published data on crop water requirements and local meteorological data), the storage capacity of the soil (supervised classification of satellite imagery; vegetation density proved to be a good proxy measure), accessibility (distance from village to potential runon site), the type of system appropriate (i.e. micro or macro; determined on the basis of slope, with a 10° threshold), and 'sociological, economic and political factors' (although nothing was reported about these factors).

The key input was a classified (supervised) satellite imagery, dividing the study area into what they call main classes, which are similar to physiognomic units (i.e. a typical combination of geomorphology, soil type and vegetation), with classes such as (# 1) 'periodically flooded depressions with dense green vegetation, naturally flooded fields with loamy-clayic soils with high storage capacity'. Such physiognomic units, the definition of which as assigned by the user can be seen to be both descriptive and interpretative with respect to the potential application, are associated with particular clusters generated by an unsupervised classification of a Spot or TM image.

Summary of options for ‘upscaling’ point measurements of runoff potential

Various hydrological models were examined by Tauer and Humborg (1992) to best explain the gauged rainfall-runoff characteristics at a macro water harvesting system set up as part of the applied research programme described above. The experimental catchment area is a rocky scree hillslope of 114 ha, the runoff from which is routed through a ‘cascade’ of fields by way of concrete structures. The rational method, isochronic, unit hydrograph, SCS, Boughton (partial area) and Orstom (developed specifically for the Sahel) models were compared, but none proved
very satisfactory, probably because most had been developed in temperate environments (although Klemm (pers. Comm., 1995) found that the SCS system gave good results for a some storms).

In addition, none (apart from the SCS, which is highly generalised, and predicated on surface types and rainfall characteristics very different than for the study area) were amenable to remote sensing as the primary data input. In the wider field of remote sensing and hydrology, there have been many attempts to take advantage of remote sensing to predict runoff from ungauged watersheds. The most common approach in semi-arid regions has been to map land use/cover to help determine the SCS Curve Number (cf Sharma and Singh 1992, Klemm 1991, Zevenbergen et al. 1988), and with some good results empirically by simple calibration. Nevertheless, Tauer and Humborg (1992) caution that the CN system is not necessarily relevant everywhere because it is designed for extreme events in the U.S. and therefore predicts virtually no runoff below 40mm rainfall, which is larger than most rain events in the Sahel. The same can be said of the rain regime of the study area (Rowntree 1988), which, although experiencing extreme events, also makes up a large proportion of annual rainfall in substantially smaller storms.

Another approach, one suited to predicting local runoff values and which holds great promise in the study area for mapping MICRO water harvesting, starts from the ground and aggregates upwards to the ‘point of visibility’ on remotely sensed imagery. This approach has been pushed the farthest in the work of Orstom groups working in Tunisia and in the Sahel (Escadafal et al. 1996; Hoepffner et al. 1996), driven by the opportunity to take advantage of an existing resource, an inventory of surface crusts and their runoff parameters as determined by rainfall simulation, by linking it to remote sensing. As the inventory is based on ‘elemental surfaces’ of 1 m2, the problem has been how to aggregate up to about the 1 ha minimum discernible area or ‘effective pixel’ on Spot, or otherwise TM imagery. Some possible approaches to addressing the vexing problem of the ‘leap in scale’ (really resolution) between that of the (implicitly ‘homogeneous’) hydrological response unit of 1 m2 (defined thus for logistical reasons by plot area) rainfall simulation plot on a distinct crust type, on the one hand, and the minimum area over which the spectral characteristics of the landscape are integrated, 400 - 600 m2 (assuming that the plot area does in fact fall within the pixel area, given georeferencing errors) have been attempted by Orstom, including:
• Casenave and Valentin (1989), establishing a relationship between categories which can be discriminated from satellite imagery, such as 'rocky slopes', to their constituent elemental surfaces for which runoff values were available. The surfaces typically linked to each remote sensing class are grouped in a manner analogous to soil associations and consist of, for example, 75% surface type A and 25% surface type B. The relationship allowed prediction of runoff on an unmapped catchment given the probability of the surface associations in each geomorphic category as determined statistically from fieldwork.

• Picking out on the imagery the elemental associations directly where they occur, given large enough patches to serve as training areas. This was attempted by Puech and Laily (1990) but only four of twelve associations could be distinguished. In response, an effort was made to correlate the surface associations to vegetation and soil types, as these are visible to remote sensing (Puech 1994) and this has proved to be feasible. Current research along this line involves the development of rapid, transect based surveys to identify the surfaces present in various geomorphic units, designed to furnish a large enough sample to accurately interpret imagery on an operational basis (Lamachere and Puech 1995, Lamachere pers Comm., 1998).

• Starting on the ground, to relating locally measured radiometric reflectance to infiltration measurements; ie to relate the two in situ and at the scale at which they operate, and then relate the surfaces to satellite imagery. This approach has been taken with crusting soils notably by Courault (1993) and Girard (pers. Comm., 1997) who were able to relate the stages of structural degradation under rainfall of a loam surface in France to Spot imagery via field spectroradiometry.

On this last point, incorporating now the work of relevant non-Orstom researchers, reflectance was found to increase as roughness decreased, indicating crusting. Epema (1992), working on salt playas in arid Tunisia, was able to distinguish six surfaces using ‘brightness’ and ‘redness’ indices built up from field spectroradiometry, and their corresponding infiltration rates using rainfall simulation. Surface characteristics were found to control infiltration and to mask the variation of the underlying soils; hence remote sensing proved more useful than traditional soil maps. Remote sensing of surfaces crusted due to physical degradation, as is dominant in Baringo, however, is more difficult because the differences between surfaces are more subtle (Tromp 1996), and not subject to discrimination on the basis of the absorption spectra of surface salts.
Ideally, one would see an improvement the resolution of the remotely borne sensing device, but without sacrificing the temporal resolution or global coverage required for monitoring what, in the next chapter, will be seen to be the transient value of crusted surfaces and hence runoff potential. The application of the various approaches to the 'scale disjuncture' problem between the area over which crusts vary and runoff generation occurs in semi-arid environments on the one hand and the resolution over which the corresponding spectral characteristics of these same surfaces are integrated on the other shall be returned to in more detail in Chapter 9, where the most relevant possibilities will be tested in lowland Baringo.

(5.9)
Approaches taken in this study

A number of indices were found to be useful in the Orstom attempts to upscale from the ESE's identified and their associated infiltration and runoff values as determined from rainfall simulation. Attempts to adapt the Orstom Sahel system for the purposes of assessing water harvesting suitability have been described above. These involved attempts to upscale the 'catalogue' values to the point 'visible' on remote sensing products by the researchers at Karlsruhe University in Mali, by creating unsupervised classifications of Spot and TM, which were used to identify main surface-cover complexes or physiognomic units (narrowly defined), which are essentially the same as the Etats de Surface making up the landscape.

It is precisely because of the potential relationship between a) the ES or land system facets or physiognomic units (all being defined in some way in a soil type – vegetation type – topographic position classification space both on the ground and in terms of factors influencing their spectral characteristics) and b) the constituent ESE’s, whose hydrological behaviour was known from 'the catalogue', which allowed the Karlsruhe approach to succeed. It must be said, however, that this involved adjusting the upcaled values (upscaled through simple additivty of these ESE values), to take into account the PAC phenomenon, assigning runoff recorded from an instrumented catchment to the ESE's/ES's mapped within that same catchment. Where such a catalogue of surface types – infiltration values does not exist, as with the Karlsruhe work in Syria (Prinz et al 1999), certain rules of thumb about runoff potential had to be employed in the absence of rainfall simulation, but it is not possible to validate the results of such an approach.
The case of the present study varies from both the ‘Mali’ and ‘Syria’ approaches in a number of ways. First-of-all, the surfaces found to exist in the study area are described in terms of the classificatory principles outlined in the work of Valentin, based as they are, on a solid understanding of the processes of crusting and sealing involved. Where the equivalent surface types are not found in the study area rainfall simulation must be carried out, and even where they are, it is of interest to determine whether these values deviate substantially from those of ‘the catalogue’ (which will be described in Chapter 10), and these compared in turn to a number of simple tests aimed at indicating relative runoff potential, for survey situations where rainfall simulation, realistically, may not be considered. This same objective was precisely the reason for the development of ‘the catalogue’; to allow assessment of infiltration (quantitative) without the use of rainfall simulation. The question, therefore, becomes whether and to what degree this ‘catalogue’ is valid outside its zone of development and whether and to what degree a similar effort would need to be repeated in other semi-arid areas, albeit likely without the ‘politically enabling environment’ which funded the Orstom long term rainfall simulation campaign. Hence the emphasis here on simple tests.

Another difference from the work of Karlruhe is in the use of remote sensing; due to the assumption, based on the findings of the literature review of water harvesting (not all of which is reported here), which revealed a breakdown of macro water harvesting systems. This was found to be due to changing socio-economic realities associated with globalisation and modernisation, such that micro water harvesting, which can be implemented without relying on the community, is more likely to succeed as an externally introduced system.

The ‘scale quandry’ discussed above, that of the disjuncture between the resolution of the hydrological and spectral data sets, is addressed in the present work by proposing a hierarchical and sequential approach to assessing water harvesting suitability. Investigations were carried out using data at a resolution corresponding to a reconnaissance scale suitability assessment procedure, illustrated by the GIS analysis the results of which are presented in Chapter 9, based on data layers mapped in the GTZ Range Management Survey (Herlocker et al, 1995; electronic form 1997). GTZ used a runoff map based on subjective assessment of the soil surveyor (Luc Touber of Wageningen), with sample sites visited stratified on the basis of a 1976 MSS (70 m) hardcopy image. At the other extreme, corresponding to a detailed scale suitability assessment for water harvesting, investigations were carried out using rainfall simulation and simple tests on of the dominant ESE at each site, and handspraying and in situ spectral measurements of
subdominant ESE’s at the same sites in order to gain an idea of spectral and hydrological variability at each site around the dominant ESE and between sites.

An *intermediate* scale has also been considered, using a Landsat TM image and rainfall simulation to determine the relative runoff potential or rankings of these sites; *relative* to allow for a comparison between the rankings using rainfall simulation and simple tests, although the absolute values of the rainfall simulations might be used, with caution, on the principle of additivity (which if modelling flows to an outlet would involve adding up the runoff yield of each classified pixel after subtracting the infiltration cost of flowing across each pixel from en route to a specified outlet, where a DEM of sufficient resolution is available to determine this). In taking such an approach, however, one would have to bear in mind the problems experienced in this respect with the Karlsruhe work and a similar overestimation of runoff yield using a similar approach in the work of Puech (1994). Given these caveats and the lack of detailed elevation data and the lack of a distinctive drainage network in the Flats, the main study area, and the focus on micro water harvesting, the emphasis here is more on relative runoff *generation* potential of pixel sized (plus allowance for georeferencing errors; 200 x 200 m) surfaces rather than on catchment hydrology.

Nonetheless, the approach of Escadafal and Guillet (1996), which is interested in the catchment hydrology of *les mares*, will be adopted, as described above, in so far as these runoff generation (relative ranking) values will be assigned from ground verification data (rainfall simulation sites, ranked by runoff potential), to the spectral clusters (an unsupervised classification using the indices \((5.3) + (5.4) + (5.5), \text{Orstom Sahel}\) or \((5.6) + (5.7), \text{Orstom Tunisia}\), defined below, on the basis of the *proportions* of each reference site area (200 x 200 m area) ‘falling’ into each spectral cluster. The resultant runoff ranking classified image will then be compared to the GTZ study ‘runoff loss’ GIS layer, and to an unsupervised classification of the same satellite image. This procedure is described in more detail in Chapter 9, along with the resulting classification of the study area in terms of (relative) runoff potential.

In short, the objective will be to ascertain whether the value added in terms of the rainfall simulations, at the level or ranking (a qualitative output), is worth the time and effort over the simple inspection of imagery classified on the basis of maximum separation of spectral classes. It is hypothesised that, given the genetic relationships revealed by both the Orstom Sahel and Tunisia work between landscape position and surface type, that rainfall simulation would only be
justified at the detailed stage of a water harvesting assessment procedure where 'hard numbers' are needed to determine runoff: runon ratios in order to design structures. A similar question was posed by the FAO in its terms-of-reference for the first High Resolution Satellite Series publication (discussed above, regarding soil mapping for a FAO project in semi-arid Botswana (Guillobez and Lantieri 1989)), but in that case whether digital processing was worth the additional time and expense over manual interpretation of visually optimised hardcopy.

Another difference with respect to the Karlsruhe work of the approach taken here is in the use of indices developed by Orstom Sahel and Tunisia found to allow separation of distinct runoff producing units on the basis of the spectral characteristics of these units. Whilst perhaps not available at the time of the Karlsruhe work in Mali, these image indices were not incorporated into the classification of water harvesting suitability later carried out in Syria either, perhaps because it was believed that the environment was too dissimilar. They have, however, been tested for Baringo, on the hypothesis that the Orstom Sahel indices will be more useful than the Orstom Tunisia system due to the greater similarity in the environments. The Orstom Sahel (cf. Puech 1997) consists of three indices:

\[
\text{Brightness Index} = \sqrt{(\text{red}^2 + \text{infrared}^2)} \quad (5.3)
\]

\[
\text{Vegetation Index} = \frac{255 \times \text{infrared}}{(\text{red} + \text{infrared})} \quad (5.4)
\]

\[
\text{Soil Colour Index} = \frac{255 \times \text{red}}{(\text{red} + \text{infrared})} \quad (5.5)
\]

Whilst the indices of the 'Orstom Tunisia system' (Escadafal et al. 1994), 'which allowed for the unambiguous discrimination between the surfaces' (pp. 77) are two:

\[
\text{Brightness Index} = \frac{(\text{max. (red, green)}) - (\text{min. (red, green)})}{(\text{max. (red, green)})} \quad (5.6)
\]

\[
\text{Redness Index} = \frac{255 \times (\text{red} - \text{green})}{(\text{red} + \text{green})} \quad (5.7)
\]
As can be seen from these indices, there is nothing particularly unusual about these band combinations or the ways in which they are calculated. They have, however, been found in practice to be useful in discriminating between surface units with distinct hydrological behaviour at the resolution of Spot imagery (20 x 20 m), which should also be applicable to TM, which in the case of the study area is available for a more recent date (1989) than Spot (1987) and for the dry season, as specified by Lamachere and Puech (1997).

(5.10)
Conclusions

This chapter has identified key studies of relevance to the objective of mapping the distribution of runoff potential in areas of crusting soils, inevitably from remote sensing, in arid and semi-arid environments. These studies have been reviewed for the purpose of identifying their advantages and limitations with respect to the objectives of determining runoff potential within a suitability assessment procedure for water harvesting. The fact that the French researchers working in the Sahel had access to a catalogue of established relationships between crust morphology and infiltration meant that their studies started 'on the ground' and at the scale of the rainfall simulator plot and then various attempts to upscale to the size of a pixel were attempted. A similar approach was the primary approach in this study, again because the primary instrument employed was a rainfall simulator utilised on a small plot and because the conceptual classificatory principles in describing crusted surfaces developed by Casenave and Valentin (1989) was also utilised in this study. Differences between the crusts occurring in the Sahel and in the study area and differences between the infiltration values of the same crusts and the implications thereof are returned to in Chapter 10 when drawing general lessons about the applicability of the ‘Valentin catalogue’ of morphology-runoff relationships to areas outside the zone in which it was developed.

Unlike the work of Orstom, however, the present study also attempted to determine the degree of variability around the dominant ESE in each Etats de Surface investigated using field spectroradiometry, in order to determine whether the dominant ESE could be considered representative of the mixel corresponding to the Etats de Surface. The results of those investigations will be reported in Chapters 9 and 10. Similarly, details of the procedure
developed to assign the values of the dominant ESE in each États de Surface (or local, narrowly defined physiognomic unit), which is the surface on which the rainfall simulation was carried out, to the corresponding spectral clusters are described in further detail in Chapter 9. Those spectral clusters are the result of an unsupervised classification on imagery of the study area translated into the indices found to be relevant for separating hydrologically distinct surfaces in southern Tunisia and in the Sahel. The indices themselves are defined in this chapter and the results as applied to the Baringo imagery presented in Chapter 9. The concept of validating the runoff map produced in this study against secondary data is introduced in this chapter and the results of the comparison presented in Chapter 9.
Chapter 6

Methods (Part 3)
Sampling strategy, Study area, Integration with previous studies in the study area

- Characteristics of the study area relevant to this research
- Sampling strategy; rationale for choice of location of rainfall simulation sites and integration with previous studies
- Ground verification data for image interpretation and integration with previous studies

Chapter Overview

(6.1)
Overview of chapter

(6.2)
Rainfall and runoff characteristics of the study area

(6.3)
Criteria for choice of and introduction to rainfall simulation sites

(6.4)
Conclusions
(6.1)  
**Overview of chapter**

This chapter aims to convey a feeling of the nature of the physical environment of the study area and particularly of the ‘reference sites’, the principal rainfall simulation sites where the simple tests described in Chapter 4 were also carried out for the sake of comparison, together with and finally details of rainfall characteristics and some results from relevant previous research in this area. The reference or ground verification sites are those used in the second field season, which are mainly but not exclusively the same as those used in the first season, allowing comparison between the 1.5 m (first field season) and 3.5 m (second field season) simulations in most cases. The sites will be presented in the form of one or two plates of terrestrial photographs dedicated to each, together with the same site from aerial photography and/or satellite imagery. The physical evidence of the effects of the crust removed treatments will be included for some sites as a preview of the presentation in graphical form of these treatments in the subsequent chapter.

This chapter will also cover what is known about the rainfall characteristics of the study area, with an emphasis on those measures of relevance to assessing water harvesting suitability and calculating runoff yield. Secondary data on runoff characteristics of some of the key sites and previous work on runoff yields are also presented.

(6.2)  
**Rainfall and runoff characteristics of the study area**

There have been few studies of the rainfall characteristics of lowland Baringo, but based on the analyses of Rowntree (1988), Rodgers et al (1985) and Roberts (1997 pers. Comm.) regarding rainfall and Bryan (1994), Wairagu (1989) and Roberts (1997 pers. Comm.) regarding runoff, the following characteristics are apparent:

- Rainfall in the study area is characterised by a bi-modal distribution, normally peaking in April and July. The implication of this is a potential dry spell in-between; indeed, only these two months have exceedance probabilities of even 50% for daily events over 10 mm, a value which can be considered to be a realistic threshold depth for runoff generation. Water harvesting could potentially bridge the gap between the first and second rainy season.
• Rain events almost inevitably fall on dry soil, meaning that a rainfall simulation campaign in this area to assess runoff potential of various surface units need not waste time determining the effects of antecedent moisture as an experimental treatment.

• There is great interannual variability on a monthly basis, but much less so on an annual basis. From an agronomic perspective, the monthly variability is of more interest, with water harvesting potentially allowing both the multiplication of rainfall in poor months and deep storage in good ones.

• Spatial variability is surprisingly little. Hence the location of the water harvesting fields (and suitability assessment on this basis in a GIS) need not take this factor into consideration.

• Runoff response is rapid and sharp, but with substantial differences between sites. Hence a sufficient number of sites are required to characterise the region and a spatially distributed GIS model of runoff potential is preferable over a generalised one.

• Secondary data indicates promising but varied runoff yield (underscoring the point above about location specificity), but these particular data need to be examined careful due to great variability in experimental conditions. The manager of one of the water harvesting projects in the study area gives a threshold runoff depth of 15 mm for any surface in the study area, whilst investigations on two major surface types using a 5 meter spray-type rainfall simulator (Wairagu 1989) found a raindepth of 13 mm and a threshold intensity of 17 mm/hr and an inverse relationship between these parameters.

(6.2.1)
Details of the rainfall regime in the study area

Annual rainfall, on a monthly basis, at three rainfall stations around the study area is presented in Figure 6.1. Note the mildly bimodal distribution. Soil surfaces exposed to a rainfall peak without the protection of vegetation cover, especially and after having been broken up by goat and cattle trampling over the previous dry season from mid March will clearly be exposed to much erosion. This also a critical period for crust formation and re-forming. Further details of rainfall characteristics, based on 19 years of data, are presented in Figure 6.2. The relationship
Figure 6.1 Annual rainfall temporal and spatial distribution, for three rainfall stations in lowland Baringo (Sketchley et al 1978)

- Maji Moto
- Perkerra Irrigation Scheme
- Snake Farm, Lake Baringo
Figure 6.2 Rainfall characteristics of lowland Baringo
(1) The relationship of storm rainfall to daily rainfall. (2) The cumulative frequency of daily rainfall. (3) The cumulative depth of daily rainfall. (all figures Rowntree 1988)
between storm depth and daily rainfall totals reveals the great infrequency of more than one storm per day. Furthermore, the cumulative frequency of daily rainfall proves to be highly ‘skewed’ towards low rainfall totals, with 90% of the storms not exceeding the 15 mm depth critical (Roberts 1985) for water harvesting in the area, however by cumulative depth, half of the total rainfall is delivered in storms exceeding this threshold.

As can be seen from Figure 6.3 the great majority of the storms in the study area fall between 4 and 9 p.m., meaning that (given that there is rarely more than one storm per day) the soil surface would have approximately 10 hours of insolation to dry before the next event. This implies, given the intense radiation in the study area, that rain rarely falls on a wet surface, and as such any rainfall simulations should be carried out on antecedent moisture dry conditions. Furthermore, for rainstorms over 10 mm depth, the majority of which are between 10 and 25 mm depth, the 30 minute maximum rainfall intensity rarely exceeds 30 mm/hr. Therefore, as water harvesting relies on the more frequent events, the intensities chosen for rainfall simulation should be between the nominal 15 mm/hr threshold and 30 – 35 mm/hr. The prescriptions determined from Figure 6.3 are confirmed by Figure 6.4; the frequency distributions of maximum 30 and 60 mm/hr intensities account for 80 and 90% of rainfall in the study area, respectively. Note that the intensity data is based on 13 years of incomplete records from one station, the only intensity data available for the surrounding area. This is likely a common situation in developing countries and a major hurdle in accurately predicting runoff yield for a local area.

Continuing with an analysis of water harvesting potential for the study area, Figure 6.5 presents some very useful data, prepared for the World Bank water harvesting project in Baringo. The exceedance probability of a rain day of the specified depth (mm) over the next decaday can be seen in the upper figure. There is clearly a bimodal distribution, peaking in April and July. Taking 10 mm as a threshold runoff depth, an exceedance probability of 50% is only achieved during two months of the year, indicating that these are the only reliable months for water harvesting. If both of these peaks fail in a given year, then even with water harvesting the prospects for dryland cropping may be inauspicious. Given sufficient rooting depth, a water harvesting system could potentially ‘tide over’ the dry period between the first and second rains. A record of dry spells from 1958 to 1980 is presented in the lower figure. March and October can be seen to be the months most prone to dry spells; as such, water harvesting can potentially take advantage of the second rains to extend the cropping season into October.
Figure Group 6.3
Rainfall characteristics in the study area; implications for assessing the potential for water harvesting using rainfall simulation (part 1)

(Left) The relationship between the maximum 30 minute intensity and daily rainfall diurnal distribution of rain events (right) Diurnal distribution of rain events (both figures Rowntree 1988)
Figure 6.4
Rainfall characteristics in the study area; implications for assessing the potential for water harvesting using rainfall simulation (part 2)

(left) The relationship between 30 and 60 minute maximum intensities (right) The frequency distributions of the 30 and 60 minute maximum intensities. (Both figures Rowntree 1988)
Figure 6.5
Rainfall characteristics in the study area; implications for assessing the potential for water harvesting using rainfall simulation (part 3)

(top) The exceedance probability of a rain day of the specified depth (mm) over the next decaday
(bottom) Record of dry spells, 1958 to 1980
(both figures Rodgers et al 1985)
The location of non recording rain gauges at the RAE water harvesting project fields, as well as the stations upon which the figures above are based, are presented in Figure 6.6. These data were acquired in Baringo and analysed in terms of the spatial and temporal distributions of rainfall and in terms of changes in spatial distributions through time. In Figure 6.7 the monthly distribution in rainfall over a seven year period is presented, and a line of best fit indicating a bimodal distribution. Under water harvesting, the ‘multiplication’ of rainfall may still allow for a crop in the case of the failure of the first rains, given sufficient soil moisture storage capacity. Note the variability in rainfall within any given month across years. A situation such as that of January 1993, identified on the figure with the arrow, would have serious implications in a year of average annual rainfall when the monthly distribution is thereby skewed out of the normal cropping season.

Two years for which temporal (monthly) data are available for all RAE fields are 1993 (white) and 1994 (black) in the upper graph in Figure 6.8. Although 1994 is an above average year in terms of annual rainfall, the proportions of the rain total received in each month is characteristic of ‘average’ distributions as identified from long term records from the Pekerra Irrigation Scheme. Although 1993 has an annual rainfall near the long term average of 630 mm, it can be seen that the distribution is highly skewed, peaking in January. As such, over the agricultural season (March to October) it is effectively an unimodal distribution, as opposed to the more typical bimodal distribution seen in 1994. This would have significant implications for any water harvesting programme predicated on assumptions about an average ‘design’ monthly distribution. In the lower graph the spatial distribution of rainfall in a ‘typical’ year such as 1994 is presented. This relatively tight spatial distribution, and consistently so across time, is representative of findings over the period from 1986, the first year rainfall data were collected, for 5 RAE fields, albeit with a number of years when only annual totals are available for some fields. Given local observations about the small spatial extent of rain events, this distribution was not expected. It does allow a water harvesting assessment procedure in this study area to disregard spatial variability in rainfall when assessing the suitability of any site and focussing instead on the nature of the site itself, as was done in this study, both in terms of runoff and ‘runon’ potential. Such an analysis for the entire study area will be returned to in Chapter 9.

(6.2.2)

Details of runoff characteristics of the study area, on the basis of secondary data
Figure 6.6
Rain Gauges in the study area

**F numbers** = field numbers of the RAE project, each with a non intensity rain gauge. Note fields 1, 4 and 13 also correspond to study sites. Field 6 falls within the study area but could not be reached by vehicle in order to obtain a GPS fix. Fields 10 and 12 fall outside the study area.

**Ovals and annotations** indicate locations of rain guages used in rainfall analyses by Rowntree (1988), with the southern gauge only used in the analyses of Rodgers *et al* (1985).
Figure 6.7 Monthly rainfall 1986-1994 across all RAE fields
Each bar indicates the rainfall for that month for the year 1986 (first bar for each month) to 1994 (last bar for each month)
Arrow indicates anomaly; very high rainfall in January (dry season)
Figure 6.8 Rainfall temporal and spatial distribution

(above) Two years for which temporal (monthly) data are available for all RAE fields; 1993 (white) and 1994 (black)
(below) The spatial distribution of rainfall in a ‘typical’ year such as 1994.
Given the low surface rugosity of the Njemps Flats (the landscape element in Figure 6.9, between Lake Baringo and the Tugen Hills), the implication for runoff assessment is that, once generated, sheetwash will extend over quite some distance (depending on conveyance losses). As such, one would expect ideal conditions for the low velocity flow which generates Depositional crusts through gravitational sorting on the basis of particle size of the sediment carried in this flow, and indeed the dominant crust type in the Njemps Flats is Depositional (with various local variants thereupon). This relative uniformity is reflected in the survey of Bowyer-Bower and Scoging (1992), who define this dominant crust type as ‘fine grained and cracked’. The common cracking indicates either clay rich soils or a clay enrichment of the crust, with the latter explanation more likely given the great variability in soil types in the area.

As ‘Depositional’ crusts, as defined by Casenave and Valentin (1989), generally have relatively high runoff coefficients, the Njemps Flats, on first principles, should be highly propitious in terms of runoff for water harvesting. For an example of a ‘typical’ landscape at the sort of scale relevant for rainfall simulation, see Plate 11. Note the characteristic ‘microsteps’, which are believed to mark the transition between a) laminar sheet flow and b) turbulent sheet flow / incipient channel flow, as well as between crusted and incipient eroded zones. These processes and patterns, in a more developed form and at a coarser scale, are visible from remote sensing in the form of interdigitated areas of gully and intergully area. Indeed, it is precisely this ‘fractal landscape’ which potentially allows one to relate investigations at different scales, albeit with considerable difficulty.

Of the surveys carried out in the study area by various researchers, some relevant results from the University of Toronto erosion study (Bryan 1994), including the runoff characteristics of two of the principal rainfall simulation sites, Lameluk and Eldume, can be considered. The average runoff coefficient was found to by Wairagu (1989), as part of the University of Toronto study, to be approximately 0.2 at the average annual rainfall of some 650 mm. To produce generalised relationships such as this on the basis of only two sites, however, is considered to be dubious, and the average runoff coefficients were found to be somewhat higher that this with the 3.5 m rainfall simulator developed for the present study. The question of averages, however, is a question of method dependence, as it must be specified with respect to the simulator type, and intensity / duration and antecedent moisture protocol need to be known. The results at two of the University of Toronto sites, using a 5 m spray-type simulator, are presented in Figure 6.10. One very apparent characteristic from these results are the very rapid response times to rainfall application.
Figure 6.9
Profile across broad land units in the study area, Baringo Kenya

The line on the standard false colour composite Landsat TM satellite image corresponds to a distance of approximately 30 km
Plate 11
Overview of the physical characteristics study area, both surface and subsurface

a) (top) A characteristic feature of the surface; ‘microsteps’, marking the transition from sheet to rill wash, and eventually to
(b) (lower right) classic incipient gulley erosional forms
(c) (bottom left) Soil profile reveals little horizon development. Note white markings at bottom; likely a calcareous and possibly saline horizon from a lacustrine stage; the study area is situated in an inter-lacustrine environment, subject in the past to periodic inundations
Figure 6.10
Runoff response characteristics at Lameluk and Eldume, 5m spray-type simulator

Results of University of Toronto research at Lameluk (a) and Eldume (b).
(both figures Bryan 1994).
Note the faster response times and higher discharge values at Eldume (b) than at Lameluk (a). The surface at Eldume is a 'Valentin-type' Erosion crust, and the latter a Sedimentation crust. Surprisingly, the sediment yield at Eldume is considerably higher than at Lameluk, presumably consisting of loose material on the surface which has not been incorporated due to the highly compact nature of the crust. The fact that there were a number of valuable datasets available in the study area, such as the work of the University of Toronto erosion project, influenced the selection of rainfall simulation sites in the present study, in order to allow for comparison between results.

(6.3)
Criteria for choice of and introduction to rainfall simulation sites

The choice of sites for rainfall simulations attempted to reconcile two criteria: to be representative of the variability in surface characteristics in the study area, and to be at or close to sites where the University of Toronto researchers and/or the sites of the Bowyer-Bower / Scoging (1992) erosion study had worked and/or where there was a water harvesting field. The rationale for being near a water harvesting field was that one could compare the theoretical assessment of runoff potential against the actual suitability as evidenced from the success or otherwise of the field.

In the case of the erosion study, this was a potentially valuable dataset, collected in 1991 and 1992 for a study comparing evidence of erosion in a 20 -25 m observation radius area (such as percentage area sheetwash) with 'point' data at the centre, factors hypothesised to be the cause of that erosion. The survey was carried out on a 1 Km systematic basis for the central part of the study area. From this 'raw' data, for the purposes of the present study 58 Area and 26 point data types or levels (i.e. 'crust type = fine grained and smooth') for 105 sample sites, some 2800 observations, were entered into a database and georeferenced in a GIS. The use of this dataset to supervise satellite imagery of the study area was attempted but is not explicitly reported due to the poor results. It should be noted that the crust classification employed in that survey is rather different from the preferred system of Casenave and Valentin (1989), which complicates the integration of data sets. This is a typical problem when comparing data sets on crusting soils, as different formal or informal classification systems are used by different authors. Finally, a Range Management study was carried out by GTZ (Herlocher et al. 1995), which is described and
utilised in Chapter 9 as part of a water harvesting suitability assessment procedure within a GIS ‘modelling’ environment.

In theory, if the study were to be driven exclusively by the potential relationship between a spectral and hydrological classification of the landscape, the sites would have been chosen on the basis of an unsupervised classification of the study area. Each site would represent one spectral cluster and be located in the centre of a large, homogenous area of that cluster. In practice a number of factors, including logistical factors, were juggled in the selection of sample sites. This created some complications, as shall be seen in Chapter 9, with rainfall simulation sites straddling several spectral clusters or classes, resulting in ‘mixels’. Such a situation, however, is not unrealistic, as the disjuncture in resolution between the hydrological measures (essentially point values) and the area to which they are attributed might result in such a situation anyway. Various possible approaches to dealing with this ‘leap in scale’ will be addressed briefly at the end of Chapter 9.

As an introduction both to the area and to the key principles and processes involved in the work, a number of the sites where rainfall simulation was carried will be presented. The locations of the rainfall simulation sites are presented in Figure 6.11. The majority of the rainfall simulation sites are located in the northern part of the Njemps Flats. Ongata Mara (2 sites) is situated on an alluvial / colluvial fan, considered to be representative of the fans which spill out onto the plains. The sites are located on two sides of one of the largest RAE water harvesting fields, field # 4. The other sites in the northern Flats are considered representative of the major land unit in the area, the alluvial / colluvial / lacustrine plain. Meisori is situated beside RAE field # 1, Lameluk and 9.4 at two ends of another very large RAE field (# 13) and near the largest FAO water harvesting site. Lameluk is the principal location of the University of Toronto rainfall simulation study. Sites 9.4 to 9.6 are in the proximity of three of the Bowyer-Bower / Scoging survey points, after which they are named, and represent together with Lameluk a transect along a catena down the Flats to Lake Baringo. In the southern part of the Njemps Flats, Marigat and Eldume are sites also chosen by the University of Toronto study, in order to allow for comparison, and the latter is also the site of a World Bank funded water harvesting demonstration. Logumukum is the site of an FAO water harvesting site and identified in a 1967 FAO range survey (FAO 1967) as suitable for water spreading.
Figure 6.11
Principal sites for detailed surface studies and rainfall simulations

(above) Northern part of the Njemps Flats.
(below) Southern part of the Njemps Flats.
The main rainfall simulation sites for the 3.5 m simulations are presented as a series of Plates of the nature of their surfaces. Note that there were problems with the simulations at a couple of these sites, due to board leakage, but they are presented here in any case as useful details about the environment in the study area are presented. Turning now in more detail to some of the key sites, at the main reference site for the 3.5 m simulations, Lameluk (Plate 12), one can observe the obvious control the surface layer has on infiltration. A side by side comparison of a control plot and a plot with the crust carefully removed confirms this visually, without even the need for quantitative analysis, which is not the subject of this paper. Ongata Mara, (Plate 13) is located on a heavily vegetated alluvial fan, here on a distinct slope (approx. 5°). A very fragile crust would lead one to expect high infiltration values, but a fairly rapid time to runoff due to the slope. This site is a good illustration of the topographically driven and fractal nature of the drainage systems which dissect the Flats.

Eldume (Plate 14), is a heavily eroded exposed b horizon, cemented (and thus one would expect this site to have one of the highest runoff values), and situated in an area of high albedo, giving a complex, distinctive pattern from the air. Contrasting this crust with Plate 13 gives an idea of the range of surface types encountered. Note again the subtlety of the differences between the ESE’s, making it virtually impossible to distinguish them, in spite of their hydrological differences, from remote sensing, even at high resolution. Logumukum (Plate 15) clearly stands out on the aerial photography if not the satellite imagery, as an ephemeral ‘lake’, and in the sense of being a (largely) closed basin is similar to les mares in the Sahel in which much of the ORSTOM work was carried out. This site is non-uniformly covered with a small gravel mulch carried down from a large runoff producing slope and/or due to local removal of fines; in fact, there is evidence of a downward translocation of fines through this ‘filter’ as removing this gravel reveals a ‘plasmic’ (to use Valentin’s terminology for a fine) layer underneath. This is the only site with layering on a truly macroscopic scale, and the only site potentially suitable for macro water harvesting. Due to this layering, one would expect a slow time to runoff, but high runoff values once achieved. In short, it should be apparent form the selected highlighting above of the some of the key sites that there is a tremendous variety in the types of crusts / surfaces across the study area, which makes it an excellent laboratory for this study. Finally, Marigat (Plate 16) is an area where there is substantial cracking and evidence of a surface, oriented enrichment of clay, indicating fine sedimentation and hence a Sedimentary crust.
Plate 12
Lameluk, 3.5m simulator

a) (top) Splash boards, from crusted plot on left and crust removed plot on right; note suppression of splash erosion by presence of crust
b) (bottom) Profile of crusted plot (left) and crust removed (right); note substantially greater depth of infiltration into the crust removed plot.
Plate 13
Ongata Mara

a) (top) Note much more rugged topography than much of the Flats, with strongly topography controlled distribution of ESE’s. Broad surface classes are:
top of intergully area (1), slope of gulley (2) (which itself is divided into rill and interrill areas in a gravity and kinetic-energy-driven fractal landscape system across lands system units / scales), and (3) drainage floor

b) (bottom) Crusted (right) and crust removed (left) surfaces; note fine cracking and embedded pebbles in this fragile crust, and powdery, non cemented nature of subcrust
Plate 14 Eldume

a) (top) Eldume
b) (bottom)
ESE 1 = very weakly developed rill system with sheet wash patterns
ESE 2 = crust without wash pattern
ESE 3 = Incipient gulley
Plate 15 Logumukum
(Clockwise from upper left):
 a) Gravel outwash at Logumukum. Note runoff source hill outcrop at back of photograph
 b) Gravel, the dominant ESE
 c) Result of 3.5m rainfall simulation; gravel removed and control, at 15 minutes
 d) Vegetation marking FAO contour bunds
Plate 16 Marigat, surface
(clockwise from upper right);

a) Profile through crust at Marigat; depth of crust approximately one to two mm
b) Vesicular porosity of crust at Marigat; surface brushed away in order to expose. Evidence of air entrapment during rainfall/crust formation, indicating low permeability and thus high runoff potential
c) One hour after a rainfall simulation, the crust is already cracking under intense insolation; indication of high clay content in this surface, most probably a clay enriched surface from sedimentation out of sheetwash originating upslope, ultimately the Tugen Hills
Conclusions

The selection of sample sites involved trade-offs between achieving representativity on hydrological and spectral criteria. For the former, it was important to ensure that a range of crust types found across the area were included in the selection of sites, while for the latter one should ideally select large, homogenous sites on spectral criteria, in order to avoid the problem of 'mixels', or pixels containing different spectral surfaces over the corresponding area on the ground, making it difficult to establish a one-to-one relationship between spectral and non-spectral characteristics of the landscape. The problem in the study area, and which is likely widely true of semi-arid environments, is that the crusts vary at a finer scale than that of the minimum resolution of the imagery, particularly if the effective resolution is taken to be a pixel +/- two or three pixels to account for georeferencing imprecision on the ground (GPS with +/- 85 m precision) and during image processing at the stage of 'rubber sheeting'. This 'problem' was exacerbated by the desire to carry out simulations at sites where secondary data were available for comparison/verification, due to the difficulty of comparing the results to runoff under natural rainfall, and therefore the site selection was not done purely on the basis, for example, of ensuring clearly differentiated clusters on an unsupervised classification.

In short, the problem of mixels is almost inevitable, which is rooted in the difference in scale at which hydrological and spectral characteristics vary. This is really, however, an issue of a difference in precision between the instruments used to assess hydrological and spectral characteristics. This in turn is due to the impracticality of carrying out rainfall simulation on large plots and the expense of high resolution imagery. For these reasons a parallel investigation was also carried out at the rainfall simulation sites, using a simple test of water acceptance as a proxy for runoff potential and a spectroradiometer at the same resolution as the scale at which the crusts vary (approx. 20-30 x 20-30 cm for the *etats de surface elementaires*).

In addition to site characteristics and their relationship to the sampling strategy chosen, this chapter also described what is known about the rainfall characteristics of the study area. This is obviously very relevant to accurate rainfall simulation, and these data were taken into account when determining the protocol to be used. As it was found that the 'typical' storm in the area starts with a short period of relatively high intensity followed by a longer period of low intensity, both intensities were used in the first field season as treatments. However, due to the desire to
improve the kinetic energy reproduction, the subsequent field season employed a more time consuming 3.5 m drop height simulator, resulting in the decision to use just one, medium intensity storm as a norm across all sites. This decision was also influenced by the finding of the strong intensity dependence of the infiltration and runoff responses, and as the primary objective of this study is to compare sites, this variable was eliminated in the second field season.
Chapter 7

Results and Discussion (Part one)

Low and high kinetic energy reproduction rainfall simulations for determining relative and ‘absolute’ runoff potential

- Results and discussion of 1.5 m drop height rainfall simulations
- Results and discussion of 3.5 m drop height rainfall simulations
- Comparison of results of 1.5 m and 3.5 m rainfall simulations
- Comparison of rainfall simulation results with runoff under natural rainfall

Chapter Overview

(7.1)
Overview of chapter

(7.2)
Results and Discussion of 1.5 m rainfall simulations; an introduction

(7.3)
Simulations included, parameters employed in analyses

(7.4)
Analyses of simulations retained; across all surfaces / sites

(7.5)
Analyses of simulations retained; on a site-by-site basis
(7.6) Analyses of simulations retained; on a surface treatment basis

(7.7) Analyses of simulations retained; across all sites

(7.8) Analyses of simulations retained across all sites; possible measures of runoff potential

(7.9) Conclusions; key parameters and controls revealed from the analyses of the 1.5 m simulations

(7.10) Conclusions
1.5 m Rainfall simulations

(7.11) Results and Discussion of 3.5 m rainfall simulations

(7.12) 3.5 m Rainfall simulation results, comparison with 1.5 m simulation results, and selective comparison between sites, on a site-by-site basis

(7.13) Results of treatments at the principal, fenced site; Lameluk, including comparison with 1.5 m simulations and with other sites

(7.14) Runoff under natural rainfall at Lameluk or on Lameluk soils
(7.1)
Overview of chapter

This chapter presents representative results from sites described in Chapter 6, the principal sites employed in this study, sites where both the 1.5 m the 3.5 m simulators were used, and from a few minor sites not described in Chapter 6. Space does not permit a full presentation of all results, but those examined here have been judiciously selected as ones illustrating the principal findings of the rainfall simulation campaigns.

The 1.5 m simulator results are first described using a range of parameters considered relevant for the comparing between sites for the purpose of assessing runoff potential. These parameters are described and then the results of the rainfall simulations compared 'statistically' in scatterplots across all sites in order to highlight any potential relationships between them which would warrant further examination. All sites are then compared on the basis of common conditions – medium intensity storms, antecedent dry and crust intact – and on the basis of a number of measures of runoff potential such as time and depth to runoff, maximum runoff potential, average runoff potential and others. From these analyses the same conclusion are arrived at as when discussing the myriad possible crust definitions and classifications and the contradictions in the literature regarding crust genesis and behaviour; the model / assumption / method / measurement dependence of the results. This became readily apparent when attempting to rank sites in terms of ‘runoff potential’.

This chapter then turns to an examination of the results of simulations carried out at the same sites (or nearby, as agricultural fields expanded onto the original sites in some cases in the meantime). This is done on a site-by-site basis, and comments often made regarding differences in runoff response to the two simulators and between sites where contrasts in responses are particularly striking. Results of simulations carried out at the fenced reference site, previously used by the University of Toronto, but on a part of the site not utilised, are then reported. At this same site overland plots were set up to assess the conveyance loss cost of runoff over longer distances than could be simulated. This was done under natural rainfall, which posed some restrictions due to the inability to monitor real time rainfall-runoff relations. As such, runoff plots were also set up at the residence and the results of rainfall and runoff measurements carried out during natural rainstorms are reported at this point in this chapter. This is followed by a general discussion of the key findings in the form of conclusions.
Results and Discussion of 1.5 m rainfall simulations; an introduction

The first part of this chapter is devoted to an analysis of the results of the rainfall simulations carried out with the 1.5 m simulator. This was done during the first field season of rainfall simulations, which corresponds to the second field season in the study area. Two 1.5 m simulators were employed, one which had been used by the University of Toronto erosion study and the other kindly provided by P Jungerius of the University of Amsterdam. As both were built at the University of Amsterdam to the same design the characteristics are similar. The calibrations of any drop forming board, however, is an individual procedure, particularly as the design of the ‘chassis’ of each simulator was different (particularly critical is the height of the water supply above the board, as well as the aperture of the tube between them and of the tube of the manometer board. Therefore calibrations were carried out individually and reported in Chapter 4, but in this chapter the results of the simulations are not distinguished on the basis of the board employed.

Simulations included, parameters employed in analyses

Figure 7.1 details the simulations which were used in the analyses of the 1.5 m simulations, starting with the scatterplot analysis (Figure 7.2). Note: a number of other sites which did not produce any runoff, such as a heavy clay area, Sereta, on the east side of the Lake, are not therefore included, but the fact of not producing runoff is also a useful result, allowing exclusion of such surface types from consideration when assessing runoff potential. On this same issue, there were many simulations not reported as a result of lack of runoff, as a result of an attempt to empirically determine the threshold runoff intensity. Naturally, such an effort risks ‘overshooting’ the intensity threshold, resulting in no runoff. As such, it would be more efficient, if less accurate, to interpolate (really extrapolate) the threshold value from the intersect, on the assumption that the behaviour of the surface during preponding can be deduced from the behaviour during runoff generation, which was considered to be questionable. The storms included in the analysis range in intensity from 19 to 77 mm/hr, over 15 sites, ranging from one runoff producing event (Lameluk) to five (Marigat) per site. Nine of the events could be
Figure 7.1 Simulations used analyses; 1.5 m first field season runs on antecedent moisture dry, runoff producing surfaces.

Number of simulation per site and range of intensities at each site, all 1996 dry crust intact 1.5 m simulations producing runoff.

- Measured average rainfall intensity
- Sites labeled: Lam, Eldume, Site 1, Logumukum, Marsat, Meisori, Ongata Mara
Figure 7.2: Scatterplot exploratory analysis of relationships between rainfall intensity and threshold and steady state response parameters for 1.5m control sites.
Figure 7.2 (cont...) Scatterplot exploratory analysis of relationships between rainfall intensity and interval and runoff coefficient response parameters for 1.5m control sites
Figure 7.2 (cont...) Scatterplot exploratory analysis of relationships between rainfall intensity and infiltration response parameters for 1.5 m control sites.
considered to fall into a ‘middle intensity’ category from 19 to 45 mm/hr, the rest falling into a high intensity category for which there is little evidence of sustained intensity rainfall in the study area (30 minute maximum), but which are probably representative of shorter interval bursts and thus relevant. Simulations were selected for inclusion in the analyses such that the effects of variability in antecedent moisture, vegetation cover and state of the surface (all included are crust intact) are eliminated, such the only variables are the rainfall intensity and the type of crust. The effects of surface treatments will be considered later, for the site where the greatest number of replicates were carried out, at Marigat.

The parameters chosen by which to characterise the hydrological response of the runoff surfaces assessed in response to the rainfall treatments applied (intensity and drop height) are described in Table 7.1. The parameters selected are essentially based on natural, ‘threshold’ responses, such as $X$ (be it time, raindepth, energy, infiltration or runoff) to / from runoff initiation or equilibrium infiltration / runoff. The ‘reference points’ for the parameters chosen are based on natural hydrological and therefore process controlled soil responses, but the $X$, the measure used to quantify the response (i.e. ‘interval runoff’, which is defined as the runoff coefficient over the interval runoff initiation — equilibrium runoff) are mainly defined in terms of the usefulness of such a parameter in terms of assessing runoff potential. The parameters proposed in Table 7.1 were set against each other graphically and against rainfall intensity (bottom corner) in Figure 7.2 to determine any trends in relationships either between the treatment and response(s) or between the various parameters which could be used to characterise the response.

(7.4)

Analyses of simulations retained; across all surfaces / sites

From Figure 7.2 a number of interesting relationships become apparent, as well as the lack of relationships between some variables which might be expected to exhibit some trend. No relationships are apparent between rainfall intensity and time or rainfall depth (which are essentially the same but with different units). Similarly, no relationships can be established between what, on the basis of the literature, is assumed to be the driving force, rainfall intensity, and average, interval or maximum runoff. Finally, no relationship is observed between intensity and Horton’s alpha, a measure of the rapidity of the infiltration decay.
Table 7.1 Details of rainfall simulations, 1.5 m simulator

<table>
<thead>
<tr>
<th>Site</th>
<th>Code</th>
<th>Date</th>
<th>Intensity</th>
<th>Int Class</th>
<th>Duration</th>
<th>Board</th>
<th>Spatial distribution</th>
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<tr>
<td>Lam</td>
<td>L</td>
<td>20-Feb</td>
<td>19</td>
<td>L</td>
<td>103</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>Eldume, Site 1</td>
<td>E</td>
<td>22-Feb</td>
<td>35</td>
<td>M</td>
<td>103</td>
<td>D</td>
<td></td>
</tr>
<tr>
<td>Eldume, Site 1</td>
<td>E</td>
<td>22-Feb</td>
<td>33</td>
<td>M</td>
<td>92</td>
<td>T</td>
<td>0.32</td>
</tr>
<tr>
<td>Logumukum</td>
<td>Lo</td>
<td>14-Mar</td>
<td>28</td>
<td>M</td>
<td>59</td>
<td>D</td>
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<tr>
<td>Logumukum</td>
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<td>14-Mar</td>
<td>62</td>
<td>H</td>
<td>15</td>
<td>T</td>
<td>0.31</td>
</tr>
<tr>
<td>Marigat</td>
<td>M</td>
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<td>77</td>
<td>H</td>
<td>28</td>
<td>D</td>
<td>0.09</td>
</tr>
<tr>
<td>Marigat</td>
<td>M</td>
<td>27-Mar</td>
<td>47</td>
<td>M</td>
<td>34</td>
<td>D</td>
<td>0.15</td>
</tr>
<tr>
<td>Marigat</td>
<td>M</td>
<td>27-Mar</td>
<td>49</td>
<td>M</td>
<td>36</td>
<td>D</td>
<td>0.19</td>
</tr>
<tr>
<td>Marigat</td>
<td>M</td>
<td>27-Mar</td>
<td>24</td>
<td>L</td>
<td>28</td>
<td>T</td>
<td>0.23</td>
</tr>
<tr>
<td>Marigat</td>
<td>M</td>
<td>27-Mar</td>
<td>37</td>
<td>M</td>
<td>45</td>
<td>T</td>
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</tr>
<tr>
<td>Meisori</td>
<td>Me</td>
<td>22-Mar</td>
<td>52</td>
<td>H</td>
<td>70</td>
<td>D</td>
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<td>Me</td>
<td>22-Mar</td>
<td>41</td>
<td>M</td>
<td>65</td>
<td>T</td>
<td>0.33</td>
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<tr>
<td>Ong Mara</td>
<td>OM</td>
<td>25-Mar</td>
<td>45</td>
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<td>H</td>
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<td>Ong Mara</td>
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<td>35</td>
<td>M</td>
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Intensity = mm/hr  
Int Class = Intensity class; 'low' / 'medium' / 'high'  
Duration = minutes  
Board = (D) Simulator board, University of Amsterdam design, current; (T) older design (essentially the same key parameters)  
Spatial distribution = standard deviation of intensity between funnels (4 or 8) as a proportion of intensity
Table 7.1 (cont...) Details of rainfall simulations in terms of parameter chosen, 1.5 m simulator

<table>
<thead>
<tr>
<th>Site</th>
<th>RESPONSE</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Parameters related to Runoff</td>
</tr>
<tr>
<td></td>
<td>Parameters (Time, Rain Depth and Energy) at Runoff Initiation</td>
</tr>
<tr>
<td></td>
<td>Parameters at 'Equilibrium'</td>
</tr>
<tr>
<td>Lam</td>
<td>20</td>
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<tr>
<td>Eldume, Site 1</td>
<td>11</td>
</tr>
<tr>
<td>Eldume, Site 1</td>
<td>12</td>
</tr>
<tr>
<td>Logumukum</td>
<td>18</td>
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<tr>
<td>Logumukum</td>
<td>4</td>
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<td>Marigat</td>
<td>6</td>
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<td>10</td>
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<tr>
<td>Marigat</td>
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<td>Marigat</td>
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<td>Meisori</td>
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<tr>
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<td>Ong Mara</td>
<td>7</td>
</tr>
<tr>
<td>Ong Mara</td>
<td>19</td>
</tr>
</tbody>
</table>

Threshold KE = Kinetic energy at initiation of runoff
Time / Depth / Cum KE at Equ = Time / Depth / Cumulative kinetic energy at what is judged to be the point at which steady state infiltration is first achieved
Table 7.1 (cont...) Details of rainfall simulations in terms of parameter chosen, 1.5 m simulator

<table>
<thead>
<tr>
<th>Site</th>
<th>RESPONSE Parameters related to Runoff</th>
<th>Parameters for the Interval 'Runoff Initiation to Equilibrium'</th>
<th>Runoff Coefficients (as calculated over various intervals)</th>
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<td>Interval Depth</td>
<td>Interval KE</td>
<td>Max Runoff</td>
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<tr>
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<td>36</td>
<td>12</td>
<td>138</td>
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<td>33</td>
<td>364</td>
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**Interval** = From runoff initiation to achievement of steady state infiltration. **Depth** = infiltration over that period, **KE** = kinetic energy received at the soil surface over that period. **Max Runoff** = maximum runoff coefficient (achieved at the point of steady state infiltration). **Average Runoff** = runoff coefficient calculated from the beginning of rainfall application to the end of the simulation. **Interval runoff** = runoff coefficient calculated for the period from runoff initiation to the point of steady state infiltration. **Av:Int Runoff** = the ratio of the latter two.
Table 7.1 (cont...) Details of rainfall simulations in terms of parameter chosen, 1.5 m simulator

<table>
<thead>
<tr>
<th>Site</th>
<th>Horton’s A</th>
<th>r2</th>
<th>Final Infiltration</th>
<th>Average Infiltration</th>
<th>Equ Infiltration</th>
<th>Extrap Infiltration</th>
<th>r2</th>
<th>Infiltration Proport</th>
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<tr>
<td>Lam</td>
<td>0.0076</td>
<td>0.96</td>
<td>0.74</td>
<td>0.74</td>
<td>0.89</td>
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<td>0.63</td>
<td>0.89</td>
<td>30.9</td>
<td>8.5</td>
<td>0.903</td>
<td>0.28</td>
</tr>
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<td>0.706</td>
<td>0.87</td>
<td>0.96</td>
<td>21</td>
<td>18.7</td>
<td>0.397</td>
<td>0.89</td>
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<td>0.961</td>
<td>0.81</td>
<td>0.95</td>
<td>30</td>
<td>17.5</td>
<td>0.951</td>
<td>0.58</td>
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<td>0.901</td>
<td>0.73</td>
<td>0.91</td>
<td>38</td>
<td>19.5</td>
<td>0.919</td>
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<td>0.68</td>
<td>0.9</td>
<td>27.8</td>
<td>15.1</td>
<td>0.961</td>
<td>0.54</td>
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<td>0.86</td>
<td>0.95</td>
<td>38.5</td>
<td>31.8</td>
<td>0.867</td>
<td>0.83</td>
</tr>
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<td>0.67</td>
<td>0.82</td>
<td>40.1</td>
<td>31.6</td>
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<td>0.79</td>
</tr>
<tr>
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<td>0.82</td>
<td>0.93</td>
<td>27.8</td>
<td>23</td>
<td>0.962</td>
<td>0.83</td>
</tr>
</tbody>
</table>

**Horton's A** = 'Horton's' alpha, exponent in exponential curve of best fit through the infiltration decay curve; a relative measure of the rapidity of the decline in infiltration and hence the 'strength' of runoff generation (not to be confused with the rapidity of the response to rainfall; threshold time/depth to runoff). **R2** is the regression equation for the fit of the exponential curve through the infiltration decay points. **Final Infiltration** = the steady state infiltration value as a proportion of rainfall intensity. **Average Intensity** = the proportion of rainfall which infiltrated over the course of the entire simulation. **Equ Infiltration** = the absolute value of steady state infiltration (mm/hr). **Extrap Infiltration** = the extrapolated value of the 'steady state' infiltration based on the Phillip's equation, at time = 10 hours (this is only of theoretical interest, as rain events in the study area rarely, if ever, last 10 hours). **R2** = the regression equation for the fit of the latter curve through the infiltration decay points. **Infiltration Proport** = infiltration 'proportionality' = the ratio of the measured value of steady state infiltration to the extrapolated value at 10 hours; an indication of the degree to which the simulation has achieved the 'true' final value if the simulation had been left to run longer.
On the other hand, a strong relationship is apparent from the Figure Group between intensity and extrapolated steady state infiltration (to ten hours, using the Phillips equation), and a very strong relationship with measured steady state infiltration. Other very strong relationships evident from the scatterplots are those between average and final infiltration rates; and between interval, average and maximum runoff coefficients. The strength of these last relationships may be partly due to the ways in which the parameters are calculated, in other words, partly data artefacts, but are also dependent on the time to runoff. If the time to runoff is long, for example, the ratio of the average infiltration rate to the maximum infiltration rate will be higher than if it is short, as the parameter ‘average infiltration rate’ is measured from the moment rainfall is applied.

From these observations and findings we can conclude a number of points of theoretical and/or practical interest. Rainfall intensity (rates of moisture and energy application which vary together), for reasons expounded upon earlier, is strongly related to the steady state infiltration rate for crusted soils (also for crust removed when analysed as a separate data set, but the sample is much smaller and not included here). The key question, however, is the implication for runoff yield, which was seen to be a function of the difference between the absolute additional loss in infiltration at a higher intensity and the absolute additional input of water (and hence potential runoff yield) at a higher intensity. In short, the increase in intensity was found in terms of net yield to more than compensate for any additional loss of runoff through increasing surface permeability (really a lessened decrease in infiltration rate, a quasi-parallel curve to that at a lower intensity); infiltration as a proportion of runoff decreases with increasing intensity.

Therefore the same raindepth delivered as a short, high intensity storm will have a higher runoff coefficient than when delivered as a lengthy, low intensity storm, in spite of having both a higher steady state infiltration rate and a higher infiltration rate at all points along the infiltration curve. This will be observed when we examine the results at individual sites. In practice, the storms in the area were observed to typically consist of a short, high intensity burst, which would seal the surface and satisfy the clay moisture demand commented on earlier and thus close any cracks, which would result in antecedent moist conditions for the second segment of the storm (one investigation into the effects of antecedent moisture will be given below). As such, meteorologically speaking (apart from peak intensities being rather low compared to other areas) the conditions in the study area are ideal for water harvesting.
In terms of theoretical considerations, even when the simulation is simulated to continue 600 minutes using the Phillips equation the empirical observation of non equi-finality is confirmed. On this point, note from Table 7.1 that the ‘infiltration proportionality’, or the proportion of the 600 minute theoretical final infiltration rate achieved at the point the rainfall simulation was arrested ranges from 0.51 to 0.89; yet even at only ‘half way’ (about 1/10th of the way, in terms of time) through the simulation, this is sufficient to elucidate the key hydrological phenomenon.

Where relationships were expected but not found to exist is also revealing. Rainfall intensity is not a predictor, according to these data, of threshold time or depth. This may indicate that there is great variability in initial surface conditions across the study area, and that these would have a substantial effect on runoff yield in the case of short events. Only once the processes of crusting and sealing outlined in Chapter 3 are allowed some time to operate, from the point of ponding onwards, do we begin to see an intensity dependent pattern emerge across these surfaces. The implication of this is that it is difficult to rank surfaces in terms of runoff potential without specifying a design rainfall depth or duration. Similarly, there was no relationship found between intensity and ‘Horton’s alpha’, which is a measure of the relative steepness of the decline of the infiltration decay, which was fitted from the time of the first ml of runoff, excluding the pre­ponding stage. Hence the time required to achieve steady state infiltration, either from the beginning of the rain event or, in this case from (interval value according to our schema) the point of incipient runoff, is not apparently intensity dependent, yet has important implications in terms of runoff yield for an events of short duration.

The ‘time/depth to runoff variability factor’ is reflected in the lack of relationships between the intensity and the maximum runoff coefficient (which is the proportion of instantaneous runoff at steady state infiltration) and average (from commencement of rainfall) or interval runoff coefficients. In other words, rainfall intensity may be an excellent predictor of steady state infiltration, but not of the parameters of interest related to runoff yield. On the other hand, there are very strong relationships between the interval, average and maximum runoff coefficients, such that any one would be acceptable as a parameter, although average runoff the most meaningful, but all of these will still be influenced by rainfall intensity in terms of runoff yield, on the same surface and with the same total depth delivered, even though a pattern cannot be established out of the variability between these variables. If this were not the case, then the scatterplots would be straight lines either totally elastic or inelastic (vertical or horizontal).
The implication of this finding, which is considered to be a contribution to knowledge in the field of soil and water conservation, is that in spite of the theoretical and empirical importance of rainfall intensity in terms of sealing and infiltration, the value of these relationships in terms of mapping runoff potential is not readily apparent; there are no 'shortcuts' to determining runoff potential from single 'magic' parameter, as runoff yield must be calculated on the basis of a specified intensity-duration pattern and for a specified surface under specified conditions. Given that a trendline cannot be fitted through these data points with any statistical validity, which represent a range of intensity-duration patterns (which in turn represent a wide range of wetting and energy rates) across a range of surfaces, the isolation of the influence of any one factor on sealing under standardised laboratory or even field rainfall simulation is of theoretical interest and will be pursued here, but from the point of view of assessing runoff potential, these factors interact in the real world in ways which are difficult to predict. It should be recalled on this point that the rainfall simulations carried out were at a fixed intensity and uninterrupted rainfall, whereas real events vary in both these respects.

The implication of this is that the conditions under which runoff potential is being assessed (for example, at such and such an intensity, to the point of steady state infiltration or for a design storm of 15 minutes) and that multiple parameters are required to satisfactorily describe the various aspects the surface response to rainfall. The way in which these factors influence the apparent runoff potential ranking of these sites will be pursued further below after first briefly examining the infiltration curves at each site whilst simultaneously examining some other variables investigated by way of treatments carried out at these sites.

(7.5)

Analyses of simulations retained; on a site-by-site basis

(7.5.1)

Logumukum

The intensity dependence of the infiltration and runoff responses is clearly evident from Figure 7.3. A 'high' (55 mm/hr) and 'medium' (28 mm/hr) storm event are simulated at this site. The time to runoff is much faster for the high intensity storm, an important determinant of runoff yield
Figure 7.3 Infiltration and runoff, Logumukum, 1.5 m simulator

Logumukum 1996

- Infiltration, 55 mm/hr
- Infiltration, 28 mm/hr
- Runoff %, 55 mm/hr
- Runoff %, 28 mm/hr
- Power (Infiltration, 55 mm/hr)
- Power (Infiltration, 28 mm/hr)

\[ y = 80.038x^{0.2671} \]
\[ R^2 = 0.6642 \]

\[ y = 55.404x^{-0.4759} \]
\[ R^2 = 0.7937 \]
in the case of a brief rain event, at four minutes as opposed to 18 minutes for the medium intensity trial. The steady state infiltration rate is achieve within a couple of minutes of runoff initiation, remarkably, for the high intensity storm, and after about 20 minutes for the medium. The runoff potential of the two events, however, is no different if measured in terms of the maximum runoff % without taking time to runoff into account, about 30% for both. This relatively low figure is due to the high steady state infiltration rates, and the values of which appear to be intensity dependence, in accordance with the findings of Bowyer-Bower (1993) for a similar environment in southern Africa. The implication of this is that, if representative of the other sites as well, that the higher intensity storms will not necessarily produce a greater runoff yield if the higher rainfall input rate is equaled by a sufficiently great, rainfall induced, increase in the infiltration rate. In short, these findings confirm the rainfall intensity dependence of steady state infiltration and thus, and due to very quick time to runoff at high intensity, the intensity dependence of runoff yield. A noteworthy feature of this site is that, in spite of 1-2 cm gravel cover, at high intensity, sealing is achieved very quickly; as the kinetic energy of the rainfall is broken by the gravel, this indicates a response to wetting on these clay enriched soils.

(7.5.2)

Eldume

Two medium intensity replicates represented in Figure 7.4 prove to be tightly parallel in terms of the infiltration curves, inspiring confidence that this is an accurate characterisation of the infiltration / runoff response for the drop height employed. Note that a relatively small change in infiltration causes a much larger change in runoff % yield. A very short time to runoff, 11 to 12 minutes, similar to the findings of Bryan et al (1994) at this site using a 5 m spray-type simulator and somewhat higher rainfall intensities. As such, on highly eroded and crusted surfaces such as this, it appears to be valid to substitute a full kinetic energy reproduction simulator with something more practical for rapid survey work. These results indicate that, at least for this site, replicates at same intensity generate very similar results. Furthermore, there is a similar time to runoff but higher infiltration than with 5 m spray-type simulator. This indicates that on highly eroded surfaces low energy simulators are essentially accurate, but that even on hardened surfaces instantaneous kinetic energy is involved in further sealing, as with both simulators wetting processes take place.

(7.5.3)
Figure 7.4 Infiltration and runoff, Eldume, 1.5 m simulator

\[ y = 55.631x^{-0.2336} \]
\[ R^2 = 0.9022 \]

\[ y = 61.195x^{-0.2923} \]
\[ R^2 = 0.9565 \]
Lameluk

In Figure 7.5 the effects of antecedent moisture on infiltration and runoff become apparent for the Lameluk site, where the simulations were carried out at different levels of antecedent moisture due to unexpected natural rainfall. A 'medium wet' (19% by weight loss over 24 hours at 100° c) surface and a dry (following Bryan et al's (1994) protocol to facilitate comparison, <5%) surface, the latter at half the rainfall intensity (10 mm/hr) as the former. As can be seen, in spite of the much lower rainfall intensity, the proportional decay in infiltration values for the wet soil is much greater and the runoff % yield somewhat higher (maximum 35 versus 27%). The steady state infiltration is 6 and 15 mm/hr respectively. The implication of this is that, not only will wet soils yield runoff at well below the rule-of-thumb depth threshold of 15 mm observed by the RAE project staff (Roberts, in Rowntree 1988) (here at 3 mm depth), but the potential runoff yield is much higher. This conforms with expectations and with the results of many other studies, however antecedent moisture status has been overlooked in this study due to the observed rapid drying of the surface in the field and on the basis of studies of rainfall patterns which indicated that at least full day passes typically passes between rain events (Rowntree 1988). In short, Even at low intensities (10 mm/hr), antecedent wet soils generate runoff at very low threshold depths; here after only 3 mm of rainfall. This confirms the importance of the wetting effect, but the practical implications of this may be limited, as soils in the study area are typically dry between storms. However, such wetting effects can be conceived of within a storm, setting up conditions for high runoff yields in the latter part of the storm. In this case, the relationship between the time to runoff and length of the storm will influence runoff yield.

(7.5.4)

Ongata Mara

At this site, near to RAE field # 4, west side, on an intergully plain near the upper reaches of a flattened piedmont alluvial outwash, the project manager, Murray Roberts complains of water logging (pers. Comm. 1997). If rainfall simulations with a 1.5 m simulator had been carried out at this site as part of a site suitability assessment procedure, one would not have concluded that this site would have problems with water logging, due to high infiltration rates across a the three storm intensities simulated; 34, 45 and 60 mm/hr. Initial infiltration and the drainage characteristics deeper in the profile, however, are different phenomenon and require different
Figure 7.5 Effects of antecedent moisture on infiltration and runoff, Lameluk 1.5 m

\[
y = 35.587x^{0.2069} \\
R^2 = 0.9288 \\
y = 18.297x^{0.2423} \\
R^2 = 0.8789
\]
tests. In terms of runoff generating potential, the rating would be rather low, at 20 to 33% maximum runoff. Time to runoff, in this case, generally exhibits an intensity dependence. As can be seen from the annotations on Figure 7.6, the small difference in infiltration between the 45 and 60 mm/hr simulations result in a large difference (about 100% at the point indicated) in runoff percentage yield. Infiltration generally exhibits an intensity dependence here, but only ambiguously so due to the similar values between the two higher intensity trials. In short, there is a general pattern of intensity dependence over the three rainfall intensities for both infiltration and runoff, but because, in this case, the infiltration curve is no higher at 60 than 45 mm/hr, the runoff percentage is much greater for the former, highlighting the differences between absolute values of infiltration and proportional values of runoff. This underscores the importance of selecting the most appropriate parameter for the intended application.

(7.5.5)

Meisori

A ‘medium’ (41 mm/hr) and ‘high’ (52 mm/hr) storm were simulated at Meisori, close to the original RAE water harvesting field, established in the early 1980’s. It is interesting to note that this field was located here not on the basis of hydrological studies, but on the basis of pragmatic considerations, important among which were tribal politics. Only afterwards was a soil survey commissioned; one suspects that this is the typical procedure on development projects! As can be seen from Figure 7.7, if rainfall simulations had been carried out at that site as an assessment exercise, using the 1.5 m simulator, they would have indicated a maximum runoff yield of about 30% over this intensity range. This is not a particularly promising yield (the average runoff would be much lower, particularly if averaged over the entire storm and not just over the infiltration curve), and yet the site appears to be prospering and a marked contrast to the surrounding area. The degree to which this is due to an exclosure effect rather than water harvesting effect, however, is not known. Examining the infiltration curves, there appears to be an intensity dependence effect, with the high intensity storm maintaining a higher infiltration curve throughout the decay, essentially parallel to that of the medium intensity storm (note exponent of the respective power curves), and the steady state infiltration considerably higher. As a result, in spite of a higher rainfall input rate, the maximum runoff % is marginally higher. Curiously, the time to runoff is also shorter with the lower intensity storm. In short, at this site there is an apparent intensity dependence of infiltration and less so for runoff, not for time to runoff. It is hypothesised that the lack of a relationship between intensity and time to runoff is
Figure 7.6 Runoff and infiltration values for Ongata Mara, 1.5 m simulator
Figure 7.7 Infiltration and runoff, Meisori, 1.5 m simulator

\[ y = 161.15x^{0.3529} \]

\[ R^2 = 0.9105 \]

\[ y = 111.83x^{-0.3494} \]

\[ R^2 = 0.9558 \]
due to temporal conditions of the surface between natural storms, whereas the intensity
dependence of infiltration is likely a reflection of more ‘inherent’ characteristics of the crust and
their interaction with rainfall.

(7.5.6)

Marigat

In Figure 7.8, ‘medium’ (24 and 37 mm/hr) (upper graph) and ‘high’ (47 and 55 mm/hr) (lower
graph) intensity simulations at Marigat demonstrate a general pattern of intensity dependence in
terms of the rate of infiltration decay, the steady state infiltration value, the runoff % curve, but
not for time to runoff. In the case of the high intensity events, however, the steady state rates
converge as per the ‘classic’ model of a soil specific infiltration envelope. The corresponding
runoff yield (given time to runoff being about the same for all simulations, a relatively brief 10 to
13 minutes) will therefore be considerably higher for rain events of equal duration. In the case of
the medium intensity storms, the ‘Bowyer-Bower’ model (1993) of intensity dependence holds
true, with steady state infiltration rates of 21 and 27 mm/hr for the 24 and 37 mm/hr storms. In
spite of the higher infiltration rate, the runoff % throughout the curve is sufficiently higher for the
37 mm/hr storm such that the increased loss is more than compensated for by the increased
rainfall input. It is this relationship, together with the time to runoff which determine runoff yield
over a fixed rainstorm duration, providing a basis, where sufficient rain data are available, for
calculating reliable runoff yields in assessing the feasibility of water harvesting. Yield could also
be calculated, of course, in terms of return to a fixed depth of rainfall, as intensity data are often
not available, but in this case the intensity dependence is invisible, and a large data set of depth-
runoff trials would be required to arrive at an accurate statistic. In short, at this site there is an
intensity dependence of steady state infiltration at lower intensities but not higher ones; however
more replication required to make definitive statements. There is a runoff yield intensity
dependency at all intensities, and with time to runoff similar at all four intensities.

In Figure 7.9(upper graph) the intensity dependence of the interval runoff coefficient (over the
period from runoff initiation to steady state runoff) becomes apparent from the simulations at
Marigat, the site with the greatest number of trials and over the greatest intensity range with the
1.5 m simulator. The logarithmic line of best fit through these simulations has an r2 value of a
respectable 0.88 over the relatively low degrees of freedom (but no less than many rainfall
simulation studies due to their time consuming nature). In terms of steady state infiltration rate
Figure 7.8 Intensity effects on runoff and infiltration, Marigat, 1.5 m

Marigat 96 Medium intensity

Marigat 96, High intensity simulations

\[ y = 68.377x^{-0.2554} \]
\[ R^2 = 0.9318 \]

\[ y = 25.852x^{0.0974} \]
\[ R^2 = 0.3509 \]

\[ y = 124.68x^{-0.3755} \]
\[ R^2 = 0.8768 \]

\[ y = 73.078x^{-0.2283} \]
\[ R^2 = 0.8519 \]
Figure 7.9 Intensity dependence of infiltration and runoff, Marigat 1.5 m

Interval Runoff Coefficient as a function of rainfall intensity, Marigat control sites 1996

Rainfall Intensity (mm/hr)

Final Infiltration, as a function of rainfall intensity, Marigat control sites 1996

Steady State Infiltration (mm/hr)

Intensity (mm/hr)
(lower graph), in concert with the findings of Bowyer-Bower (1993) for Swaziland, this parameter was also found to be rainfall intensity dependent, but this time with a linear best fit and r² of 0.89.

The steady state infiltration ranges from 20 to a remarkable 50 mm/hr; this compares with a range from 8 to 33 mm/hr over a similar intensity range at Bowyer-Bower’s sites, and of 13 mm/hr at Marigat for a 5 m simulation at 32 mm/hr by Oostwoud (1992) on an antecedent moist plot using water from the Chemeron dam. Although there are substantial differences in protocol, it is assumed that the value for the 5 m simulator is more accurate than for the 1.5 m simulator due to higher kinetic energy reproduction, and thus that the trend in infiltration dependence is valid but that the absolute values need to be shifted, a movement of the curves to perhaps a parallel position. If a systematic relationship could be established between the two, then a more practical rainfall simulator could be used just a few simulations carried out at key sites using a reference simulator. There is a linear relationship between intensity and steady state infiltration, when interval runoff is graphed on a logarithmic scale. Other measures of runoff are not as well correlated with intensity; implying parameter dependence of relationships and need to consider a range of parameters. The steady state infiltration at this site was considerably higher than with 5 m spray-type simulator; there are probably effects due to differences in energy, but on this clay rich soil saline water used with the 5 m simulator makes comparison difficult, which underscores need for standard protocols and differences between simulator designs.

(7.6)

Analyses of simulations retained; on a surface treatment basis

Still regarding Marigat, the principal site for the 1.5 m simulations, one must also consider the effect of the treatments related to altering the crust in an attempt to address the research question regarding the surface control of runoff. These treatments consist of a series from ‘undisturbed’ to ‘crust removed’, with ‘intermediate’ forms of crust disturbance being ‘trampled’ (a board with nails being dragged three times in the direction of and at right angles to the slope) and ‘punctured’ (the nail board simply placed once on the plot). The puncture treatment is designed to assess the effect of damaging the integrity of the surface seal whilst minimising the additional surface roughness introduces. The ‘trampled’ treatment, on the other hand, is designed to do the opposite; to maximise the surface roughness while allowing the crust to remain in the form of
fragments, or large crust topped aggregates, to determine whether the crust will reform and as an indication of the effects of goat trampling (albeit here without compaction). As can be seen from Figure 7.10, both the time to runoff and threshold rainfall (naturally correlated) decrease in a 'textbook' fashion from crust removed to trampled to punctured to crusted. There is little difference between the crust removed treatment at 67 and 79 mm/hr; in fact, the time to runoff increases with the latter, surprisingly. In short, crusting is clearly a key control on runoff at this site, there appears to be insufficient kinetic energy at a drop height of 1.5 m even at high intensities to reform a crust rapidly over the course of one rain event, and trampling results in a substantial loss of runoff yield through delayed runoff generation. This also implies that multiple storms are required to reform the crust, confirming current modelling of crusts as evolutionary entities on an inter-storm scale.

In short, one can simulate a 'crust disturbance gradient', which corresponds to a 'classic' sequence in terms of time and depth to runoff in response to a surface control on sealing. This appears to confirm the hypothesis that the current, initial state of the surface and not rainfall characteristics is the prime control on time / raindepth / energy to runoff initiation, as the rainfall intensity was similar in all these simulations. As this initial surface state, however, is a transient condition, the time / depth / energy to runoff cannot be readily predicted.

Turning now to the effects of the same crust treatments in terms of infiltration, it is apparent from Figure 7.11 that in spite of a higher initial rainfall/infiltration rate, the crusted control rapidly decays to a lower steady state infiltration rate than either the trampled or punctured treatments. Interestingly, the trampled treatment, which has crusted material remaining on the surface, though having a lower rainfall intensity treatment and lower initial infiltration rate, has a shallower decay curve and a higher final infiltration rate than that of the crust removed plot. Although requiring replication to arrive at any definitive conclusions, the latter observation implies that rainfall energy is more important than the state of the crust / no crust in determining infiltration and runoff. This may also, however, simply have to do with surface roughness impeding flow to the gerlach trough. In short, the steady state infiltration is negatively correlated to the degree of crusting, confirming crust control on infiltration, but the gradient of this relationship is less marked than anticipated.

(7.7)
Figure 7.10 Effects of surface treatments in terms of time and raindepth to runoff, Marigat, 1.5 m simulator
Figure 7.11 Effects of surface treatments on infiltration, Marigat, 1.5 m
Analyses of simulations retained; across all sites

In Figure 7.12 the threshold raindepth and depth to steady state infiltration (first and second bars) are exhibited for all sites for medium intensity storms on antecedent dry crust intact surfaces. The difference is the interval depth. It is apparent that there is no particular correlation between threshold depth and depth to steady state. Both are important, together with the actual value of steady state infiltration, in predicting runoff yield. There is a pattern in so far as the relationship between depth to runoff and steady state by site; for example, Eldume has a very rapid response, but then a lengthy decline to steady state, whereas for Ongata Mara both parameters are achieved after a much longer ‘cost’ in terms of potential runoff foregone. Together with the values of infiltration at the latter point, and the rainfall intensity, these two ‘naturalistic’ or response defined points are natural contenders in parameterising the infiltration/runoff responses, a data reduction exercise, to allow a more concise comparison between sites, particularly as the values of and relationship between them appear to be generally characteristic of each site.

There is no relationship between depth to runoff and interval depth across all sites, however between replicates within a site a distinctive, characteristic pattern emerges which ‘fingerprints’ the hydrological behaviour at each site. This ‘fingerprint’ is defined in terms of the combination of the absolute values and proportional differences between depth to runoff and interval depth at each site. In conclusion, parameters which singly or together have a meaning in terms of runoff yield can be tested in various combinations to identify hydrological fingerprints for the surfaces in a study area. This finding, it is argued, represents a contribution to knowledge. It is recognised, however, that these findings are only indicative and need to be tested in other study areas to determine whether this approach has a more global validity. Multivariate statistical analysis would be warranted where sample numbers are large enough, which is unusual in the case of time consuming rainfall simulation. An analytical approach analogous to image classification routines identifying separable clusters in multivariate feature space is promising.

(7.8)
Analyses of simulations retained across all sites; possible measures of runoff potential
Figure 7.12 Depth and time thresholds, medium intensity storms, 1.5 m simulator

Sites are grouped here: E = Eldume, then Lo = Logumukum, M = Marigat, Me = Meisori and OM = Ongata Mara. The threshold raindepth and depth to steady state infiltration (first and second bars) are exhibited for all sites for medium intensity storms on antecedent dry crust intact surfaces. The difference is the interval depth.

Ceteris paribus, Marigat and Logumukum have the highest runoff potential in a fixed duration storm.
In Figure 7.13 some possible measures of runoff potential are presented, based on all the simulations retained, across all sites. In the upper graph, time to runoff, threshold rain depth, maximum runoff coefficient, and interval runoff coefficient are exhibited. All four are somewhat correlated, whilst the first pair and second pair are strongly correlated, as expected. In the lower graph, average runoff percentage is added to the analysis, together with 'efficiency' parameters (the latter being defined as 'interval coefficient / raindepth to steady state infiltration'), and the sites ordered on the basis of greatest to least average runoff (averaged over the entire rain event). Interestingly, no matter how they are calculated, all indices' trendlines parallel that of rainfall intensity, with some deviation for the efficiency measure, which is largely correlated to raindepth to steady state infiltration. When ordered by average runoff, the sites are very generally ordered by the intensity of the simulated rainfall; as such this treatment appears to have a greater effect than that of site type/location. In short, these results support the idea of the centrality of kinetic energy (rate) in not just generating runoff but in reorganising afresh, it would appear, the surface during the course of the rain event, even from 1.5m height.

When runoff potential across all sites is ordered by average, interval or maximum runoff, sites are ordered generally according to the intensity of the rainfall used to characterise that site. In other words, all measures of runoff have trendlines which parallel those of rainfall intensity and the apparent runoff potential of any site may be spread across the range of sites according to the intensity of the rainfall used for the various 'replicates' at that site. The implication of this is very significant and can be considered a contribution to knowledge: the principle of the intensity dependence of steady state infiltration, though not applicable to any runoff measure when represented as a non-site-specific scatterplot (as seen earlier), acquires a logic with ordination as per this figure, and has very serious implications in the use of rainfall simulation to determine runoff potential for assessing water harvesting suitability.

Another conclusion one can draw from Figure 7.13 is the fact that rainfall simulation protocol, unless specifically investigating the effects of rainfall intensity (in which case a great number of simulations would be required if it is also, unlike almost all such studies reviewed in the literature, a truly multi-site comparison) should define one design intensity, based on local rainfall data, where available, for the purpose of comparing inherent differences between sites. This recommendation was applied to the second field season. This finding, in terms of theoretical import, indicates that rainfall characteristics (the joint rates of moisture and energy application) are more important in determining runoff than the surfaces themselves. This contradicts the
Figure 7.13 Some possible measures of runoff potential

Some measures of runoff potential relevant to assessing suitability for water harvesting; dry crust intact 1996 1.5 m simulation sites

- Time to runoff (minutes)
- Threshold rain depth
- Maximum runoff coefficient
- Interval runoff coefficient

Runoff potential, dry crusted surfaces 1996, greatest to least, 1996 1.5m simulator, ordered by average runoff

- Maximum Runoff
- Average Runoff
- Interval Runoff
- Rainfall intensity
- Raindepth to steady state infiltration
- Runoff 'efficiency'
findings of the Orstom Sahel group, who posit a surface dominated response and on the basis of which their system of runoff mapping is constructed. This may partly explain the deviations in runoff values from those of the 'catalogue' observed by other users of rainfall simulation in the same study area. This may be due to the limited number of intensities used in their work, which emphasises comparisons between sites. Multi-intensity storms were applied in the Orstom work, but in this author's opinion the results from such a protocol are very difficult to interpret. In short, according to these findings, the coefficients $A - D$ are less important than the term $P$ in determining $L_r$ (runoff). Whether the moisture rate or energy rate are more responsible for this intensity dependent response is still an open question.

Note that the second field season built this lesson into the rainfall simulation protocol and experimental design by using one design intensity, but without overlooking the possibility of a change in runoff rankings at two design intensities by also using a very low intensity, which was also designed to capture empirically the threshold intensity, but generally failed to produce runoff, thwarting these two objectives. On the other hand, at least by systematically comparing crusted controls and crust removed surfaces at every site the relative importance of the crust in controlling runoff vis-à-vis the underlying soil might be revealed to be site dependent. As such, one could thereby separate the surface and rainfall controls on runoff on a site-by-site basis.

Finally, by running simulations at the same intensity but with different instantaneous kinetic energy and comparing them on the basis of cumulative kinetic energy, together with contrasting the crust and crust removed treatments at Logumukum, which has a natural mulch, and by comparing energy-less handspraying with rainfall simulation, it was hoped to separate the wetting and energy effects of the apparently intensity dominated response of runoff, amongst other objectives.

In Figure 7.14 runoff potential is ordered by interval runoff percentage and by an 'efficiency' measure. If the ability of a surface to translate rainfall into runoff yield is considered purely over the period of runoff generation, then the site order of runoff potential (upper graph) would be the result. This excludes the effect of time to runoff, which is highly variable, perhaps the result of initial conditions which are not necessarily characteristic of that surface type. If, on the other hand, we consider the time to runoff and particularly the time to the maximum runoff endstate, steady state infiltration, then one could devise a measure (here 'efficiency') which weights the runoff potential so as to downgrade the rating proportionately to the time before maximum runoff is achieved (lower graph). This is important given that the length of the rain events is limited,
Figure 7.14
Runoff potential ordered by interval runoff % and by an ‘efficiency’ measure

Runoff potential, from greatest to least, ordered by interval runoff %, 1.5m dry crusted sites 1996

Runoff potential, dry crusted 1996 sites, 1.5 m simulation, from greatest to least, ordered by runoff ‘efficiency’ measure (interval runoff % / raindepth to steady state infiltration)
and particularly the initial high intensity burst. This has been done by simply dividing the interval value (average percentage runoff) by the total time to steady state infiltration. In the latter case, quick response surfaces such as at Logumukum and Marigat move up in runoff potential.

If depth to runoff is taken into account, then the rankings are different than otherwise, and the intensity dependence of the rankings broken, reflecting the lack of a relationship in the scatterplots between intensity and time or depth or cumulative energy to runoff. See figure annotation for definition of 'efficiency' measure, which downgrades runoff rating proportionally to depth to runoff, given the important proportion of rainfall in Baringo consisting of small events (Rowntree, 1988). Intensity is no longer correlated to the runoff rankings apparently because the infiltration cost to achieve ponding is highly variable even at the similar intensities on the same surface, as a function of the history of the surface (revisiting the concept of a crust as a transient entity).

When depth to runoff is not weighted (it still contributes to but is spread over the calculation of average runoff), all other measures of runoff are intensity dependent, indicating that, and confirmed by observation, that initial runoff time and depth is unpredictable, but once a threshold depth (= depth to runoff) is attained, a characteristic generally intensity dependent infiltration decay occurs at all sites. As such the depth ponding can be understood to represent a complex set of interactions having to do with the initial state of the surface, a surface controlled response, whereas from the point of ponding onwards, the consistent pattern of intensity dependent infiltration indicates that this stage of the infiltration process is a rainfall controlled response. In short, the question should not be whether infiltration in semi-arid soils is surface or rainfall controlled, but rather at what stages in the course of rainfall application does each control dominate and why. Although this point can clearly be pushed further, the lack of replication and the nature of the research design does not allow us to answer it unambiguously. As a theoretical insight however, and given the implication (in terms of altering apparent runoff ranking when the surface controlled depth to runoff stage is explicitly employed in a multiple parameter measure), it is argued that this finding represents a contribution to knowledge.

In Figure 7.15 in the upper graph runoff potential across all sites is ranked according to the steady state infiltration coefficient. Such a comparison is useful if the rain events in the area are of sufficient duration to achieve this condition and of the rainfall intensities range used in the simulations, which vary from 20 to 80 mm/hr, with the majority falling in the 'medium-high'
Figure 7.15 Runoff potential, all sites, 1.5m simulations, by infiltration

Runoff potential, 1996 1.5 m dry crust intact simulations, from greatest to least, ordered by steady state infiltration coefficient.

Runoff potential, from greatest to least, ordered by the absolute steady state infiltration rate, all dry crust intact sites 1996 1.5 m simulations.

Steady state infiltration (mm/hr)

Rainfall intensity (mm/hr)
window 30 – 60 mm/hr. The lower graph is similar but ordered by the absolute steady state infiltration rate, in mm/hr. Whilst also intensity dependent (Bowyer-Bower, 1993), this measure is perhaps more useful, as its expression is not mathematically defined with respect to the intensity of the particular simulation. The implication of the particular choice of definition is significant in terms of runoff ranking; for example, from the top to bottom graph, in the top 5 places there is a loss of two sites from the ranking and a reordering of the remaining three. There is a remarkable correlation between rainfall intensity and runoff potential in the lower graph, which suggests that this is an intensity-dependent and hence unreliable measure where there is much variability in intensity between sites. Across the range of intensities used, ranking according to the steady state infiltration coefficient, in the upper graph groups sites as blocks, which is more credible, whereas in the lower graph the ranking according to absolute steady state infiltration spreads sites along the ranking axis as a function of intensity. This is still valid for predicting absolute infiltration at these intensities.

Whilst the absolute steady state infiltration, in mm/hr, is strongly intensity dependent, the ‘relative’ steady state infiltration value, i.e. as a coefficient (a proportion of rainfall intensity) is not intensity dependent. Thus the site specific control on runoff would appear to be more important than the intensity control, given that, even across a range of intensities for replicates at each site, the coefficient measure of runoff potential generally groups replicates from each site in blocks together in the ranking, unlike the absolute measure, which splits them widely across the rankings as a function of rainfall intensity of the particular simulation, which seems less plausible. This is considered to be an important finding. It would, however, appear to contradict some of the findings presented above, but the conclusion to be arrived at from this scenario, as per the triangulation approach favoured in this study, is that each measure, as found for crust definitions, influences the apparent behaviour of that which is being observed. These are not mere artefacts, however (apart from when strictly the result of the mathematical formulation), but rather different optics on the multifaceted interactions which occur in the real world, as concluded in Chapter 3 when reviewing the oft contradictory crusting literature. There are complex interactions between a) the wetting and energy and chemistry effects of rainfall and b) the myriad histories of the surfaces in the study area; all within one site, not to mention variability during rainfall simulation between two apparently identical simulations.
Conclusions; key parameters and controls revealed from the analyses of the 1.5 m simulations

The comparison of all runoff and infiltration parameters at all sites over the first field season leads, as is apparent from Figure 7.16, to one outstanding conclusion; the intensity dependence of the steady state infiltration. This contradicts, for any one site where multiple intensity simulations were carried out, the classic conception of an infiltration envelope which meets at a common steady state value for a particular soil type (and condition), corroborating the work of Bowyer-Bower (1993). This implies that the soil surface is not just responding to the rainfall in terms of a given infiltration rate or storage capacity, but that the nature of the surface itself has been reorganised under the energy of the raindrops. To what degree this apparent transformation is permanent remains to be investigated. In terms of a cross-site comparison, there is another important implication; that the presumably 'characteristic' and widely used parameter, steady state infiltration, is actually largely a function of rainfall properties and not of site properties. Naturally, the two cannot in practice be separated, particularly when one is interested in runoff yield, and this leads one to the conclusion that runoff potential must be explicitly defined with respect to both. There are many ways to mathematically characterise the interaction between rainfall properties, specifically rainfall rate, and runoff response, and over a range of possible boundary conditions. Whilst steady state infiltration is of interest, it is no predictor of runoff yield, the parameter of interest, without relating it explicitly to the rainfall intensity. Those possibilities most sensible in terms of predicting water harvesting yield will be favoured. It is anticipated that the particular definition of runoff potential will paint very different pictures as to which sites are the most and least promising in terms of potential runoff yield. Due to the rainfall intensity dependence of the infiltration response (which is really a response to the rate of energy application, with complex interactions with the water layer on the soil surface), in the second field season a research protocol should try to minimise the variability in rainfall intensity in order to allow comparison on the basis of site characteristics, without the complexity of comparing across multiple rainfall intensities. The latter is certainly possible, but dictates a very large number of simulations, especially if they are to be replicated for statistical analysis of significance, which would mean that only one or two sites could be studied. Ideally two intensity groups would be studied, one medium and one low, corresponding to the initial peak and subsequent lengthy lower intensity period which appears to characterise the local rain events.
Figure 7.16 Relationship between steady state infiltration and rainfall intensity, 1.5 m simulations

Steady state infiltration as function of rainfall intensity, control sites, dry, 1996

\[ y = 0.6694x + 1.3264 \]

\[ R^2 = 0.8851 \]
In short, the outstanding, consistent overall finding: intensity control of absolute steady state infiltration value. This is the result of the clearly process dependent nature of this observation, a consistent interaction between surface and the wetting and/or energy components of rainfall as a rate dependent function. Crust disturbance gradient experiments in this study and review of the literature lead one to accept a rate of the energy application rather than of water application per se (i.e. wetting effect) explanation for this. In terms of runoff rankings, however, the steady state infiltration coefficient, as outlined above, is considered to be a measure more characteristic of each surface, across whatever rainfall protocol which may be employed, which would undoubtedly vary if adopted as a survey approach to assessing water harvesting suitability. Hence in the subsequent field season this measure (really it’s inverse mathematical equivalent, maximum runoff coefficient) is emphasised as a simple way of parameterising runoff potential, bearing in mind the effect of time / depth to runoff and retaining absolute steady state infiltration as a complementary process based site (albeit intensity dependent) characteristic.

Indeed, it is precisely the largely rainfall ‘independent’ (both in scatterplots and runoff rankings) maximum runoff coefficient parameter (as the intensity dependent infiltration process which, ceteris paribus, determines the runoff coefficient accounts for such a relatively small proportion of the runoff yield by the time a steady state is achieved) together with the rainfall dependent absolute steady state infiltration value which could prove to be a useful means of ‘fingerprinting’ the surface-rainfall interactions whilst providing a robust predictor of runoff potential. This would inform a suitability assessment procedure of both theoretical and practical interest. As such, both the absolute steady state infiltration value and maximum runoff coefficient, which are both measured at the same and process based point of quasi equi-finality, will be prioritised in the next part of this chapter as parameters when exploring the surface-rainfall interactions in the second field season.

(7.10)

Conclusions

1.5 m Rainfall simulations

The findings from the first field season fed into the research programme, together with the discovery of the problem of variability in calibrations, by altering the research design in the second field season to focus on one intensity class, ‘medium intensity’ (18 – 30 mm/hr),
complemented by simulations of 'low intensity' storms (6 – 12 mm/hr) in an effort to directly measure threshold intensity. In addition, a greater instantaneous (3.5 m drop height; 70% kinetic energy reproduction) impact energy was employed in response to substantial deviations in time to runoff and steady state infiltration in the results of the 1.5 m simulations vis a vis the 5 m University of Toronto spray-type simulator. However, as many of these simulations proved to be below the threshold intensity and no runoff generated, those simulations are not reported. It was concluded therefore that the less ideal but more practical approach of extrapolating a line of best fit to the intercept through the values of rainfall simulations carried out at various intensities would be recommended for future research instead. The range of intensity over the classes set for the second field season is due to the ‘natural’ variability in the calibrated intensity using the Amsterdam type simulator design, as discovered in the first season. This variability still affected the simulations in the second field season, but at least the value of the actual intensity was known through continuous monitoring made possible with the improved simulator design developed for the second season.

(7.11)

Results and Discussion of 3.5 m rainfall simulations

This part of this chapter reports selected results of rainfall simulations carried out with the 3.5 m simulator. This part of the chapter is divided into two halves. The first half presents representative results from each of the key sites described in Chapter 6, the same sites and in the same order as with the 1.5 m simulator (which included a few additional sites). The results are presented in the form of a single graph for each site, each with multiple treatments plotted, in order to facilitate comparison between their effects. As sufficient replications were not possible at these sites for a statistical assessment of the significance of and differences between them, the visual presentation and graphic interpretation is favoured. In addition, due to the limited replication, no claim is made regarding the reliability of the results. Treatments, however, which are repeated at all sites, such as a comparison of crusted (control) and crust removed plots constitute a large enough population that one can attach a high subjective confidence to the trends which emerge from the analyses thereof. In the case of this particular treatment, designed to address the key research hypothesis about a surface control on runoff, the research hypothesis of a surface control on runoff is unambiguously confirmed. These results also confirm the findings of Hoogmoed (1987) in the Sahel, who utilised a similar experimental to assess a similar hypothesis.
The second half of this part of the chapter reports results of various treatments using rainfall simulation carried out at one site, Lameluk, the fenced reference site. The phenomenon investigated which yielded both interesting and relevant results are reported here, including:

- the effects of the interactions between antecedent moisture and crusting and the implications in terms of runoff potential

- the effects of instantaneous kinetic energy in terms of the ability of the 1.5 m and 3.5 m simulators to reform a crust which has been removed

- the same, but including crusted controls;

- the effects of the various degrees of crust disturbance and at two levels of rainfall intensity

- the implications of vegetation cover (which increases markedly in years of good rainfall) for runoff yield (which is hypothesised to decline over the rainy season for this reason)

- the intensity dependence of runoff coefficients and the error bars around them

- the intensity dependence of runoff ‘efficiency’ (see figure for definition of efficiency)

- a comparison of the 1.5 m and 3.5 m simulators on the basis of equivalent cumulative energy

- a calculation of runoff yield (in mm) for Lameluk, to demonstrate the relevance of rainfall simulation as a planning tool for water harvesting suitability assessment.

(7.12)

3.5 m Rainfall simulation results, comparison with 1.5 m simulation results, and selective comparison between sites, on a site-by-site basis

(7.12.1)
Logumukum

In Figure 7.17 a low and medium intensity storm are contrasted, and across the surface treatments 'crust' intact and removed. The crust in this case is different than at any other site; it is not in fact a crust but a fine gravel outwash up to several cm deep in places. This surface wash was brushed away gently to expose the underlying ‘plasmic’ surface which was assumed to be the impermeable layer generating local runoff, upon which the adjacent FAO micro water harvesting site depended. The higher intensity (18 mm/hr) storm, as expected, generated faster time to runoff and higher runoff coefficients than the 9 mm/hr storm, both very high at 68 and 52% respectively. As the infiltration rates are very similar, the higher intensity storm naturally produces higher runoff coefficients. When the gravel buffer was removed, it was expected that, as with the medium intensity storm (25 mm/hr), the runoff coefficient would increase, but in the case of the low intensity storm (12 mm/hr) the opposite occurred in spite of a more rapid time to runoff. This leaves some ambiguity as to the effect of the presumed ‘mulch’, but in any case it can be concluded that runoff potential at this site is very high indeed (achieving the remarkable 0.9 coefficient with surface removed, 25 mm/hr).

In the case of Logumukum the low intensity trials produced runoff, indicating the low intensity threshold at this site and hence reliability of runoff yield and very high maximum runoff coefficient. As expected, the higher intensity events generated a higher proportion of runoff (= runoff percentage) than the low intensity events, and when the surface (a mulch of gravel) was removed, a distinct increase in runoff, indicating a distinct energy component of the runoff response compared to the effect of wetting ‘alone’ in the case of the gravel mulch control (albeit at a slightly higher rainfall intensity). This is a good example of where the variability in intensity between the two halves of the simulator board can render interpretation more complicated. At the lower intensity storm with gravel removed the runoff yield decreased, for reasons which may have to do with the proportionately greater effect of any measurements errors at very low intensities.

Even though undertaken at higher intensities (28 and 55 mm/hr), the runoff value which would be attributed to Logumukum with the 1.5 m simulator, a maximum of 30%, is much lower than with the 3.5 m simulator, which achieves a maximum of 70%, and in half the time / depth to runoff when at a similar intensity. This confirms the great importance of instantaneous kinetic energy in sealing this soil. It has been argued that a mulch vs. no mulch experimental design, as at
Figure 7.17 Runoff and infiltration values for the dominant surface at Logumukum, 3.5 m simulator

Logumukum 1997

- Runoff %, 9 mm/hr
- Infiltration, 9 mm/hr
- Runoff %, crust brushed off, 12 mm/hr
- Infiltration, crust brushed off, 12 mm/hr
- Runoff %, 18 mm/hr
- Infiltration, 18 mm/hr
- Runoff %, crust brushed off, 25 mm/hr
- Infiltration, crust brushed off, 25 mm/hr
- Poly (Runoff %, crust brushed off, 12 mm/hr)
- Poly (Runoff %, 18 mm/hr)
- Log (Runoff %, crust brushed off, 25 mm/hr)
- Log (Runoff %, 9 mm/hr)
Logumukum, allows one to separate the wetting effect of the rainfall from that of the energy component. However, even with the 'mulch' intact, the 3.5 m simulator resulted in a much greater runoff yield value for this site at a similar intensity than with the 1.5 m simulator, which implies that this gravel cover only partly dissipates the impact energy. It is hypothesised that the impact energy is transferred mechanically through the gravel mulch to a compacting and sealing surface underneath. If this is the case, then this finding stands out from the 'classic' mulch experiments referred to in Chapter 3, and indicates that direct impact may not always be necessary for substantial energy-derived sealing to occur.

Kamar (1994) found for Baringo that a euphorbia mulch results in a greater decrease in runoff than a stone mulch (in this case an artificial single layer of medium sized stones at Lameluk, unlike the 1 to 2 cm natural outwash fine gravel layer at Logumukum), which she attributes to 'rock flow', invoking a phenomenon suggested and subsequently elaborated by Poessen. (1985). The lesser runoff with a euphorbia mulch she attributed to the water absorbing capacity of that material. These experiments, however, were only carried out with one instantaneous kinetic energy treatment per intensity. The preferred interpretation based on the Logumukum results (which is not rock flow, given the tortuosity of the flow path along 0.5 m of fine gravel together with a high observable porosity due to a poor packing organisation due to the relatively great homogeneity in the gravel size class at the surface – rain interface due to the gravity sorted nature of the outwash) would be a mechanical transfer of impact energy. If this is the case, which would need to be investigated further, then this might represent a contribution to knowledge.

(7.12.2)

Eldume

Runoff initiation takes about 50% longer once the solid erosion crust has been removed at this site, as can be seen from Figure 7.18, less of a difference than had been anticipated. The maximum runoff coefficient for both treatment and control are very high, 0.7 and 0.9 respectively, and the difference between them less than at most other sites in the study area, which indicates that the subcrust surface here is also relatively impermeable. As such, even in the case of crust breakage in high intensity storms or under livestock trampling, this surface could be relied upon to yield high runoff coefficients. Indeed, a World Bank water harvesting demonstration site is located beside this site. The final infiltration rates are remarkably low; for the control, 2 to 3 mm/hr.
Figure 7.18 Runoff and infiltration values for the dominant surface at Eldume, 3.5m simulator
The effect of crusting is readily apparent from the contrast between the crust and crust removed treatments, however lesser proportional differences in maximum runoff between them than between the crust and crust removed results at other sites indicates, surprisingly, that this cemented crust does not have as great an effect on inhibiting infiltration, and does not require as much energy to reform when removed, as at other sites. It would appear that the subcrust soil from which the crust forms either rapidly reforms under the effect of kinetic energy or, more likely – given the thickness of the original crust - seals very strongly due to the wetting effects of rainfall. A seal develops very quickly, however the crust is clearly, as discussed in Chapter 3, a product of multiple cycles of wetting and drying, and in this case probably over a period of several years or more.

Compared to the 1.5 m simulation results, which took place with intensities in the mid 30’s as opposed to low 20’s for the 3.5 m simulations, even when the crust is removed, the maximum runoff coefficient is substantially higher for the latter (70% vs. 50%), indicating that instantaneous kinetic energy together, as hypothesised above, with a strong sealing response to wetting, are responsible for the high runoff potential indicated for this site with both simulators. The greater differential between the 1.5 and 3.5 m simulator results on the control surface at Logumukum as opposed to at Eldume indicates that cemented crust at Eldume mitigates the instantaneous energy effect of the 3.5 m simulator, rendering a low energy and more portable simulator less inaccurate on such surfaces. The much stronger response to a higher instantaneous impact energy at Logumukum indicates that, as hypothesised above, a transfer of energy mechanism is present, rendering this surface more sensitive to variations in energy, runoff more energy dependent, than at Eldume. Thus one would expect a greater rainfall intensity dependence of runoff for a standard rain depth at Logumukum than Eldume, due to the changes in drop size distribution and therefore velocity and thus energy as well as even greater impact energy per unit area as a function of rainfall intensity.

If a comparison is made at this site between the 1.5 and 3.5 m trials, even if graphed against equivalent cumulative kinetic energy (not presented here), the 1.5 m trial requires 50% more energy to initiate runoff and even after 100 minutes, which represents double the cumulative energy application of the 3.5 m simulator at equi-finality, (at 50 minutes; double given the higher rainfall intensity of the 1.5 m simulation), the average steady state infiltration rate is 18 mm/hr, as opposed to 3 mm/hr for the 3.5 m simulator. This indicates that different processes are dominating the surface response to rainfall; in the case of the 1.5 m simulation, the surface
responds primarily to the moisture aspect of the rainfall, whereas in the case of the 3.5 m simulator the response is dominated by the energy aspect of the raindrops, which are above a critical threshold required to reorganise this highly cemented surface.

Even though different processes appear to dominate in the crust and crust removed treatments, these differences of theoretical interest identified by way of the experimental design are irrelevant in terms of runoff potential (ranking, at least), and the same is true of the rankings with the 1.5 m and 3.5 m simulators; in all cases, Eldume rates very high. We highlighted when discussing the results of the first season the difference between the use of absolute and proportional parameters at equi-finality, confirming both the concept/measure dependence of the results and the necessity, as argued earlier, of characterising the surface according to both a measure providing insight into the processes at work and a measure alerting us to the implications thereof, if any, in terms of runoff potential.

The maximum runoff coefficient under the 5m spray-type simulator at this same site on antecedent dry conditions at 25 mm/hr target intensity over 30 minutes is 65%, as opposed to (at 22 mm/hr and 30 minutes to equi-finality) 90% for the 3.5 m run. This difference may be due to a different surface (the exact location of the University of Toronto experiment is not known within +/- 100 m), and even if the identical spot were used, given the transient nature of crusts as discussed in Chapter 3, the values could be expected to be different. The 1.5 m simulation at the 'same' site had a maximum runoff % of 45% at the same cumulative energy as at 40 minutes (equi-finality for the 5 m simulator) with the 5 m simulator and at the same intensity (34 mm/hr); as opposed to 67% for the 5 m simulator (middle graph – 'Eldume 2'). In comparison to both the 3.5 m drip-type and 5 m spray-type, in other words across a range of variables, including kinetic energy and water chemistry and drop size distribution and the spatial and temporal variability of rainfall intensity, the surface responses under the widely used 1.5 m simulator deviate substantially from the - on theoretical grounds in terms of processes believed to be responsible for sealing – 'reference' simulators. As such, it can be concluded that any advantages gained from this design in terms of portability are outweighed by the concomitant loss of accuracy.

It can be concluded that the 3.5 (70% kinetic energy reproduction) and 5 m (90%) simulators exhibit the same process based response (time to equi-finality) at a nearby location on an apparently homogenous eroded 'b' horizon, albeit at a lower depth and cumulative energy for the 3.5 m simulator, which is the value of this less variable (at a given intensity) response parameter
when making comparison across a range of other variables. As such, and given that the runoff predicted at this site is at least as high as with the 5 m simulator, that the research hypothesis that an average kinetic energy reproduction of 70% would be sufficient to induce sealing such that an accurate picture of runoff potential emerges from the results is confirmed. Indeed, the runoff % predicted is higher (though closer when average runoff is considered) due, it is hypothesised, to the salt rich water used in the 5 m simulations, which may have inhibited sealing in some way. Due to the lack of data and the complexities of these interactions, this must remain an area for future research.

(7.12.3)

Ongata Mara

A ‘textbook’ response to the gradual destruction of the crust, for medium intensity storms, is apparent at this site in Figure 7.19 The highest runoff coefficients are achieved by the control and ‘punctured’ surfaces (a remarkable 85 to nearly 100%, putting it on par with Eldume). Although detaining runoff initiation, puncturing the surface has no effect on maximum runoff coefficient; the energy imparted by the rainfall is sufficient within one storm to completely reseal the surface. There is a major jump down, however, when surface roughness is introduced as the crust is physically broken up, which is not completely reformed by the end of one hour at 25 mm/hr (note, however, that this was not found to be true of the same treatment at Lameluk, but is consistent with the 1.5m simulations at Marigat). Finally, as found with virtually all similar treatments at other sites, the crust removed treatment clearly demonstrates the gain in runoff coefficient resulting from the phenomenon of crusting in the study area. Surprisingly, however, the time to runoff was no greater for this treatment. In short, this experiment represents a ‘model’ sequence of runoff as a function of the degree of crust disturbance, as with the 1.5 m simulator trials at Marigat, indicating that the surface control is very important across the study area and irrespective of instantaneous kinetic energy.

Time to runoff was much greater for the punctured and trampled treatments than for the crusted control, but the steady state infiltration rate the same as the control for the punctured but not trampled treatment. This may confirm (in this case, up to a certain degree of crust disturbance) the conceptual model considered when analysing the results of the first season, of a surface dominated response up to the point of ponding, after which a rainfall dominated response is indicated by a highly typical pattern of quasi-parallel, intensity dependent, infiltration curves.
Figure 7.19 Runoff and infiltration values for the dominant surface at Ongata Mara, 3.5m simulator.
However, in this case, above a threshold surface disturbance (somewhere between the punctured and trampled levels), this relationship is altered. This indicates that the Stage 2 rainfall dominated response hypothesised earlier is actually contingent upon the presence of a largely intact crusted surface, and as such is not so much a rainfall dominated response but a predictable and consistent interaction between the rainfall and surface once the unpredictable time / depth / energy to runoff, still hypothesised to be a function of the surface history (analogous to Boiffin’s (1984) observations about the history dependent evolutionary trajectory of crusts developed on initially largely homogenous soil) has terminated in incipient ponding. Surprisingly, the time to runoff was no greater for the crust removed than crusted treatment, confirming the unpredictability of the complex interactions between the surface and rainfall occurring in Stage 1 of this conceptual model.

(7.12.4)
Marigat

Two medium intensity controls, at site with a ‘debris dam’ characteristic of this area, and the effects of the latter compared to a low vegetation cover plot are reported here and represented in Figure 7.20. From the range of the control replicates, it can be seen that there is proportionally much greater variability in time to runoff than maximum runoff coefficient, the latter a remarkable 80 to nearly 100%, making this site highly promising in terms of runoff yield. The vegetated plot falls within the control range and as such it can be concluded, if this is representative, that at a low vegetation cover, as for much of the early part of the first rainy season, there is a negligible effect on the runoff yield that could be expected. The debris dams, on the other, appear to have a substantial effect on runoff, but still translate half of rainfall at this intensity, after some 45 minutes, into runoff.

Time / depth / energy to runoff for a 20% grass cover and a debris dam treatment cannot be separated from the same parameter for two control plots, given the error bars for the latter, confirming the effects of initial surface conditions in Stage 1 of the conceptual model, whereas for stage 2, as predicted, the treatments can be separated at the point of respective equi-finalities from the controls. In all cases, maximum runoff percentage is very high, making this one of the most highly ranked sites in terms of runoff potential for water harvesting. Compared with the 1.5 m simulator at the same intensity, the 3.5 m simulator indicates up to six times greater maximum runoff percentage, which indicates the strongly energy dependent runoff response at this site, in
Figure 7.20 Runoff and infiltration values for the dominant surface at Marigat, 3.5m simulator
spite of having the highest measured clay content (apart from Sereta, which produced no runoff) of the sites where such data were available, which would otherwise lead one to assume a wetting dominated effect, in the absence of data on clay mineralogy. Even when compared on the basis of equivalent cumulative kinetic energy, the maximum runoff percentage is some four times greater for the 3.5 m simulator. Comparing this discrepancy with the doubled value on this same basis for Eldume, one can conclude:

1. That the response at Eldume is less energy dependent than at Marigat, perhaps because the crust is cemented and therefore less subject to rearrangement by drop impact, and would seem to confirm the conclusion reached in the absence of the comparison with the 1.5 m – 3.5 m Marigat differential that swelling rather than impact accounts for sealing with that surface, pointing to the value of triangulation as an interpretative framework and

2. That the 1.5 m simulator cannot be considered to be reliable at the quantitative stage of the runoff potential assessment procedure, but that even at a earlier stage, where ranked values are considered to be proportional to actual runoff, that this is not valid, due to the disproportionate differences demonstrated here from the reference values between sites. These differences are somewhat reduced when calculated over the entire simulation (average runoff percentage), but the advantage of comparison at the point of equifinality is to standardise the comparisons on the basis of process determined threshold.

(7.12.5)

Site 9.6

For medium intensity storms, the infiltration curves for a control and crust removed simulation are featured in Figure 7.21. It is interesting to note the rapidity of the decline in infiltration value of the control as opposed to the crust removed treatment. After this rapid decline the power curves of best fit are parallel, with a steady state infiltration rate of about 6.5 mm/hr for the control and 15 mm/hr for the treatment. Note the characteristic ‘roll waves’ which were present in nearly every simulation in this study. It is hypothesised that these ‘pulses’ of runoff are due to the accumulation and release of sediment dams in the surface and/or in the Gerlach trough, but the regularity is uncanny. Given their respective average rainfall intensities, the control and treatment have maximum runoff coefficients of 0.70 and 0.21 respectively. This indicates that the dominant surface of this site (and the not dissimilar sites 9.4 and 9.5, which experienced
Figure 7.21 Runoff and infiltration values for the dominant surface at site 9.6

Site 9.6 Rainfall simulations; crusted and crust removed

Crusted, 22 mm/hr
Crust removed, 19 mm/hr

- Power (Crusted, 22 mm/hr)
- Power (Crust removed, 19 mm/hr)

$y = 39.955x^{-0.2449}$
$R^2 = 0.9565$

$y = 67.571x^{-0.5722}$
$R^2 = 0.4393$
operational problems with the simulations) is very suitable, on the criteria of runoff alone, for 
water harvesting. As this surface is representative (judging from image interpretation and 
classification and fieldwork), by extension so is much of the central Njemps Flats, as recognised 
by a number of development agencies since the late 1970's.

'Roll waves', as with most of the simulation results, after achieving steady state infiltration, are 
highlighted in this figure by plotting over a smaller range by not displaying the runoff curves. 
This phenomenon could be attributed (Oostwoud and Bryan 1994) to cycles of erosion. These 
roll waves were not included in the present study in calculation of Horton's alpha nor in the 
determination of steady-state thresholds, requiring thus some subjective judgement through visual 
inspection of each result when graphed.

(7.13)
Results of treatments at the principal, fenced site; Lameluk, including comparison 
with 1.5 m simulations and with other sites

(7.13.1)
Effects of antecedent moisture and crusting on runoff

Standard saturated conditions were obtained at this site by carrying out a previous simulation on 
this site; the dry crust and crust removed curves are from the first and the saturated from the 
second simulation. Note that the second simulation does not decrease the steady state infiltration 
with either the crusted or crust removed treatments, confirming the hypothesis that crusts develop 
over a series of wetting and drying cycles

The saturated crusted surface (33% by weight) has a considerably shorter threshold runoff time 
than that of the dry control plot; 8 and 16 minutes respectively. During a short storm or short 
storm segment of runoff generating intensity, this difference could have implications in terms of 
runoff yield. Eventually the (instantaneous) runoff coefficient becomes similar for both. When 
the crusts are removed, this surface type at Lameluk, when saturated, again exhibits much shorter 
threshold runoff times than crust-removed dry; 29 minutes and 48 minutes; the ratio between the 
two is less than that separating their crusted counterparts, but the absolute value of the difference
between wet and dry much higher. Runoff values are also much lower than for the crusted plots at a similar rainfall intensity. This confirms the hypothesis that crusting is a key factor controlling runoff generation and a key predictor of runoff yield; the maximum runoff coefficient being 0.7 and 0.3 respectively for the crusted and crust-removed antecedent dry plots. The maximum runoff coefficient is higher with both crusted and crust-removed plots for the dry plots; in both cases there is a point at which the dry plots overtake their saturated counterparts in runoff yield; the reason for this is not known, as the reverse was expected, however more replication would be required before any definitive conclusions could be reached. Perhaps the previous simulation on the wet plots created some crust breakage.

It is salient to note that there is a proportionally shorter time / depth / energy to runoff for antecedent saturated soils in the case of both crusted and crust removed pairs of treatments. This indicates that whether or not an impermeable layer has already developed, that sealing due to wetting appears to be one of the factors corresponding to the variability in Stage 1 of the proposed model. In other words, the degree of ‘antecedent sealing’ is one of the main factors explaining time / depth / energy to runoff.

(7.13.2)

Effects of drop height on crust formation

In Figure 7.22, in the upper graph, one generally finds a pattern that is expected, except that runoff initiation begins at the same time for both the 1.5m and 3.5m plots. When the crust is removed, the 1.5m simulator, as expected, requires considerably more time. When these comparisons are made, however, on the basis of cumulative kinetic energy, as in the lower graph, it becomes apparent that, contrary to expectation, surface sealing / crust forming on the crust removed plots takes no longer under the lower drop height, at 240 joules/unit area and on the crusted plots, infiltration lower for the 1.5m plot at the same energy. If representative, this indicates that the 1.5m simulator could substitute for the taller version.

The 1.5 m simulator operating on a crust removed surface at Lameluk, whilst requiring a greater raindepth to seal the surface, eventually achieves the same runoff % as a crust removed surface under the 3.5 m simulator. Another, slightly lower intensity, 3.5 m simulation does not achieve the same runoff % as either the other 3.5 m or the 1.5 m trials; furthermore, there is no pattern in the depth to runoff. In short, it would appear that removing the crust exposes considerable
Figure 7.22
Effects of drop height and crust removal; comparison on the basis of cumulative energy, Lameluk
variability at immediately adjacent plots, that the crust masks such inherent variability of the subcrust surface from which the crusts were formed. This would appear to confirm the two stage conceptual model developed to explain the rainfall simulation findings, with Stage 1, (various parameters) to runoff / ponding being a function of the variability of the surface rather than a function of rainfall.

The 1.5 m and 3.5 m simulators achieve the same maximum runoff %, which was never the case on crust intact surfaces; indeed, the 1.5 m simulator achieves this at a lower cumulative kinetic energy, in contrast to the crusted trials above, in which even at greater cumulative kinetic energy, the lack of instantaneous kinetic energy cannot be compensated for. This indicates that on crust intact surfaces, a threshold instantaneous kinetic energy is required to reorganise the existing crust, above and beyond the sealing effects of wetting.

(7.13.3)
Effects of crusting and drop height on runoff

In Figure 7.23 a comparison on the basis of cumulative raindepth of crusted and crust removed 1.5 and 3.5 m simulation plots at a ‘medium’ intensity range (18 to 25 mm/hr) reveals that crust removal doubles the depth required for runoff initiation for the 3.5 m plot and doubles to quadruples that for the 1.5 m simulator. Depth to runoff initiation is double that of the 3.5 m crust removed plot for the 1.5 m counterpart. A more stable and probably characteristic measure is that of maximum runoff coefficient; the 1.5 m crust removed plot, in this case, has a value twice that of the 3.5 m counterpart, which was not anticipated. The runoff yield to be expected from this surface type, however, as measured with the 3.5 m simulator is at least twice that as at the lower board height, in the case of the control plots. From this comparison, it would appear that a single storm event with the 3.5 m simulator is not at all sufficient to achieve the runoff potential of this surface type once the crust is removed, however in the case of the 1.5 m simulator, it is sufficient to achieve the (much lower) maximum runoff coefficient measured / obtainable with this instrument.

In short, differences between crust and crust removed treatments were found to be much greater for 3.5 m simulator than for 1.5 m simulator; in fact, the 1.5 m crust removed plot was found to have double the runoff % as the 3.5 m crust removed. This confirms the model of a surface controlled initial condition (which is also applicable to the subcrust or – artificially - crust
Figure 7.23 Effects of crusting and drop height on runoff, Lameluk

Comparison of 1m and 3m crusted and crust removed, Lameluk 97
removed state), largely independent of or at least with no specific correlation to instantaneous or cumulative kinetic energy or wetting rate; but than a rainfall controlled response once the surface is sealed / ponding has occurred (which is also applicable to the crust once formed over multiple event from a crust removed state, which was seen to require a threshold instantaneous kinetic energy in order to reorganise the current structure of the surface). In other words, if the same dichotomy developed to explain the intensity dependence or non dependence within one storm on a crusted or crust removed surface or to explain the different responses between them; if this same dichotomy / sequence can be applied on a between storm model of crust development from an initial crust removed state to a crusted state, then we could potentially integrate the proposed conceptual model to be of more universal value. This would be a desirable theoretical advance and such formulations, though not fully developed here - as more systematic replication and quantification would be necessary - do conform with our latest understandings, as seen in Chapter 3, of the transient nature of the crust and of the importance of both wetting and energy effects, the importance of both instantaneous and cumulative energy, and the distinction between crusting and sealing. If, therefore, some steps have been taken towards a conceptual, integrating model on the basis of the interpretation of the rainfall simulations carried out in the study area and in the light of the literature in this field, then this could be considered to be a contribution to knowledge. The question of the development of the crust over time has been tested and the results reported in the next section.

(7.13.4)

Effects of surface treatments and runoff, on the basis of cumulative energy

A medium intensity storm, 27 mm/hr, is compared in Figure 7.24 to a low intensity storm (11 mm/hr) and a medium intensity storm (27 mm/hr) on a plot on which the crust has been left but has been gently ‘trampled’ (broken up, without compaction) in terms of the efficiency or return to unit energy applied, with respect to the runoff coefficient. The lowest intensity storm had the highest efficiency, as expected, but surprisingly this was followed by the trampled surface and then the medium intensity control. Efficiency can be gauged from the slope of the curves as well as the energy to runoff initiation. Bringing in the values of a 10 and 28 mm/hr storm on crust removed plots, it is apparent that the crust removed plots have, as expected, much lower runoff efficiencies; the difference from their crusted counterparts could be thought of as the efficiency gain in runoff yield resulting from the crusting process, which has been ‘paid for’ by the cumulative energy imparted by antecedent storms to a particular surface. The lower intensity
Figure 7.24 Effects of surface treatments and intensity on runoff, in terms of cumulative energy, Lameluk 3.5m

Surface treatments and intensity classes on infiltration and runoff

- Infiltration, 11 mm/hr
- Runoff %, 11 mm/hr
- Infiltration, crust removed, 10 mm/hr
- Runoff %, crust removed, 10 mm/hr
- Infiltration, 27 mm/hr
- Runoff %, 27 mm/hr
- Infiltration, 'trampled', 27 mm/hr
- Runoff %, 'trampled', 27 mm/hr
- Infiltration, crust removed, 28 mm/hr
- Runoff %, 28 mm/hr, crust removed
- Log. (Runoff %, 28 mm/hr, crust removed)
- Log. (Runoff %, crust removed, 10 mm/hr)
- Log. (Runoff %, 11 mm/hr)
- Log. (Runoff %, 27 mm/hr)
- Log. (Runoff %, 'trampled', 27 mm/hr)

Cumulative rain depth (mm), equivalent energy (dimensionless)
crust removed plot, as with the crusted plot, produces runoff at a lower depth/energy threshold, but does not achieve as great runoff coefficients. If representative, this implies that lower intensity storms are more efficient when applied to a precrusted soil, but less so on a severely disturbed crust.

In the case of Lameluk, contrary to the crust disturbance gradient tests on Ongata Mara (3.5 m) and Marigat (1.5 m), the trampled crust has a somewhat higher runoff % (top end of control obscured by legend), indicating that at Lameluk less energy is required to reseal the crust fragments than elsewhere, for reasons which are unknown.

Using the slope of the line between runoff % and depth or energy, together with depth or energy to runoff as measures of unit return in runoff % to unit depth or energy applied, an ‘efficiency’ measure, a low intensity (11 mm/hr) storm is seen to be far more efficient than a medium intensity (27 mm/hr) storm in spite of attaining a lower maximum runoff %. This may be related to the reduced turbidity and erosion and occurring at the surface due to a lower rate of energy application, as proposed earlier and from our understanding of the literature, which also explains why lower intensity storms attain lower steady state infiltration rates. In terms of runoff yield, however, as shown earlier, this efficiency does not translate into higher runoff unless one could choose to deliver a given annual volume of rainfall as long, low intensity storms, in which case the crusting which translates this rainfall into runoff would not develop; in other words, one would find oneself in a temperate environment.

This implies that once the crust is formed, or under ‘antecedent crusted’ conditions, the dominant process is that of wetting for low intensity storms due to their inability to deliver instantaneous kinetic energy at a sufficient rate to overcome the structure of the surface which has been formed thanks to the energy imparted from previous, higher intensity events. This is not to say that crusts develop in a linear fashion with cumulative energy; on the contrary, they have been conceptualised as a cyclical phenomenon. Although we interested in the sealing process and effects, and accordingly have defined crusts in Chapter 3 in an explicitly functional manner (effects on infiltration), the relationship between sealing and crusting is not straightforward. If, for example, sealing is dominated by wetting processes in low intensity storms and by energy processes in higher intensity storms on crusts, what of the dominant processes, in terms of rate dependence, on ‘initially’ crust removed soils?
Once the crust is removed, which is conceived of here as a ‘savings account’ of cumulative energy over the history of that surface (with many deposits and withdrawals) and of the effects of cycles of wetting and drying, the efficiency of low intensity rainfall is seen to be less than that of a medium intensity event, which indicates that the rate of kinetic energy is the key control at this initial stage of the crust development process, as the surface is saturated, by definition, once ponding is attained, such that the decline in infiltration from that point is primarily a function of the energy rather than wetting effects of the (according to the conceptual model developed) rainfall intensity dominated Stage 2.

(7.13.5)

Intensity dependence and variability in the runoff coefficient

In Figure 7.25, the absolute final infiltration values for the 11 mm/hr simulation is, as expected, lower than that of the two 27 mm/hr and one 24 mm/hr medium intensity class replicates at Lameluk. This is anticipated given the likely disturbance of the soil surface under the higher kinetic energy rate of the higher intensity simulations. The runoff coefficient of the 11 mm/hr simulation, however, is considerably greater than that of the 24 mm/hr plot, which was not expected. In spite of a higher infiltration rate, it was anticipated that the much greater rainfall intensity would more than compensate for this. Without a greater number of replicates it is not possible to say whether this is an exceptional case, but the variability in runoff coefficient for the three medium intensity storms indicates that sufficient replication is important for rainfall simulation. The time requirements to achieve this precision, however, may be impractical under real world survey conditions, making simpler alternatives possibly more attractive at least for non key sites. If it is not possible to unambiguously distinguish between these intensity classes, then it is more profitable to compare a very high and very low intensity, if these values are also relevant intensities with respect to the intensity class distribution of natural rainfall at the study site, if such data are available. In the case of this study area, the intensity classes examined here; ‘medium’ (about 20 to 40 mm/hr) and ‘low’ (under 15 mm/hr) are the most common 30 minute maximums.

The variability within a group of medium intensity events (two at 27 mm/hr, one at 24 mm/hr) in terms of runoff percentage was compared in this study to that of a 11 mm/hr storm, and the latter found to fall within the range of the former. This is surprising and does not match the general pattern found across all sites, but is highlighted to draw attention to the variability possible at one
Figure 7.25 Intensity dependence and variability in the runoff coefficient, Lameluk 3.5m
site and the danger of not allowing for sufficient replication, which as discussed earlier, involves a choice between intra and intersite comparison. If, however, a relatively large total number of simulations has been carried out across sites but otherwise over a limited range of treatments, as in the second field season (i.e. only 2 target intensities), then general patterns emerge across / in spite of site variability, in spite of the inability to draw certain conclusions about any one site.

(7.13.6)

Intensity dependence of runoff 'efficiency' in terms of cumulative energy, runoff yield implications

'Return' to a unit of raindepth and/or energy in terms of instantaneous runoff yield (proportion of runoff converted into runoff, at any instant in time) was found, as per Figure 7.26, to be inversely related to rainfall intensity, in so far as the 11 mm/hr trial proved to be the most efficient when measured in this way, whilst the 27 mm/hr storm was more efficient than the 24 mm/hr replicate. This result was anticipated, given that the water accumulating on the runoff generating surface in high intensity storms may act as a barrier to crust formation; effectively diffusing the impact energy, whilst the energy of turbulent water in this layer is hypothesised to keep soil particles in circulation which would otherwise seal surface apertures. Given the much higher absolute rates of water input, however, the runoff yield as an absolute value will still be considerably greater in higher intensity storms, per unit time. For a storm of a given depth, on the other hand, the runoff yield, if these values are representative, would have a higher absolute runoff yield. It should be noted, however, that many of the low intensity simulations at various sites, an attempt to establish empirically the threshold runoff intensity, did not generate runoff, and thus this population is too small to draw definitive conclusions. A single parameter of efficiency would be the slope of the line on these when plotted on these axes.

In short, lower intensity storms shown to be more efficient than higher intensity storms, as discussed above and the reasons for which provided in the annotation. A runoff efficiency of 60% is attained in a low intensity after 14 mm raindepth, but 'costs' one medium intensity storm twice this much in cumulative infiltration / relative energy, and for another medium intensity storm this is never attained.

(7.13.7)
Figure 7.26 Intensity dependence of runoff 'efficiency' in terms of cumulative energy, runoff yield implications, Lameluk 3.5m

![Graph showing the relationship between cumulative rain depth and runoff efficiency per unit rainfall/energy, Lameluk.](image)

- Runoff efficiency, 27 mm/hr
- Infiltration, 27 mm/hr
- Runoff efficiency, 24 mm/hr
- Infiltration, 24 mm/hr
- Runoff efficiency, 11 mm/hr
- Infiltration, 11 mm/hr

- Linear (Runoff efficiency, 24 mm/hr)
- Linear (Runoff efficiency, 27 mm/hr)
- Linear (Runoff efficiency, 11 mm/hr)

Equations:

\[
y = 2.2572x + 25.892
\]

\[
y = 1.6722x + 13.59
\]

\[
y = 0.972x + 12.207
\]
Effects of drop height and crust removal; comparison on the basis of cumulative energy

Generally a pattern that is expected is evident from Figure 7.27, upper graph, except that runoff initiation begins at the same time for both the 1.5m and 3.5m plots. When the crust is removed, the 1.5m simulator, as expected, requires considerably more time. Turning now to the lower graph, when these comparisons are made on the basis of cumulative kinetic energy, it becomes apparent that, contrary to expectation, surface sealing / crust forming on the crust removed plots takes no longer under the lower drop height, at 240 joules/unit area and on the crusted plots, infiltration lower for the 1.5m plot at the same energy. If representative, this indicates that the 1.5m simulator could substitute for the taller version.

In short, on a crusted control at Lameluk, a 3.5 m medium intensity event requires the same time but more cumulative energy to induce ponding than a medium intensity event using a 1.5 m drop height, however the former eventually attains a marginally lower steady state infiltration rate. With the crust removed, the results are the same with either one. If these results are representative, then, when converted to cumulative energy there is apparently no instantaneous energy effect, however these results contradict the results from other sites where comparisons were made, above, between the results of the first and second field seasons, which point to a threshold instantaneous kinetic energy explaining within-storm crust (as expressed as seal) development on crusted and, to a much lesser extent, crust removed plots.

(7.13.8)

Drawing conclusions: Rainfall simulation as a planning tool for water harvesting

The absolute runoff yield in terms of mm per unit area, Lameluk, is extrapolated for a ninety minute storm at three intensities in Figure 7.28. This can, of course, then be converted into volume yield given the runoff coefficient of the catchment area as determined from rainfall simulation and the size of the catchment area, as well as an estimate of the transfer cost per unit distance travelled from source area to runon zone, the value of which could be derived from overland plot experiments. From such lines of best fit the yield at a given time can be calculated, depending on the length of the design storm at the intensity class(es) anticipated, if intensity-duration-frequency data are available, which is normally not the case in semi-arid environments in developing countries, or at least not lengthy records. Thus a number of educated guesses
Figure 7.27
Effects of drop height and crust removal; comparison on the basis of cumulative energy, Lameluk
Figure 7.28  Rainfall simulation as a planning tool for water harvesting, based on runoff yield at Lameluk, 3.5 m simulator
would be required. The average runoff yield at any intensity will, of course, increase as the length of the storm increases, as the 'fixed cost' of achieving runoff initiation will be spread over a longer and longer period of calculation. Thus the time or depth to runoff initiation is important, however this parameter proved to be highly variable in the case of this research. Whilst it may be tempting to use the maximum runoff coefficient / steady state infiltration rate as a more 'characteristic' value of a surface, which discounts the boundary conditions of each run (the initial state of the surface), it is precisely the initial state of the surface which is both of interest and relevance to this study, particularly given the relatively short rain events in the study area, or at least short periods of maximum intensity, in which the greatest runoff yield likely would occur.

In short, runoff yield per unit time has been shown at this site to be intensity dependent, in spite of an inverse relationship between intensity and runoff efficiency; as discussed earlier, this is the result of an increase in the rainfall input more than compensating for the increased infiltration cost of crust disturbance during higher intensity events.

(7.14)
Runoff under natural rainfall at Lameluk or on Lameluk soils

(7.14.1)
Water acceptance as a proxy for crust development over a rainy season

Rainfall simulation size runoff plots of Lameluk soils were removed to the field station, as described in Chapter 4, so that the temporal scale of an entire season was assessed with validation plots under natural rainfall, crusted and crust removed, and monitored in terms of the evolution in zero energy water acceptance after each wetting drying cycle. This experiment plays a role in satisfying the research objective of testing the hypothesised definition of a crust as a transient entity in space (demonstrated by the rainfall simulations across sites) and in time (within-storm; as demonstrated by the rainfall simulations at each site). Furthermore, it accords with a unified conceptual model of crust evolution (by stages, with different processes dominating at different stages and under different initial conditions - crusted or crust destroyed - and different rates of wetting and energy application). As such, the temporal scale of an entire season was assessed with validation plots under natural rainfall, crusted and crust removed, and monitored in terms of
the evolution in the volume of 'zero' energy water acceptance after each wetting drying cycle using the handsprayer, as a nondestructive proxy measure of crust development.

The water acceptance curves upon drying of three crust-removed plots after natural rain events of varying intensity and duration across 3 replicates over part of the rainy season appear to indicate a cyclicality of crust formation and destruction, as can be seen from Figure 7.29. Infiltration declines to a minima, and then the crust appears to break, as observed by Patrick and Berliner (1993) in Israel, judging from the sudden increase in infiltration on the 24th of April. This implies at the very least that the runoff potential assigned to a particular surface, especially by non crust-inducing low energy simple techniques such as the handsprayer, must be thought of as a time specific value. Furthermore, the range (precision) of such values still needs to be determined and the degree of overlap between the 'temporal error bars' between sites ascertained. It is also possible, however, that the variability apparent from the handsprayer would not be as great during actual rain events, as the processes of crust formation during the application of energy may result in similar runoff values for a given intensity irrespective of the time sequence.

The work of Casenave and Valentin (1989) suggests a linear evolution in runoff potential (increasing) as the surface degrades, but this if for an initially vegetated surface. Vegetation developed on these plots over the course of the season, which may have influenced these results. In sum, however, it is believed that the pattern here reflects an actual change in runoff potential as a function of cyclical crust breakage and formation, and as such, as argued above, the limits of the 'runoff envelope' would need to take this variability into account in any specification of site runoff potential. The practicalities of characterising each site on this basis, however, using rainfall simulation rather than a handsprayer would be questionable, due to the time requirement of rainfall simulation. As such, handspraying offers a possible alternative under specified conditions.

When the crust removed results are compared with the crusted plots (not shown), a net reduction in water acceptance (taken to be a reduction in porosity due to a restructuring of the surface under the impact energy of rainfall) is apparent with both treatments over this period of the rainy season. In both cases there appears to be a 'cycle' of crust disturbance / erosion and reforming, very similar on both crusted and crust removed plots (totalling 6 replicates, over 7 events), but with higher infiltration for the crust removed plots. The implications of these findings are that the model of crust as a transient entity appears to have been confirmed, and therefore that there are
Figure 7.29
Crust evolution cycles over the course of a rainy season, based on water acceptance using a handsprayer, following each natural rain event.
temporal limitations on the validity of any runoff assessment survey. As such there is a need for a low-cost and rapid crust monitoring system: ideally remote sensing and handspraying, calibrated to rainfall simulation, in order to update the runoff potential values on a regular basis at a reasonable expense.

(7.14.2)
Validations of rainfall simulations against natural rainfall on Lameluk soil plots

As described in Chapter 4, runoff plots were set up at the field station and natural rainstorms monitored for simultaneous rainfall – runoff, with rainfall intensity being calculated on a five minute interval during the storm using graduated cylinders with funnels. One of the storms was simulated using a rainfall simulator and using rainwater collected at the site, in order to ensure equivalent water chemistry. Note also that one of the natural rainfall plots had a screen placed at the height of the rainfall simulator (3.5 m) in order to simulate the energy used by the simulator, and the results compared against the other plots.

The basic characteristics of the three rain events producing runoff on the validation plots of Lameluk soil, as can be seen from Figure 7.30, are essentially similar and fit the larger rainfall patterns described by Rowntree (1988) for this area. They are also similar in intensity range to the majority of simulations carried out in the first field season and almost all of those carried out in the second season. This would confirm that the design storms upon which the simulation protocols were based are sound. The cumulative rain depth pattern for the storms (upper graph) indicate low runoff depths of only 5 to 6 mm, well below the threshold depth suggested by Roberts of the RAE project of 15 mm (Rowntree 1988) for runoff initiation. The intensity pattern (lower graph), as anticipated, consists of a peak burst of 30 to 45 mm/hr (5 minute maximum), followed by a longer, lower intensity segment of 5 to 15 mm/hr. The rainfall simulations are constant intensity storms mainly in the range of 17 to 28 mm/hr and thus can be considered to reproduce the average intensity of the first ten or fifteen minutes of a typical storm in the area. If runoff has not occurred by about 15 minutes, then the instantaneous energy of the simulator is perhaps not sufficiently high.

The runoff coefficients are very low for the events of both the 21st and 22nd of April, as can be seen from Figure 7.31, storms with the same cumulative rainfall depth as that of the 23rd, but at a lower peak intensity. These storms essentially represent threshold depth/intensity conditions for
Figure 7.30
Cumulative rain depth and rain intensity, natural rain events at validation plots
Figure 7.31
Response of plots of Lameluk soil to natural rainfall, 21/4/97 and 22/4/97

Runoff response under natural rainfall, 21/4/97
Runoff coefficient 0.8 – 2.7 %

Runoff response under natural rainfall, 22/4/97
Runoff coefficient 0.6 – 2.8 %
runoff for the Lameluk soil, which is representative of much of the central Flats. In fact, as the rainfall simulations at the various sites indicated that many of the other sites have higher values than Lameluk, it can be concluded that threshold runoff depth for water harvesting is very low, probably from 3 mm, for some locations, lower than previous research (Bryan et al, 1994) using rainfall simulation had indicated, making lowland Baringo an ideal area for water harvesting on the criteria of runoff potential. Curiously, of the three crusted plots, only one generated runoff on the 21st, as opposed to two of the crust removed treatments. In the case of the subsequent event all plots generated runoff, which is surprising given that the intensity pattern of the former is higher (common to 10 minutes, then dropping off for the 21st but not the 22nd) but with cumulative raindepth 20% higher. It is curious to note that most of the runoff occurred during a period of negligible rainfall after 20 minutes, indicating high surface detention due to vegetation cover. The similarity between crust and crust removed indicates that the crust has already formed.

The lower raindepth but higher intensity storm on the 23rd produced very high runoff coefficients, indicating that even for a storm of only 5 mm depth, a runoff yield can be expected if there is a sufficiently high intensity burst at the beginning of the storm. Given the multiplier effect of water harvesting, and the low conveyance losses indicated by the overland plot experiments, even such a small event (of which the majority of storms in the area consist, if not the majority of total rainfall volume), could contribute to maintaining the root zone with moisture. Surprisingly, the greatest runoff resulted from a crust removed plot, although this had only 10% vegetation cover as opposed to 40% for the highest producing crusted plot. The net yield from the crusted plots were greater. The crusted plot under the 3.5m screen produced the greatest runoff in spite of the storm energy having been broken at this height, but the crust removed plot under the screen produced the least runoff. This would indicate that individual plot characteristics are more important than the distinction between the kinetic energy at 3.5m and the height of terminal velocity. Similarly, there was no correlation between vegetation cover and runoff. The time to runoff and the runoff coefficients are higher here than for the rainfall simulations, even under the 3.5m screen. This can likely be explained by the fact that the rainfall landing on the 3.5m screen with the natural rain trials is doing so at a certain velocity, whereas for the drip-type simulator it is virtually zero after a 20 – 25 cm drop. In addition, there may be even higher intensity peaks within the 5 minute intensity interval measured.
The natural rainwater rainfall simulations on the validation plots were modelled after the event of 21st April, which is believed to be typical of the lower intensity storms which make up the majority of events (based on Rowntree 1988), and are thus a more reliable basis on which to calculate runoff yield as the length of dry spells between them (Rodgers et al. 1985) will be shorter than the more spectacular high intensity high volume events. The event of 21st April was of 20 minutes duration and, generated very little runoff over the 45 minute period from commencement of rainfall to the end of runoff. With the simulation, as can be seen from Figure 7.32, the runoff coefficient averaged over 50 minutes is between 19 and 26%, much higher than for the natural event, however at 25 minutes, the peak runoff under the natural event, a peak runoff of 10 ml/minute is recorded, and for the simulation from 15 to 26.

The time to runoff is much shorter under the simulation, and the variability between the plots reduced. The differences are likely due to the fact that the simulated rainfall was applied for a continuous period and over 50 minutes as opposed to 20 minutes and then 25 minutes of runoff under negligible rainfall, as with the natural rain event. A recording rain gauge was installed by the University of Toronto, but it was stolen, and thus the exact intensity patterns of the local rainfall cannot be mimicked precisely. The fact that the crust removed plot # 3 has the highest runoff coefficient indicates that the crust has been reformed by this time. Runoff values are lower than at Lameluk on undisturbed soil, possibly due to differences in water chemistry. The two plots which had been under the screen have somewhat lower runoff, indicating that energy application from natural rainfall has indeed been reduced.

In short, from these experiments it can be seen that under natural rainfall threshold raindepth is very low; 3 mm for soils removed from Lameluk, which had the highest infiltration rates of all the sites where simulations took place. Furthermore, under natural rainfall, even for a storm of 5 mm, maximum runoff values can reach almost 100%; however variability is also great between the surfaces, and which is not correlated to vegetation cover, which approaches the 40% threshold determined by rainfall simulation for these same soils (in situ, at Lameluk).

Although the maximum runoff % on some plots under natural rain event reached very high values, in the case of the modelled event (21st April), which was chosen because of the low intensities and the typical ‘step’ pattern of one burst and then a plateau, and which was believed to represent a threshold event. The average runoff % is much lower than that of simulated rainfall, however this is because the simulation was allowed to continue until the state of equi-
Figure 7.32
Validation plots of Lameluk soil under rainfall simulation mimicking natural events in water chemistry and intensity pattern.

Runoff response of validation plots; rainfall simulation mimicking natural rainfall; using rain water & variable intensity rainfall (5 minutes at 30 mm/hr and then 15 mm/hr).

- Plot 3; crust removed
- Plot 4; crusted
- Plot 5; crust removed; under screen
- Plot 6; crusted, under screen

Average runoff coefficient 26%
Rc 25%
Rc 20%
Rc 19%
finality (50 minutes). In the case of the natural rain event runoff only occurred during the short initial burst, with an apparent threshold intensity above 15 mm/hr (difficult to assess due to the time lag between rainfall and runoff attributed to vegetation). Implication: if representative, which would need to be assessed by way of instrumented plots, the ‘threshold’ intensity (to maintain runoff after a short runoff generating burst of 30 mm/hr 5 minute average intensity) is higher than expected; greater than 15 mm/hr.

(7.14.3)
Overland flow conveyance loss experiments

Overland plots were set up, as described in Chapter 4, in order to determine how representative the rainfall simulations are in terms of larger runoff surfaces. This relates to the concept of the partial area contribution phenomenon, discussed in Chapter 3. The runoff coefficient from the four plots over five runoff producing rain events are represented in Figure 7.33, from the latest in the season (left) through the earliest. The plot lengths (left to right for each date) are from 0.5m to 13.5m, a tripling of length each time. Average vegetation cover increases from the first event, at 20%, to 40% by the end of the experiment. Unfortunately only raindepths are available, not intensity.

A difference in intensity pattern almost certainly explains the difference in runoff between the 22nd and 27th, both of which were relatively major storms, 41 mm. Assuming the latter to be a high intensity storm, the conveyance losses range from some 25% over 1.5 m to 80% over 13.5 m. These are the sort of values which had been anticipated, but the losses for lower depth (and presumably, in the case of the 22nd, lower intensity) storms are much higher. Unfortunately the experimental design did not allow for simultaneous rainfall-runoff readings, but such work on similar loam soils in southern Israel by Patrick and Berliner (1993) indicate a strong correlation between peak intensity and runoff coefficient over various plot lengths. There is considerable variability here, however, between the relative values for the plot lengths across the dates, which is unexpected, however the results from the 27th and 30th are very similar in this respect and will be assumed to be representative. Based on this assumption, it can be seen that as the plot length triples from 1.5 to 4.5 m there is a decrease in runoff efficiency of between 25 and 50%, and as the distance is again tripled, a further loss of around 25 to 30%. The runoff coefficient drops by a maximum factor of 2/3 between 1.5 and 13.5 m, which provides an indication of the conveyance loss to be expected with external catchment meso water harvesting.
Figure 7.33 Results of overland flow conveyance loss experiment

Runoff efficiency of overland plots

White box = raindepth mm

<table>
<thead>
<tr>
<th>Date</th>
<th>Runoff Efficiency</th>
<th>Cover</th>
</tr>
</thead>
<tbody>
<tr>
<td>1_5_97</td>
<td>0.5m</td>
<td>6</td>
</tr>
<tr>
<td>30_4_97</td>
<td>1.5m</td>
<td>8</td>
</tr>
<tr>
<td>27_4_97</td>
<td>4.5m</td>
<td>27</td>
</tr>
<tr>
<td>24_4_97</td>
<td>4.5m</td>
<td>39</td>
</tr>
<tr>
<td>22_4_97</td>
<td>13.5m</td>
<td>39</td>
</tr>
</tbody>
</table>

39% average vegetation cover
In short, there are higher conveyance losses than anticipated, but this is difficult to interpret without intensity data. Two events of the same depth but presumably different intensity pattern generated very different runoff percentage values; confirming, indirectly, the hypothesis of intensity dependence of conveyance cost. If this is the case, then when upscaling from rainfall simulation plots, rainfall intensity needs to be explicitly considered when calculating net runoff yields. Finally, for the same intensity (i.e. during one event), variability between slope lengths is great, which does not confirm the anticipated inverse relationship between runoff yield and slope length. This indicates that the state of surface, including variable vegetation cover, appears to be more important over these slope lengths than slope length itself in determining conveyance losses and runoff yield. As such, rainfall simulation, which provides a measure of runoff potential as a function of the state of the surface, can be considered to be a reliable indication of runoff to be expected over larger areas if the state of the surface of those larger areas can be determined. This raises the question of how to assess the state of the surface over larger areas, and of the variability in hydrological properties within an area of 'uniform' spectral properties (i.e. within one pixel) if remote sensing is used to map the state of the surface. These issues will be addressed in Chapter 9.

(7.15)

Conclusions

Relating the results of the rainfall simulations to the literature and implications for runoff assessment

One of the outstanding results presented in this section is the rainfall intensity dependence of runoff potential (when using the steady state infiltration rate as the measure of runoff potential) across all sites and for all treatments and at all intensities. This indicates the predominance of this factor as a control on runoff, but by way of the surface, of course, through a reorganisation thereof, and where high intensity storms inhibit seal formation through the turbulent effects, it is hypothesised, of the impact energy, combined with the movement of a depth of water on the surface resulting from the high wetting rate. This confirms a similar finding (Bowyer-Bowyer 1993) in Swaziland using in situ simulations, who noted this phenomenon and contrasted it to the 'classic' model developed for temperate soils of equifinality, but without elaborating upon the mechanisms responsible. A similar finding was first reported (it is believed) in an important
study by Romkens et al. (1990) using laboratory simulators in the U.S., who found that final seal conductance was a function of rainfall intensity.

This also relates to the findings of Patrick and Berliner (1993) in the Negev, where a crust specific threshold intensity was discovered above which runoff yield declined under micro water harvesting systems, which was attributed to crust ‘breakage’. The question of the dynamic relationship between crust and seal formation and erosion addressed in Chapter 3 and incorporated into the latest process based models also comes to mind, and although this was also seen from the literature review to be slope dependent, in part, in the case of the study sites the slope is negligible and similar in all cases. Gimenez et al. (1992), using laboratory simulations and packed soil columns (caveats regarding which have been mentioned earlier) found that after 5 minutes of a high intensity burst under variable rainfall intensity, surface seals attained maximum observable thickness and minimum macroporosity (> 30 um), whilst planar voids (> 500 um) were eliminated. Under continuing rainfall, however, the seal thickness reduced due to erosion and planar voids reappeared.

Romkens et al. (1985) postulated that at higher rainfall intensities there is a higher rate of removal of detached particle. Working with laboratory simulations, they found that for the same cumulative rainfall energy, the hydraulic conductance was greater at greater rainfall intensities. This does not, however, allow us to separate the energy effects from the wetting effects, as both the rate of moisture and rate of energy application to the soil surface vary together with changes in rainfall intensity. Turning now to the effects of the interaction with the nature of the surface of the soil, Romkens et al. (1990) found that an initially cloddy soil seal development was a function of rainfall intensity, but with flat surfaces (as in Baringo, unless broken by trampling, which is common), seal development was a function of rainfall energy. This suggest that, for a surface consisting of aggregates, the wetting effect is most important; simple wetting tests with aggregates from flat crusts were carried out in Baringo, the results of which, therefore, would be applicable, if the findings of Romkens et al. (1990) hold true, for cases of disturbed crusts.

Indeed, the crust was disturbed in various ways in situ as one of the treatments carried out in the present study, all on the same surface type – at Marigat, in the case of the 1.5 m simulator - and the results reported in this chapter. Where crusts are not disturbed, the cumulative energy of the rainfall rather than the wetting rate is postulated on the basis of the literature and as hypothesised to be the key control on the runoff yield. In short, one would expect to see a rainfall intensity
dependence with both the crusted and crust removed treatments, as indeed is the case for the Baringo data across all treatments, but the reasons for this same intensity dependence, analysing our results in the light of findings with other crusting soils, would be different; for the crust removed treatments, due primarily to wetting effect, but with crusted controls due primarily to the rate of kinetic energy application. Furthermore, through the conception and use of a handsprayer in the subsequent field season, we were able to separate (in an indicative manner) the effects of wetting and energy by comparing the runoff rankings as measured on the same surface using a rainfall simulator (which, according to Romkens et al. (1990) is primarily an energy control on sealing in the case of flat crusted soils such as in Baringo) and a handsprayer (which measures crust-controlled reduction in water acceptance due to wetting effects), the results from which are reported in the subsequent chapter. As such, we have satisfied a number of our research queries.

The practical implication of this finding when using rainfall simulation to determine rank surfaces in terms of runoff potential as part of a water harvesting suitability assessment exercise, is that these simulations should be carried out within a narrow intensity range in order to isolate the effect of the surface response, which also ties into one of the other major findings of this study, the variability from a calibrated intensity of the widely used ‘Amsterdam-type’ rainfall simulator, and which was partly overcome (this variability was continuously monitored) in the design of a new simulator. Another important implication in terms of water harvesting is that, to the degree that rainfall intensity controls the infiltration rate across a particular set of surfaces being compared, so much less important are differences between the surfaces in determining runoff yield. At high intensities, the effect of differences in steady state infiltration between surfaces, however, is diminished, due to the low proportion of potential runoff yield (rainfall) lost to infiltration. At low intensities, however, differences between surfaces in infiltration rate will be very important and thus still need to be determined. This is particularly true where rainfall occurs, as in the study area, in many smaller and low intensity storms and it is precisely by taking advantage of this rainfall by multiplying rainfall yield by constructing systems on the surfaces with the highest runoff yields (for a given rain depth? intensity? duration?) that water harvesting, and rainfall simulation in identifying these surfaces and quantifying their effects, can promote the rural economy, assuming that the socio-economic factors are also appropriate.

This is why, from the point-of-view of the application of interest, the finding, for the study area, on the basis of the simulations carried out, of the rainfall intensity dependence of the response of the surfaces assessed is very significant. The actual impact of this phenomenon, however, is also
a function of the proportion of runoff lost to infiltration, the rate of decay of the infiltration curve, the time and depth to runoff and the duration and intensity patterns of the rain events in the study area and not just of the steady state infiltration rate, attractive as that is as a ‘standardising’ and ‘natural’ parameter; all of which returns us to issues addressed earlier concerning:

a) the (local rainfall) data dependence of rainfall simulation
b) the measurement and definition dependence of the analysis of the results of rainfall simulation; as will be seen in this section when attempting to determine the most relevant amongst the many parameters related to runoff potential when ranking the surfaces

In addition, it is important to remember when thinking about the rainfall intensity dependence of the steady state infiltration that this state may never, in fact, be reached with many of the smaller storms; in which case it is rather parameters such as depth and time to runoff and the rapidity of the decline in infiltration (‘Horton’s alpha’) which are the most significant factors. As demonstrated by the comparison of rankings using different measures of runoff potential, and tying this in to the present discussion, an understanding of both the pedo-hydrological processes and the implications thereof in terms of runoff yield are necessary to assessing water harvesting suitability. If this study, as illustrated by the results and interpretations of this first section, has succeeded in drawing attention to this issue and the complexities involved and to the measure and method dependence of any attempt to rank runoff potential, then it could be considered to have made a contribution to knowledge and satisfied many of the objectives set out for this study.

Any runoff assessment procedure must take into account a number of temporal dimensions when representing the spatial distribution of runoff potential. Ideally, all spatially distributed values would vary proportionately with each other over time; in practice, of course, this is highly unlikely. This now returns us to our conceptual point of departure, that of the complexity of trying to map a phenomenon which varies greatly in both space and time. Whether this variability can be monitored, such as from remote sensing, is an open question which is a topic of future research. Whether the variations are sufficiently great to justify, economically, a monitoring procedure is unknown. It is technically feasible to readily adjust runoff parameters (whichever one(s) may be chosen), in a GIS modelling environment, and impressive, colourful outputs produced. Such an attempt, however, would likely lead to spurious precision given the number of question marks around the input data, the way they are method / measure / model dependent, the multifarious variables (discussed in Chapter 4) involved in rainfall simulation, the
complexities of the responses and range of possible interpretations thereof, as is apparent from this section, and the inherently dynamic nature of the soil surface. Therefore, a modest and simplistic GIS approach has been taken here and to which the subsequent, much briefer, sections lead to and culminate in an example water harvesting suitability assessment procedure; sophistication in analysis will be appropriate as more is learned about the nature of the input data.
Chapter 8

Results and Discussion (Part two)

Rapid, low cost tests of relative runoff potential and comparison with results of rainfall simulation

- Results of simple tests
- Results specifically with the handsprayer
- Infiltration trends in the landscape over a larger area, using the handsprayer
- Comparisons between simple tests and rainfall simulation

Chapter Overview

(8.1)
Overview of chapter

(8.2)
Determining variability in infiltration around the rainfall simulation sites, using low energy water acceptance as a proxy measure for runoff potential, comparison with rainfall simulations, and value of the handsprayer

(8.3)
Summary of handsprayer results at individual sites

(8.4)
Intra and Inter site variability in infiltration, using the handsprayer
(8.5)  
Comparison of rainfall simulation and handsprayer rankings of runoff simulation across sites and between measures of infiltration

(8.6)  
Revealing infiltration trends over larger areas of the landscape with the handsprayer

(8.7)  
Results of interest with other 'simple' tests employed as possible indicators of runoff potential

(8.8)  
Conclusions
Overview of chapter

As rainfall simulation is so time consuming, it is not possible to characterise any surfaces other than the dominant etat de surface elementaire (ESE) at each site, to use the conceptual model and terminology of Casenave and Valentin (1989), explained in Chapters 3 and 5. A major motivation in this study was, as outlined in Chapters 1 and 4, to attempt to substitute rapid, cheap and replicated measures of runoff potential for rainfall simulation. Therefore the relative ranking of surfaces (i.e. of the study sites) was compared using both measures, the results of which will be presented in this chapter. As such, it was also of interest to determine whether handspraying with a control and crust removed treatment, exactly like the rainfall simulation protocol, would highlight processes such as surface control of runoff. If they did, then the handsprayer could be considered to be a potentially useful tool when working with crusting soils. In addition, the water acceptance values of the surfaces generated by handspraying, which are essentially measures of the wetting-only effect on sealing, could be contrasted with the rainfall simulation values for the purpose of separating wetting and energy effects.

Chronologically, this chapter begins by reporting the results of handsprayer tests used to determine the variability in infiltration between the ESE's occurring around the rainfall simulation sites, conceiving of this low energy water acceptance as a proxy measure for runoff potential. The objective of this exercise was to determine how representative the dominant (in terms of the proportion of the surface of the Etats de Surface occupied by) ESE is at each site, as the dominant ESE was chosen at each site for rainfall simulation. A concomitant objective was to determine the relative variability in infiltration with each effective pixel (200 x 200 m area) corresponding to the area around each rainfall simulation spot. This would aid in assessing whether the ES or effective pixel at each location could be separated on hydrologic criteria, which serves as a basis for a corresponding study of the separability of the sites on spectral grounds, in order that a comparison could be made between the two, which is reported in Chapter 9.

This topic is then followed in this chapter by a comparison between the rankings in runoff potential of the study sites according to rainfall simulation and according to various 'simple' tests, particularly the handsprayer, as well as an evaluation of the usefulness of the handsprayer to reveal infiltration trends over larger areas of the landscape, in this case along a transect towards the Lake. The potential advantage of a simple measure of runoff potential at such a scale of
investigation is the rapidity of the test and thus the number of locations which can be assessed. The idea behind such an investigation is to achieve a greater representative of the variability across a study area by increasing the number of sample sites, as well as the number of replicates at each site, in order to reduce the disparity in spatial coverage between the hydrological and spectral measures. Finally, some conclusions are drawn about whether and under what conditions rapid, low cost measures of runoff potential could substitute for quantitative, high kinetic energy reproduction rainfall simulation values in the context of a suitability assessment for water harvesting.

(8.2)
Determining variability in infiltration around the rainfall simulation sites, using low energy water acceptance as a proxy measure for runoff potential, comparison with rainfall simulations, and value of the handsprayer

The variability in water acceptance, taken to a proxy measure for runoff potential, around each rainfall simulation was assessed using the handsprayer. The various ESE’s identified within each 200 x 200 m area (the ‘effective’ pixel size of the satellite imagery employed, taking georeferencing errors into account) were assessed, typically with several replicates at each ESE. The rainfall simulation site was considered to be an association of elementary etats de surface (ESE’s), in other words an Etats de Surface. Furthermore, for most of these ESE’s both a control and crust removed treatment were carried out. The objective of this exercise, illustrated below with results from selected sites, was to determine:

a) whether the particular ESE used for the rainfall simulation within this Etats de Surface is representative of the ES as a whole (the minimum unit ‘visible’ from remote sensing)

b) the degree of variability within the ES and

c) whether the ESE’s can be clearly separated in terms of water acceptance, where separability is defined in terms of minimum overlap between the error bars of each ESE, given that three replicates are available at least for the dominant ESE at each site. The dominant ESE is that which makes up the greatest proportion of the ES and which is the ESE on which the rainfall simulation were carried out.

d) Whether the effect of crusting is apparent even when using a low energy measure of runoff potential, by contrasting a control and ‘crust (really surface) removed’ treatment
At Logumukum, as can be seen from Figure 8.1, when the gravel ‘mulch’ is brushed away ('crust' removed treatment) an underlying layer controls infiltration/runoff, as can be seen from the dramatic drop in infiltration when the upper layer is removed. The values at the end of the control run overlap the initial infiltration values of the crust removed treatment, indicating that after about a minute of spraying the water has penetrated the mulch. If this final infiltration value, however, were taken at face value, the handsprayer would seriously underestimate the runoff potential at this site. Hence it can be seen that highly absorptive materials on the surface of a site can result in misleading results, unless a deductive approach is taken to corroborate the values. Note the much greater variability between replicates for the control than the gravel brushed treatment, which is undoubtedly due to different thicknesses of mulch; nonetheless, there is no overlap between the range of control and treatment runs, allowing one to draw clear conclusions about a layered system. There is some ambiguity, however, in terms of the comparison with the rainfall simulations, as the latter had opposite responses to surface removal, dependent on intensity, the reasons for which are not clear.

Turning now to an example of a more typical surface in the Njemps Flats, Figure 8.2 represents the results of handspraying for crusted and crusted removed interrill areas and for the interrill ‘drains’ at site 9.6. Note that the diameter of a typical interrill area is approx 30 cm and the depth of a rill only about 5 – 10 mm deeper than the crest of the interrill, so the assessment of variability is being carried out in this system at a very fine scale. There is clearly a crust effect, judging from the line of best fit through the replicates describing the infiltration characteristics of the interrill (surface type on which the rainfall simulations were carried out at this site) ESE, compared with the same surface with the crust removed. This is particularly evident in terms of initial infiltration (16 mm/hr crusted, 23 mm/hr crust removed), but also the final value (6 and 10, respectively). Comparing these curves to those of the rainfall simulation, they appear similar apart from the steep decline of the crusted response to simulated rainfall, due to the application of kinetic energy.

There is no overlap at the beginning of the curves between control and treatment, but some at the end. Nonetheless one would conclude from this, correctly, in the case of the absence of rainfall simulation data, that there is a crust controlled hydrological response at this site, signaling the importance of characterising the crust if one wanted to carry out a runoff assessment exercise in this area. This demonstrates one possible use of the handsprayer, as a tool at the reconnaissance stage of a suitability assessment exercise. Another benefit of using the handsprayer, as apparent
Figure 8.1 Handsprayer, Logumukum

Infiltration rate is calculated on the basis of the average spray area.
Figure 8.2
Assessing the variability in ESE’s and the effect of crustation, with the handsprayer, Site 9.6.
from this example, is the assessment of the effects of crusting at multiple scales; these results indicate that crusting is a control at both the scale of the handsprayer ‘plot’ and at the plot size of the rainfall simulator used. The handsprayer is also relevant to the research question of the relative effects of the wetting and energy components of rainfall, as only the former is at work with this device. In this case it is apparent that, even without inducing sealing through rainfall simulation, an hypothesized ‘swelling’ effect of water in the crust removed treatment rapidly brings the two treatments to a similar infiltration rate.

Yet another possible value of handspraying is the determination of some ‘inherent’ (at a particular moment in time) value of saturated hydraulic conductivity of the crust without disturbing it with energy application. Finally, the handsprayer can be used to indicate the hydrological variability at a rainfall simulation site between ESE’s, as this is too consuming with rainfall simulation with multiple sites and treatments, even without replicates. In the case of this site, the rill values are very similar to that of the interrill, which is not surprising given the subtlety of the rilling. There is also greater variability between replicates in the interrill ESE, likely a function of differing depths of sandwash on the surface.

Continuing now with the theme of the variability of ESE’s, at Eldume, as seen from Figure Group 8.3 the variability between three replicates of handspraying on the crusted dominant surface at Eldume reveals a complete separability of the crusted control from the crust removed treatment. As such, using the handsprayer one could unequivocally conclude that the crust has a significant hydrological impact on infiltration at this site, and thus that runoff mapping at this site should be based on crust characteristics. Similarly, one would conclude from this data that the crust trampling so common in lowland Baringo will have a substantial effect on runoff yield, which implies that fencing is critical for water harvesting schemes in such an area. Rainfall simulation, however, would allow one to qualify the second conclusion, as the runoff coefficient is so high even with the crust removed that it would not be necessary to fence the runoff, only runon area, which makes it a much more attractive economic proposition. The sandwash ESE (interrill area plus 90% sand cover) somewhat overlaps the range of variability of the interrill, meaning that ascribing a lower value to this ESE would be somewhat justified. It is anticipated, however, under rainfall simulation that this really represents only the buffer effect of the sand, which would delay runoff but not alter the final runoff coefficient.
Figure 8.3
Variability in infiltration between ESE’s and assessing effect of crust using handsprayer, Eldume
The infiltration curve in mm/hr (given certain assumptions about wetted area) are presented on the right for the crust and crust removed. These values are very similar to the final infiltration rates under rainfall simulation, however this figure is sensitive to the definition of the (principal) wetted area under the handsprayer. Therefore; for explicit comparison with the rainfall simulations, the total infiltrated volume was used instead as an index of relative runoff potential and the rankings according to the two instruments compared (below).

The difference between the control and crust removed treatment at Lameluk on actual rainfall simulation plots are shown in Figure 8.4. The difference between the two is fairly marginal, which is surprising, and does not correspond to the results of the rainfall simulation. This is an exception to most other sites, where the crust and crust removed plots had very different infiltration values according to handspraying. It is possible that there is a relatively high clay content, which produces high infiltration values with the handsprayer even on crusted surfaces. The variability between the handsprayer replicates, as usual, is quite tight.

Twenty four hours after the simulations, these same plots were sprayed once again, and the results appear sensible; for both the control and treatment the final infiltration rate dropped (by about 40%) and both curves shifted downwards. This would seem to confirm that the handsprayer is a useful tool for identifying changes in the infiltration capacity of the surface, and that the rainfall simulations (3.5 m in this case) are ‘permanently’ reorganising the nature of the soil surface. The implication of the latter is twofold; first of all, it inspires some confidence that the sealing processes are being induced by rainfall simulation, and secondly that a rainfall simulation plot should not be used more than once unless this phenomenon is the object of investigation.

(8.3)

**Summary of handsprayer results at individual sites**

(Results not illustrated visually for every site)

At Logumukum, there is a very substantial surface effect; the comparison of the control with the surface removed replicates reveals the hydrological implications of the layered nature of the system without having to resort to rainfall simulation but without, clearly, supplying any absolute values. If the gravel were not brushed away, one would obtain a misleading runoff ranking of this site, as the volume delivered is not sufficiently great to saturate the buffer and reveal the
Figure 8.4 Effects of crusting and of rainfall simulation, Lameluk
The '24 hour' plots are the same plots as those represented by the graphs to their left, but 24 hours after rainfall simulation
effects of the plasmic layer beneath. Thus this instrument must be used within an understanding of the processes being addressed.

At Ongata Mara there are distinct hydrological behaviours observed across the averages of 3 replicates for the ESE’s, with the highest infiltration in the rills and the lowest on the stony rill sides, where the surface material has been eroded into the rills. As such, the relative values correspond to hydrological logic and to the topography controlled approach taken by Valentin to crusting surfaces. Note, however, that even Valentin did not assess hydrological characteristics at a sub m² (= size of runoff plot) resolution; as such this investigation builds on that work by identifying relative sources and sinks at a finer scale and this, together with the applications, represents, it is argued, a contribution to knowledge.

At Eldume the dominant (eroded ‘b’ horizon on which rainfall simulations took place) ESE can be distinguished on hydrological terms. The handsprayer confirms the hypothesis that the surface selected for rainfall simulation would have the lowest highest runoff potential of the ESE’s at the site, and these surfaces have distinct infiltration curves (parallel, with little, if any overlap). The limitations of the handsprayer, however, as with Logumukum, at least if used uncritically, is revealed by the 90% sandwash over erosion crust example: apparently a high infiltration surface, but once this ‘mulch’ is brushed away, as at Logumukum, the values drops dramatically. Conversely, when the erosion crust is removed, as with the rainfall simulation, there is a great increase in infiltration, confirming a surface (and specifically crust) control, but the curves do not, unlike with the rainfall simulator, converge. This may be due to an insufficient wetting volume but almost certainly due to the lack of energy to seal the soil. As such, this confirms a conceptual model of a Stage 1 energy control on the development of crusting, starting from an ‘antecedent crusting = zero’ initial surface state scenario. Furthermore, assessment of the error bars through the replicates of the dominant ESE and the crust removed replicates indicate unequivocal separation between control and treatment, indicating the potential value of the handsprayer, as this conforms to what one would expect on the basis of a knowledge of the impact of crusting from the literature.

At Site 9.6 the non crust surfaces of a cattle track and grassy area can be distinguished from the crusts but not from each other, on spectral criteria. The differences between the crusted ESE’s, as observed in the field are extremely subtle. In hydrological terms the dominant ESE, the interrill area selected for rainfall simulation is confirmed to have the highest runoff potential and
removing the crust confirms the crust control evident form this same treatment under rainfall simulation. The cattle path had much higher infiltration than with 65% grass cover, indicating a crust control, however the difference in runoff may not be as great, revealing a limitation with the handsprayer. An analysis of the error bars around the replicates of the rill and interrill ESE’s strongly overlap: from a hydrological point-of-view, and taking a functional definition of crusting surfaces, they can be considered to be the same ESE, in spite of the visual difference in infiltration decay curves. As such, the spatial scale of investigation of the rainfall simulator (0.5 x 0.5 m plots) can be considered to be appropriate in terms of integrating source and sink areas which are virtually indistinguishable at a finer scale. This presents yet another possible use of the handsprayer.

At the reference site of Lameluk, it was found that there was little difference registered with the handsprayer between crust and crust removed treatments carried out on actual rainfall simulation plots, possibly due to a high clay content resulting in high infiltration on both, which would be a source of error for the handsprayer, which does not deliver sufficient volume to satisfy the clay demand and move the infiltration curve to the point where clay expansion seals and dramatically reduces infiltration. Whatever the reason, this is not a random error, as it is observed for 3 sets of comparisons, each containing three replicates. This indicates that the handsprayer produces replicable results and is responding to a process.

A comparison of pre and 24 hr post rainfall simulation plots using the handsprayer indicates a drop of approximately 40% in infiltration with both crust and crust removed plots. This indicates that the handsprayer is responding to processes of surface reorganisation and not just to the swelling demand of the soil, which makes one confident about its application to monitoring crust changes on the validation plots. In addition, it reveals that changes under the 3.5 m simulator are ‘permanent’, and that even with the crust removed, indicating that crust formation is dominated by the energy rather than wetting effects of rainfall, even though wetting effects may be important within the storm in producing runoff for that event by contributing to the sealing process.

(8.4)

Intra and Inter site variability in infiltration, using the handsprayer

The ability to separate three rainfall simulation sites, which have been shown on the basis of rainfall simulation to have distinctive hydrological behaviour, can be seen in Figure 8.5 to be
Figure 8.5
Discrimination between rainfall simulation sites using handsprayer values and multiple replicates

Intra and intervariability in handspray curves, rainfall simulation surfaces, Eldume, site 9.6 and Ongata Mara

Lines demarcate zones of scatter, similar to error bars, around the average total infiltrated volume, denoted by the large white circle, for each site.
distinguishable on the basis of the handspraying as well. The range of variability between three replicates at each site on the dominant (location of rainfall simulation) surface does show a marginal amount of overlap between sites, more so at the beginning of the spraying than at the end. The greater spread of values at the end of the handspraying cumulative infiltration curve reflects true differences between replicates, as the initial infiltration volume is limited not by the infiltration capacity of the surface so much as the speed at which spraying can be maintained. By the end of the spraying the various moisture but not energy dependent swelling and sealing processes have been largely activated, and differences in the texture and chemistry of the top few mm of the surface at different spots likely accounts for the different curves. The range in total volume infiltrated between replicates at any one site increases proportionately to the average total volume infiltrated for all replicates at that site; the reason for this is not known.

In short, three sites which have been shown on the basis of rainfall simulation to be hydrologically distinct can be separated unambiguously with the handsprayer, with little if any overlap of error bars. Separation of surfaces, however, says nothing about the relationship between the rankings according to rainfall simulation and according to handspraying, and it is to this question which the study now turns.

(8.5)
Comparison of rainfall simulation and handsprayer rankings of runoff simulation across sites and between measures of infiltration

Within the data set of all crusted and crust removed 3.5 m rainfall simulations, a reasonably strong correlation ($r^2 = 0.73$) was found between the steady state infiltration rate (mm/hr) of the 3.5 m simulations, across all sites and treatments, and ‘Horton’s’ alpha, the latter being a measure of the relative rapidity of decline of the infiltration curve, as can be seen in Figure 8.6 (upper graph). In other words, at those sites with low steady state infiltration values, the decay to that value is relatively rapid. As it is precisely the combination of these two characteristics of the infiltration curve which essentially determine (interval) runoff yield, those sites, identified on the basis of either of these parameters, can be confidently identified as having a high runoff potential. In calculating Horton’s alpha, the final infiltration value used to define the lowest point to be fitted was identified by visual inspection as the first point at the lowest infiltration rate before ‘roll waves’ commence, the duration of which is simply a function of the length of the time that
Figure 8.6
Correlations within the 3.5 m and handsprayer data sets, respectively; parameter selection upon which to base comparisons between the simulator and handsprayer.
the simulation is continues after this point and would otherwise bias the apparent rate of decay if included in the calculation. In the case of the handsprayer (lower graph), the two key parameters, total volume infiltrated and steady state infiltration, are largely interchangeable ($r^2 = 0.81$), however the former measure is preferable as it obviates the need to ascribe a wetted area for calculation purposes.

At some sites, for a number of reasons, no runoff occurred or the results were not considered to be valid (leakage etc) for one or the other of crusted and crust removed conditions under rainfall simulations, and thus a complete comparison on both crusted and crust removed treatments across all sites with the handsprayer is not possible. There are, however, a sufficient number of sites from which to draw some conclusions. It can be seen from Figure 8.7 that, in terms of the relationship between crusted and crust removed infiltration values, the handsprayer at Logumukum registers a large difference in total infiltration volume, but the same experiment using rainfall simulation resulted in no change in the final infiltration rate. This difference has to do with the time scale of each protocol; the handsprayer being applied over 90 seconds, and the simulator often an hour or more. In the case of Logumukum if spraying had been maintained for, say, an hour, then the mulch effect would become insignificant when integrated over the entire volume infiltrated. In a case such as Eldume, however, with a nonabsorptive crust, the relationship between infiltration at this site when crusted and when the crust is removed is much as measured by both techniques is closer.

For the crusted control sites at which both simulations (medium intensity) and handspraying was carried out, there appears to be a common trend but no statistically significant relationship between these modes of assessing relative infiltration and hence runoff potential. Note that the sites Ongata Mara and Logumukum have 'above average' values in terms of handspraying infiltration (i.e. on the upper side of the line of best fit). When the crust is removed, however, the correlation improves greatly; to a modest $r^2 = 0.65$, albeit with fewer data points. Logumukum drops below the line of best fit revealing the sensitivity of this instrument to absorptive surface materials; with the surface mulch in place, the handsprayer indicates misleadingly high infiltration / low runoff potential. This implies that a caveat needs to specified for the use of the handsprayer on such surfaces where the initial infiltration rate is high due to a high absorptive capacity of the surface (a gravel layer or a clay-rich soil or clay enriched surface), but where the infiltration rate rapidly declines once this demand has been satisfied. A similar phenomenon was observed in the field with handspraying but also with rainfall simulation and the
Figure 8.7 Crust and crust removed values for 3.5 m simulator and handsprayer on a site-by-site basis

All sites, crusted and crust removed, 3.5 m simulator, medium intensity storms (18 - 31 mm/hr) and hand sprayer

- □ Hand sprayer, crusted
- □ Hand sprayer, crust removed
- △ 3.5 m Simulator, crusted
- ○ 3.5 m Simulator, crust removed
overland flow plots on highly cracking clay surfaces. No ponding or flow would occur before the cracks sealed, which required a considerable ‘cost’ in terms of raindepth to gain any runoff yield for a potential water harvesting system. The maximum infiltration values for the crust removed trials are somewhat higher for handsprayer and considerably higher in the case of the simulations than the crusted controls. The proportionally greater difference in infiltration in the case of the simulator is presumably due to an altering of crust conditions which does not occur with the energy-free handsprayer; as such it can be seen that a control / crust removed protocol using the handsprayer would somewhat underestimate the importance of crusting as a control on runoff.

Two measures of runoff potential were used with the handsprayer; steady state infiltration and total volume infiltrated. The comparison with the steady state infiltration values of the same sites using the 3.5 m simulator shows a reasonable similarity in the ranking of runoff potential apart from sites with a coarse surface layer or clay rich soils or with clay enriched surfaces. There are several sites (Lameluk 27/3 and Marigat) where substantial differences in runoff ranking position would result from the use of either the final infiltration rate or total volume infiltrated with the handsprayer. As the parameter ‘total volume infiltrated’ results in less variability between the three Lameluk replicates, something confirmed by the simulator results there, this parameter will be considered more reliable, and would on the basis of first principles be favoured in any case as it is a measure averaged over the entire curve. On the other hand, in the case of Marigat, a clay rich soil, the volume measure is more misleading than the steady state infiltration rate, as the high absorptive capacity of the clay is reflected in the first part of the infiltration curve, the value of which contributes toward the total volume infiltrated, whereas by the end of the handspraying the surface is becoming saturated, resulting in a relatively much lower value than that of the total volume infiltrated.

(8.6)

Revealing infiltration trends over larger areas of the landscape with the handsprayer

The above comparisons reveal that the handsprayer can be quite a useful tool for ranking relative runoff potential if a number of caveats are kept in mind with respect to surfaces with high absorptive capacity, due for example to a high clay content or a ‘mulch’ / two layer system. However, one might ask whether this instrument is of use on a coarser scale, revealing broad
patterns of infiltration trends as it is potentially useful in such a capacity due to its portability and rapidity. Assuming on the basis of first principles that there is a decrease in infiltration potential from the Tugen Hills down to the Lake as the torrents spread out and sediment clog-blocking fines, a transect of several kilometers using the handsprayer was tested to confirm this supposition, as an informal mode of verifying its utility in such a capacity. Other data were also collected in conjunction with Lisa Rebello along this same transect, such as evidence of water movement / type of erosion, tree cover etc. This transect will be described in more detail in Chapter 9.

**Figure 8.8** presents a sample result of the trends which can be revealed along this catena using the handsprayer, due to the high number of replicates which can be carried out (every five minutes). This result indicates that the runoff potential increases towards the Lake, at least along this particular catena. This is probably explained by sheet flow replacing channel flow with distance from the source area. Furthermore, the reduced variability between replicates as one approaches the Lake would be expected due to the ‘masking’ effect of any soil variability by the development of a relatively uniform surface seal laid down in sheetwash. This implies that the sampling density required to capture a given degree of variability in runoff potential should decrease towards the Lake.

Relative infiltration, which is determined every 100 m along a 28 site transect down a very shallow slope in the centre of the Njemps Flats, can be seen to decline by about 40% over the course of the transect. The value at each site (apart from #’s 10 and 20) is the mean of three replicates spread several meters apart. The standard deviation around the mean (here as a percentage of the mean, to make comparison independent of the actual value of the mean) is also seen to decline, to halve from 30 to 15% between the start and end of the transect. The two circles (points 10 and 20) are sites at which 5 replicates were carried out around the entire 50x50 m site, and yet have only mildly above average percentage standard deviations, which inspires confidence that replication carried out over a smaller area is a representative of the variability over a larger area, up to the scale ‘visible’ to remote sensing platforms.

Therefore, in a survey for assessing runoff potential, such geostatistical findings from rapid assessment techniques such as the handsprayer are important in maximising the cost-effectiveness of fieldwork, and especially of rainfall simulation, which is time consuming. Different processes, however, are at work during rainfall simulation as opposed to the very low energy hand spraying,
Figure 8.8 Trends in relative infiltration along a catena from west to east towards Lake Baringo, hand sprayer

Relative infiltration is determined every 100 m along a 28 site transect down a very shallow slope in the centre of the Njemps Flats. The two circles (points 10 and 20) are sites at which 5 replicates were carried out around the entire 50x50 m site.
indicates that those simulations which have a low final infiltration rate have a high rate of decay, such that, for events of a given intensity, apart from the question of time or depth to runoff, those storms with a low final infiltration rate will have a high runoff potential, as they arrive at this value quickly in a relative sense. Thus the choice of final infiltration rate as a key parameter for characterising a surface for the second season seems to be vindicated, and as suggested in analysing the results from the first season, the addition of a parameter such as depth to runoff (or, for multiple intensity storms, maximum runoff coefficient) would be advantageous. Having studied many possible parameters and parameter combinations, ones describing both the infiltration behaviour and the runoff yield, it is concluded that it is not possible to adequately describe the surface — rainfall interactions for the purpose of water harvesting suitability with any single parameter. This revisits the issue of the complexity of the infiltration phenomenon on these soils, largely on account of the complex and still little understood processes of sealing and crusting, combined with the lack of data on rainfall characteristics, and the inherent variability in rainfall simulation.
and as such geostatistical data derived from handsprayers may not be valid in assisting the planning of rainfall simulation campaigns.

(8.7)

Results of interest with other ‘simple’ tests employed as possible indicators of runoff potential

As discussed earlier, one objective of this study was to assess the degree to which simple tests, interpreted together, could substitute for rainfall simulation in terms of ranking relative runoff potential. The tests the results of which are briefly reviewed here consist of three natural groupings:

- Crust porosity, an intact sample taken from the crust of the rainfall simulation plots after the simulation and allowed to dry 24 hours at 100° and taken to be a measure of residual microporosity of the crust.

- Crust sampled carefully to exclude the subcrust, but breaking up the crust in the process, which is then sieved and various tests applied on the basis of site, aggregate class, and water chemistry

- Ring infiltrometers of various sizes: of interest; whether larger rings gave what are judged to be more accurate values of either runon or runoff potential (here examining only runoff).

Ranking of runoff potential by microporosity, where microporosity is assumed to be inversely related to runoff potential, this measure does not conform with rankings by rainfall simulator, and spreads the Lameluk sites throughout the sample. This indicates that at one site there may be a range of microporosity after the same rainfall treatment (a medium intensity storm) but that the values of these surfaces are not standardised as a result in terms of porosity, ranging from a 20 to 33% change in weight for Lameluk upon drying. As such, in spite of standardising on intensity and duration (equi-finality), the particularities of the surface are very apparent and are not dictated by rainfall characteristics. This conforms with our model of a crust as a transient entity in an historical context.
Ranking was also attempted in terms of the proportion of dry sieved aggregate classes, in which runoff potential was hypothesised to be positively related to the fraction of larger aggregates (not soil aggregates, but crust aggregates, and as such a measure of ‘crust resilience’). Both ends of the rankings conform with the rainfall simulation rankings, but the middle does not, indicating that very stable or very unstable (with respect to physical disturbance; an energy, not wetting response) surfaces can potentially be classified in terms of runoff potential thus. This also indicates a relationship between mechanical strength and sealing, a relationship about which many contradictory findings are reported in the literature, mirroring the rankings here. Thus the classic penetrometer or shear vane is seen to be of some value.

Ranking was also carried out in terms of (clay) expansion over 12 hours in tap (simulator source) water and rainwater; neither corresponded to the rainfall simulation ranking, but Eldume stands out by this measure, as having the highest runoff potential. This indicates that the wetting response alone is not sufficient to characterise the surface: structure is extremely important, which is formed over the course of the rainy season, as per the conceptual model hypothesised, even if sealing by swelling is important within an event in terms of runoff yield. Therefore, if a simple test does not address the energy component of rainfall, then the test should be carried out in situ with the structure intact, as with the handsprayer. Large differences in clay expansion according to water chemistry are noted for Eldume, which was surprising, and Marigat. This indicates that at these two sites water chemistry will potentially strongly influence results, and this is likely the explanation for the much lower infiltration rate with the 3.5 m simulator at Eldume than with the 5 m spray-type simulator with a higher energy reproduction but using salt rich water from the Chemeron irrigation scheme. These two factors undoubtedly interact in complex ways, but the great value of a simple test such as this is to signal a potential water chemistry issue.

Across almost all the simple tests (essentially measures of wetting) Logumukum emerges as having the lowest infiltration / highest runoff potential, whilst in the rainfall simulation ranking it has a high potential by absolute value of the final infiltration rate. Logumukum can be seen to be a ‘hydrophobic’ soil, and thus allows one by way of the battery of simple tests to confidently conclude that the wetting effects are proportionately more important than the energy effects at Logumukum than at other sites. As such, a high volume simple test such as the backpack sprayer
would be more appropriate at this site than the handsprayer (unless the mulch is removed). This is an example of the application of the triangulation approach across multiple simple tests.

Finally, the ring infiltration tests will also be mentioned. Contrary to expectations, the small rings, having therefore a higher perimeter: surface area ratio, and hence proportional influence of boundary effects, showed lower infiltration values than the larger rings, which is attributed to the lesser disturbance of the crust as less force is required to insert them. More work needs to be done with these tests, but very small rings appear to be promising on crusting soils, and could be used either for runoff or runon (simulating, realistically, a standing head of water behind a bund). As with all simple tests, a constant experimentation is necessary. Given the dearth of literature on this subject and the systematic comparisons to a reference value, as well as the development of some novel equipment and measures, the use of simple tests in this study might be considered to be a contribution to knowledge.

(8.8)

Conclusions

Sites which have an initial wetting control on infiltration, such as Logumukum, will be less successfully characterised with the most successful simple test, the handsprayer, than those, like Eldume, which require a threshold instantaneous kinetic energy to reorganise the soil surface. In this case, the handsprayer, though assessing sealing according to wetting, obtains a closer response to that of rainfall simulation than with surfaces where the control changes from a wetting to an energy controlled response.

For crust removed treatments, the relationship between the total volume infiltrated with the handsprayer and the final infiltration rate with the 3.5 m rainfall simulator is $r^2 = 0.65$. With the surface intact, there is no statistical relationship, due to and confirming the hypothesis above of a change in control in a two stage model which varies between sites. With the surface removed there are ‘constant’ conditions, a response solely of wetting, in the case of the handsprayer, which is what it is measuring. If Logumukum and Ongata Mara are removed from the crusted treatments, the $r^2 = 0.67$ but at a lower degree of freedom ($n = 6$). This indicates that, hydrologically, Logumukum and Ongata Mara stand out from the other sites, which is another useful application of the handsprayer. The 2 layer system at Logumukum has been explained,
causing a switch from a wetting to energy controlled response at some point near the saturation of the gravel layer and immediate surface beneath, not overlooking the energy effect at operation from the beginning involving an hypothesised mechanical transfer through the mulch. At Ongata Mara the situation is less obvious, except that the RAE project manager complains about water logging here (but not at the other fields), likely indicating a high clay content. A high density of micro-cracking was observed in this the fragile crust, very different from the 4 or 5 mm deep readily detachable plates of sedimentary crusts more common on the Flats. This is no doubt due to its topographic position, unique in being on a distinct slope. It would appear that this is a 'Runoff' crust according to the Valentin system.

A parameter of 'total volume infiltrated' groups the values of the three Lameluk sites more closely (apparent runoff potential) with the handsprayer than 'final infiltration rate' [using an ascribed wetting area]. Final infiltration rate, however, gives a closer fit to rainfall simulation rankings for initially swelling and later energy dominated responses at clay rich sites such as Marigat, as the effect of the swelling is discounted when only the last point is taken. This revisits the issue of measure dependence which has been a consistent theme throughout this study.

Based on other findings from this research, it has been concluded that soils which are clay rich or which have clay enriched crusts (for example, sedimentary crusts with many fine layers) result in the greatest discrepancy between handsprayer and rainfall simulation results. These discrepancies, however, are not in fact believed to be due primarily to differences in energy between the two modes of water application, but rather due to absolute amount of water which can be absorbed by clays before the storage-excess component of the runoff controls is satiated. In the case of the handsprayer the relative runoff potential is underestimated, as the infiltration rate and infiltrated volume is still great by the end of the two minute test, when in fact it rapidly falls off after a threshold volume of rainfall, as indicated by rainfall simulation on the same soils. The reverse is true in soils with a gravel cover over a less permeable layer. Therefore a combination of factors must be considered when interpreting the results of the handsprayer for rapid assessment purposes. It does, however, remain valid as an approximation of trends in runoff potential when such caveats are borne in mind, both in terms of the logic of the hydrology of the study area and when compared with the results of the rainfall simulations.

A very good correlation was found for the 3.5 m simulator between the final infiltration rate and Horton's alpha for all medium intensity storms, once the latter was corrected for roll waves. This
indicates that those simulations which have a low final infiltration rate have a high rate of decay, such that, for events of a given intensity, apart from the question of time or depth to runoff, those storms with a low final infiltration rate will have a high runoff potential, as they arrive at this value quickly in a relative sense. Thus the choice of final infiltration rate as a key parameter for characterising a surface for the second season seems to be vindicated, and as suggested in analysing the results from the first season, the addition of a parameter such as depth to runoff (or, for multiple intensity storms, maximum runoff coefficient) would be advantageous. Having studied many possible parameters and parameter combinations, ones describing both the infiltration behaviour and the runoff yield, it is concluded that it is not possible to adequately describe the surface–rainfall interactions for the purpose of water harvesting suitability with any single parameter. This revisits the issue of the complexity of the infiltration phenomenon on these soils, largely on account of the complex and still little understood processes of sealing and crusting, combined with the lack of data on rainfall characteristics, and the inherent variability in rainfall simulation.
Chapter 9

Results and Discussion (Part three)
Linking spectral and hydrological measures in a GIS environment to map runoff potential

- Results of classifications using Orstom indices
- Assessment of hydrological and spectral variability within a ‘pixel’, using handspraying and field spectroradiometry
- Comparison of calculated runoff potential with an independent assessment
- A GIS based ‘modelling’ approach for assessing suitability for water harvesting, illustrated by the case study area
- Relevance of the methodology employed to link hydrological ‘point’ measurements to remotely sensed area data, for the assessment of runoff potential and water harvesting suitability in Baringo
- Possible ways forward in upscaling hydrological point measurements.

Chapter Overview

(9.1)
Overview of chapter

(9.2)
Investigation of image characteristics and application of Orstom indices, Baringo imagery
(9.3) Application of Orstom indices to Baringo imagery

(9.4) Subpixel investigation of hydrological and spectral variability at the rainfall simulation site at the resolution of the ESE's

(9.5) A physiognomic approach to landscape mapping of runoff potential; assigning rainfall simulation values to 200 x 200 m mixels

(9.6) Comparison with an independent assessment of runoff potential on the basis of relative runoff potential

(9.7) A GIS based spatial 'model' of water harvesting suitability

(9.8) Conclusions and possible ways forward
Overview of chapter

This chapter starts out with an examination of the characteristics of the 'reference' image, with a view to anticipating the degree of spectral variability across the study area and particularly the degree to which the bands are separated, as an indication of the ease with which the variety of surfaces can be separated. The image of the study area is then presented using the indices developed by Orstom for southern Tunisia and for the Sahel, which were found to separate areas of hydrologically distinct behaviour. The degree to which the indices appear to be worthwhile in the case of the study area is investigated.

The next part of this chapter reports the results of investigations into hypothesised relationships between spectral and hydrological variability around and between rainfall simulation sites, using the same resolution instruments and at the scale of the 'natural' variability of the crusting surfaces, the 'ESE', to use a concept developed by the French for the Sahel. This is followed by a discussion of a physiognomic approach to landscape mapping, in other words, using the same concept as the fine scale investigations, based on the ESE's, but this time at a scale 'visible' with remote sensing, which corresponds to the Etats de Surface in the French system of crust classification. The ES is an association of ESE's, and corresponds to a 'mixel' in spectral terms, as the hydrological characteristics of the surface covered by an effective pixel varies at a subpixel level.

This chapter subsequently addresses the issue of how to assign 'point' (equivalent to ESE's) measures of runoff potential to a spectral map of the study area (a satellite image) covering the entire surface, in units much larger than the size of the rainfall simulation plots. The results of the map of runoff potential of the study area created by linking the rainfall simulation values to the imagery, according to a procedure developed for this study but based on one of the approaches taken by the French in the Sahel, is compared to secondary data on runoff potential in order to validate the method employed. A visual comparison is made between the two and then other datasets from that same study (a range management study in a GIS format) are utilised to illustrate how a suitability assessment procedure in a GIS based analytical environment incorporating various datasets would work. Finally, the resulting classification in terms of suitability for water harvesting is compared for validation to the locations chosen by various
water harvesting projects for their fields and some interesting conclusions arrived at implicating the importance of social factors in an assessment methodology.

(9.2)
Investigation of image characteristics and application of Orstom indices to Baringo imagery

A detail of the Flats is presented in Figure 9.1. On this image a classic drainage system south of Lameluk is displayed, together with locations of the rainfall simulator transect (boxes in white). Arrows indicate direction of flow into the drainage system from the runoff generating smooth, high albedo, low vegetation intergully crusted plains (purplish end of the spectrum) to the drainage canal (blue/green end, marking dense vegetation along the gully edge).

A further enlargement of the same area as in the black box on the left is presented on the right. The central drain is indicated by the longest line, and progressively shorter lines indicate zones. These correspond to Etats de Surface, or, at a finer scale of investigation, the same geometry repeating itself in a fractal gravity-driven landscape system of self-similarity scaling from Etats de Surface to Etats de Surface Elementaire. These ‘radiate’ out from the drain in a highly predictable fashion, arrows here moving from the lowest (base cut) level in the drainage system to the highest. This same pattern, which is so predictable in the field, is also apparent on the imagery. This is strong evidence for a similar demarcation of the landscape on spectral and hydrological terms, and thus the potential relevance of remote sensing to runoff assessment in these environments. There should ideally be a ‘gradient’ of runoff potential corresponding to this zone sequence, either highest at the centre (drain) to least at the catchment divide or vice versa.

Note that all the rainfall simulation sites represent mixels; there are no ‘pure’ spectral units, at this geometric resolution (30 x 30 m pixels and allowing for +/- 3 pixel error to account for a georeferencing error of +/- 85 m established with the single GPS plus rubbersheeting warping errors when pasting the image to the ground control points). This implies that it is important to investigate the spectral variability in the immediate vicinity of each ‘point’ measure of runoff potential carried out with the rainfall simulator and to assess the variability in runoff potential within each areal unit to which these point measures are generalised in order to relate them to the
Figure 9.1
Drainage system detail of the central Flats in an unsupervised clustering on bands 2/3/4
remote sensing imagery. This task is too time consuming using the rainfall simulator itself and therefore, having established reasonable confidence in the handsprayer, was done by comparing the variability in water acceptance around a rainfall simulator site with variability in spectral characteristics of that same area using a field spectroradiometer, such that the two measures are carried out at the same scale (approximately 30 x 30 cm units). As such one can determine the variability in both spectral and hydrological terms within a single pixel (30 x 30 m), a unit which is otherwise normally considered to have a single value for each. The results of these investigations will be reported later in this chapter.

(9.3)

Application of Orstom indices to Baringo imagery

Turning now to the results of applying the Orstom indices to lowland Baringo, Figure 9.2 presents the indices found to be useful for discriminating between runoff surfaces by the Orstom Sahel programme, whilst Figure 9.3 represents the equivalent for Orstom Tunisia. The ‘Sahel’ indices Vegetation and Brightness are very promising, judging from a knowledge of the study area, but the Soil Colour index less so, perhaps because of the reduced variability of this parameter in the field. It is possible that crusting has masked soil colour variability of the great range of soils (Gerits 1994) present in the study area. Red and infrared have similar response from bare soil, and hence it can be seen from the inclusion of red + infrared in all three indices that the ‘Sahel’ system is largely based on separating bare soil from vegetation; Puech (1994) noted vegetation dominated spectral responses with surprisingly little vegetation cover. With the Brightness Index the lightest areas (apart from a possibly salt rich fringe around the Lake) is Eldume, which has one of the highest measured runoff values and the most eroded surfaces. This indicates the possibilities for using various combinations of bands’ for overall albedo for runoff assessment purposes (in areas of reduced vegetation cover); here the square root of red squared and infrared squared. The combination of a vegetation index and brightness index should be a powerful classification tool, as vegetation in the study area is a marker of linear features (gulleys), which represents ‘borders’ of predictable associations of land facets in the intergulley areas; at the resolution of TM imagery, however, these detailed patterns can cannot be mapped except at a broad scale. Ideally a multiscale solution would allow promising areas to be mapped in greater detail.
Figure 9.2 Indices in the Orstom Sahel classification routine of crusted surfaces for runoff assessment
(from left)

a) Vegetation index. Accurately identifies areas of dense tree cover (Tugen and other peri-Lake hills, light grey) and swamp areas and larger irrigation scheme (whitish grey). Represents the spatial distribution of the bimodal histogram of DN values of this index for this scene (see 'Histograms of indices').
b) Soil colour index. Much of the Flats are 7.5 or 10 YR, but the apparent uniformity in the image is greater than that observed in the field; this is due to the peaked and high histogram (DN 120-155).
c) Brightness index. Overall albedo, but specifically designed as a measure of (bare or low vegetation cover) soil reflectance and hence possibly correlated to the degree of crusting and thus runoff class.
Figure 9.3
Indices in the Orstom Tunisia classification routine of crusted surfaces for runoff assessment

(left) Brightness Index.
(right) ‘Redness’ Index.
The ‘Tunisia’ system the Brightness index is very promising, at least as a product optimised for visual interpretation; apparently because the effect of the maxima – minima routine, which ‘exaggerates’ contrast, together with the difference in absorption of vegetation in the red and green bands. The Redness index actually contains more contrast than apparent from this image, but the values are skewed toward the low end of the histogram. The Brightness index generates a high contrast image for the purposes of visual interpretation, which is the result of the particular formula used, effectively a contrast maximising procedure of opposing the maximum and minimum values of each pixel location across bands (red and green). The implications for accuracy of classification, however, in an unsupervised routine together with the accompanying ‘redness’ index remains to be seen. The fact that vegetation marks the gullies aids in demarcating the land systems on the Flats; the contrast between the rough, gullied and vegetated facets (poor reflection characteristics) and intergully, much less vegetated, eroded crusted flat surfaces (ideal reflection characteristics) potentially allows for excellent discrimination between these two land systems, at a scale commensurate with the resolution of the imagery.

In the case of the Orstom Tunisia ‘Redness’ index. The difference between values in the red and green bands are used in this index, which is therefore effectively a vegetation index, given that active vegetation reflects more strongly in the green than the red band. The combination of two indices which tend to emphasise vegetation, in particular given the reflectance characteristics (roughness and absorption) of the land systems in the study area, make the Orstom Tunisia routine promising for lowland Baringo, in spite of having been developed for a near vegetationless stony arid environment in southern Tunisia (which explains the lack of an explicit vegetation index).

Attention should be drawn to the fact that the ‘Tunisia’ Redness index is very similar to the ‘Sahel’ Soil Colour index, with the result that the difference between the two systems, at least as applied to the study area, boils down to the lack of an explicit vegetation index in the ‘Tunisia’ system (which was developed for an arid zone). The similarity between the ‘redness’ in the Orstom Tunisia system and Soil Colour index in the Orstom Sahel system are striking, but less surprising when the formulae are examined, as both employ bands 2 and 3, albeit in different formulations. The Vegetation index in the Orstom Sahel system consists of the infrared band divided by the bare soil line composed of red plus infrared. This index has a bimodal distribution.
for the study area, potentially indicating the ability presence of two distinct classes of vegetation cover, either different percentage cover and/or different species and/or canopy structures. Given the similarity between Soil Colour and Redness, the principal differences between the two systems lies with differences between their ‘Brightness’ indices and the use of a vegetation index in one but not the other.

There is a substantial difference between the results with their relative formulations of a Brightness index. On first appearances, the images of Baringo created from the brightness indices used by Orstom ‘Sahel’, developed for sandy semi-arid soils in Burkina Faso but applied elsewhere in the Sahel, and that of Orstom Tunisia, developed for rocky arid surfaces in southern Tunisia, are merely inverse. This is surprising, given that the former employs bands 3 and 4 whilst the latter bands 2 and 3, and that they are formulated in very different fashions. But inspection of their histograms reveal that, even if reversed, the shapes are considerably different. Both are bimodal (excluding the corner background pixels), indicating, at a most basic level, an accurate division of the image into ‘bright’ (eroded loam soils of the alluvial / colluvial fans) and ‘dark’ (rocky volcanic hills). The implications of these differences need to be examined in terms of classification accuracy. The brightness indices are important, given the findings of many of the spectral studies of crusting soils, which was the importance of albedo as the key differentiating characteristic between crusts (but not necessarily between crusts and other surface types, such as vegetation). The importance of albedo as a basis on which to distinguish between crusts formed from physical degradation (as opposed to chemical degradation or biological activity) is principally due to the parallel nature of their response curves across the spectra measured.

The classifications of lowland Baringo using each system are presented as Figures 9.4 and 9.5. Figure 9.4 is a classification employing the indices ‘brightness’ ‘soil colour’ and ‘vegetation’ developed for use in the Sahel. These indices were specifically developed on sandy, crusted soils in Burkina Faso with low vegetation cover, and as such have some similarities but also significant differences to the study site (loam soils and rocky hills, higher vegetation cover). Nonetheless this combination of indices using an unsupervised clustering procedure produces 9 classes which provide an accurate broad outline of the distribution of physiognomic classes, but is disappointing in the dearth of subclasses within the Flats. The classification is less nuanced than using the original TM bands, and as such these indices cannot be considered ‘exportable’ to other semi-arid areas without adjustment. Figure 9.5 is an unsupervised classification using band 1 and
Figure 9.4 Classification of lowland Baringo using Orstom Sahel synthetic channels
Figure 9.5 Classification of lowland Baringo using Tunisia Orstom synthetic channels
Escadafal's 'redness' and 'brightness' indices developed for arid Tunisia. The basic demarcation is accurate, grouping the Flats southwest of the Lake with the Loruk area northwest and the pocket of loam soil on the east littoral. It also successfully draws attention to pockets of arable soil (clusters 3 and 4) within the general background of volcanic step faulted hills (cluster 1). However, at a finer scale, the Flats are not subdivided in as nuanced a manner as some of the unsupervised classifications using the original TM bands. Given the differences, however, between the area for which the indices were developed and the Baringo area, they nevertheless prove themselves to be versatile, and as such can be broadly recommended as an aid in demarcating runoff classes in both arid rocky areas with chemistry dominated crusting and semi-arid areas with crusting originating in physical degradation.

It is surprising that the Orstom Tunisia indices provide a better depiction of the physiognomic units found in the study area, surprising because the environment for which it was developed is more dissimilar to the study area than the Sahel and because of the reduced number of indices. The 'Sahel' indices discriminate between more spectral clusters (9 as opposed to 7), but the differentiation between crusted surfaces in the Njemps Flats, the main study zone, is better with the 'Tunisia' indices. It is hypothesised that this is due to the contrast maximising routine employed with the Brightness index in the latter, which implies in turn that crusting is strongly related to albedo and that albedo, to confirm the findings of the literature review, is therefore a key to discriminating between (physico-chemical) crusts. The results of investigations at a finer spatial (but equivalent spectral) resolution using field spectroradiometry on the constituent ESE's within the physiognomic classes delineated in these images will be presented later in this chapter in order to confirm or deny this explanation.

If, in fact, albedo is the key, and if albedo, furthermore, as hypothesised, is related to runoff potential (a smoother surface, so less surface detention and probably at the end of an outwash system, in which case a net accumulation of the pore clogging fines from upslope), then panchromatic imagery could prove just as useful as satellite imagery, in which case temporal changes in crusting and runoff potential could be ascertained, if the illumination etc. conditions of the images could be calibrated to each other, with a time series of historic imagery. This is not attempted here, but simply presented as a possibility. In the case of the study area, the aerial photography had very different ranges in greyscale, even within each data set, which made comparison difficult. For example, taking the 1967 imagery as an example, one half of the study area was photographed on January 10, and the other half on the 13th. The second lot is 'muddy'
(degradation in greyscale), which appears to be the result of having left the chemistry over some days without replenishing the developer before printing the images from the later flight.

The results of applying a seven class clustering algorithm of the Orstom Tunisia brightness and redness indices using the TM89 ‘reference’ image (used in all the classification because of the higher spectral resolution than Spot) are presented as Figure 9.6. A reduced number of classes vis-à-vis the clustering on the original bands (24 classes) helps to generalise the image for simplifying the assessment procedure. Comparing all sites, the majority of sites consist of two ES’s; a light blue cluster #2, which corresponds to the highest albedo most crusted areas furthest from the drains, and a red cluster #4. The latter cluster represents the majority of the Flats, which is an area of lightly rilled and incipient gully plains between the areas generating overland sheetflow and the channel flow of the drains; a kind of hydrological and geomorphological ‘transition’ zone but the dominant land facet. The demarcation between clusters 2 and 4 in the field is often the beginning of erosive flow. It is because of the reduced erosion of the crust in cluster 2 that a runoff gradient from this class (highest) to the drains (lowest) is hypothesised, in accordance with the theory and observation of the importance of crusting as a control in this environment.

Turning now to the location of composition of rainfall simulation sites in terms of these clusters, Ongata Mara is a distinctive cluster from the others, #5, which is typical of areas of dense vegetation, while Logumukum is predominately this class but with patches of cluster #2. Marigat is similar to the sites on the central Flats, a mixture of clusters #2 and 4, whilst Eldume also has a subdominant presence of cluster 3, which seems to be associated with vegetation, as this is the principal cluster in the Pekerra Irrigation Scheme. In short, one would expect from this classification that the properties of the Flats and Marigat sites to be within the same range, whilst Ongata Mara, Logumukum and Eldume would all have different values from these and from each other. In fact, the Flats (Lameluk and site 9.6) and Marigat are at either ends of the runoff spectrum (lowest and highest, respectively), with Eldume and Ongata Mara having similar values to Marigat.

This finding begs the question of whether and how to use the use of the relationship between the spectral clusters and the hydrological values at each site to map runoff potential over the image, which will be addressed later in this chapter. First, however, the attempt to create a supervised classification of crusted areas and runoff potential in the image using a much larger ground
Figure 9.6
Principal sites in north (right) and south (left) Flats, classified by unsupervised classification using the Orstom Tunisia indices
verification dataset than is possible with the time consuming rainfall simulations will be reported. This will be followed by an assessment of the variability in hydrological and spectral properties around each rainfall simulator sites, using the handsprayer and Milton Multiband Radiometer, respectively. Finally one approach to the problem of ‘mixels’ and the scale discrepancy between hydrological and spectral measures, proposed by Lamachere and Guillet (1996), reviewed in Chapter 5, is taken for the study area. In that additive approach, the runoff value is determined for each surface unit in the study area, and the proportion of runoff applied to each portion of a mixel relative to the contributing area of each runoff unit.

In the case of the present study, due to georeferencing uncertainties, it is not possible to state which spectral clusters (using the Orstom Tunisia indices) is unequivocally associated with which rainfall simulation site. Therefore a broader area around the site is chosen, which normally ends up incorporating more than one spectral cluster. As such, the problem becomes the reverse of Lamachere and Guillet (1996); the task here is to assign a runoff value (in relative terms) to each spectral cluster on the basis of its ‘constituent’ rainfall simulation sites, across all rainfall simulation sites. For example, if spectral cluster # 2 is found principally at the Logumukum site, and to a minor extent at the Lameluk and Marigat sites, the relative runoff value assigned to that cluster will be the runoff ranking of each of these three sites, multiplied by the proportion of each site consisting of that cluster. As this is an indirect approach, and reliant on a small number of ground verification sites, and for the same reason difficult to verify the results of, it also desirable to explore whether the evidence of actual runoff can be mapped across the study area. As a comprehensive dataset was kindly made available (Bowyer-Bower and Scoging 1992) of, among other things, crust type and erosion type on a 1 km grid sampling basis, the possibility of using this dataset to train the image classification routine to map crust type and evidence of water movement was attempted.

(9.4)

Subpixel investigation of hydrological and spectral variability at the rainfall simulation site at the resolution of the ESE’s

As rainfall simulation is so time consuming, it is not possible to characterise any surfaces other than the dominant ESE at each site. As, however, any ‘upscaled’ value of the site will essentially be a point at the resolution of one image pixel, and as this single value (hydrological and spectral)
actually consists of the contributions of the constituent ESE’s, if the variability around two
dominant ESE’s at two sites being compared results in a substantial overlap in error bars, then it
will not be sound to attempt to upscale thus. As a result, this variability was investigated.

Another major motivation was, as outlined earlier, to attempt to substitute rapid, cheap and
replicated measures for rainfall simulation, and thus the ranking of surfaces was compared using
both measures, the results of which were presented in Chapter 9. As such, it was also of interest
to determine whether handspraying with a control and crust removed treatment, exactly like the
rainfall simulation protocol, would highlight processes such as surface control of runoff. At the
same sites similar resolution (approx. 20 - 25 cm radius) spectral characterisation of the ESE’s
was undertaken to determine if, at the resolution of the finest scale (according to the Valentin
system) ‘natural’ or effectively homogeneous hydrological unit, spectral characteristics were also
distinguishable the one from another. If not, then, as the hydrological resolution of investigation
should ideally match the minimum spectrally distinguishable resolution, some form of
amalgamation and ‘upsampling’ of hydrological (essentially ‘point’) measures to the minimum
resolution at which of the spectral characteristics can be distinguished is necessary. If, one the
other hand, both hydrological and spectral measures vary at the same scale, that of ‘natural’
hydrological units in a crust controlled environment, then they should ideally be mapped at that
scale. Of course, for practical purposes this presents a problem, as the resolution of the spectral
data available is much coarser than the resolution at which the hydrological measures are taken,
be they rainfall simulations or handsprayer plots. Possible ways of overcoming this leap in scale /
resolution will be commented upon in the concluding section of this chapter.

(9.4.1)
Comparisons between hydrological and spectral variability of constituent ESE’s of
the rainfall simulation sites

A number of conclusions can be arrived at regarding the comparison between hydrological and
spectral measures around the rainfall simulation sites. At Ongata Mara the spectral
characteristics of the ESE’s do not offer much hope of being able to distinguish them on the basis
of remote sensing, even using a linear unmixing algorithm on pure endmembers. The interrill
divide, the peak of the divide between incipient gullies, stands out from all other ESE’s in bands
3 and 4, which may partly explain why the definition of linear features is so good on the imagery
for this area but detail with the features non-existent. In terms of hydrological characterisation,
the ESE on which rainfall simulation was carried out is about midway between the infiltration values of the other ESE’s and as such is broadly representative of the average runoff potential of this site. The lowest runoff potential according to this measure is the rill, which is logical, and highest the stony rill side (likely an erosion crust). In a site with strong topographic control such as this, however, the handsprayer or indeed the rainfall simulator can only give a measure of runoff generation and is not very informative about behaviour as part of a drainage system, apart from giving an indication of the conveyance losses to be expected as water passes over each ESE.

In spite of the fact that there is no clear separation on spectral grounds between the ESE’s, apart from the strongly angled divide between incipient gullies, distinct hydrological behaviour was observed between each ESE, with the highest infiltration in the rills and the lowest on the stony rill sides, from which the surface material has been eroded down into the rills. As such, the relative infiltration values correspond to a hydrological logic and to the topography controlled approach taken by Valentin to crusting surfaces, even though Valentin did not assess hydrological characteristics at a sub m2 (= size of runoff plot) resolution. Therefore this investigation builds on that work by identifying relative sources and sinks at a finer scale and, together with the applications, represents, it is argued, a contribution to knowledge.

In short, at this site and at this fine scale of investigation, one could not expect to be able to distinguish between hydrologically distinct surfaces on spectral terms. This does not necessarily exclude, however, the possibility that at a particular resolution(s) that one can distinguish between hydrologically distinctive units using their respective spectral properties. Indeed, it is hypothesised that this would be a promising area for future work, given the manifest self-similarity of scaling in terms of hydrology in the Baringo lowlands, and the fact that this hydrological logic is readily apparent from unsupervised satellite imagery.

At Eldume, as can be seen from Figure 9.7, the dominant (interrill eroded ‘b’ horizon on which rainfall simulations took place) ESE can be distinguished in spectral terms, on the basis of albedo, across all four bands, from the other ESE’s making up this Etats de Surface. Note that the reflectance values across all bands drops when a faint rill wash pattern is present on the surface, and then continues to drop as the percentage sandwash on the surface increases. The latter ESE are indistinguishable on a spectral basis from the rill areas (which are likely of a similar coarse material composition).
The arrows indicate changes in infiltration between ‘crusted’ and ‘crust’ removed treatments; note that ‘crust’ removed may actually mean brushing off surface sandwash for those ESE’s.}

Figure 9.7
Spectral and hydrological characteristics of ESE’s at Eldume

Reflectance of ESE’s at Eldume, using MMR

Cumulative infiltration of ESE’s and surface remove treatments, hand sprayer, Eldume
The infiltration tests with the handsprayer indicate that the erosion crust on which the rainfall simulations were carried out is indeed the area of highest runoff potential, and crust removal reveals the effect of this dense surface on infiltration. A very large proportional difference in infiltration is recorded by the rainfall simulation between crust and crust removed, but the runoff coefficient is close by the end of the simulation, unlike the handsprayer results, revealing a limitation in determining hydrological behaviour from handsprayer results. When the sandwash on this surface is brushed away, the value of infiltration drops to that of the erosion crust, as suspected; if this ‘crust’ removed treatment were not attempted on the sandwash surfaces the effect of this ‘mulch’ would give misleading results with the handsprayer. In any case, the handsprayer confirms the hypothesis that the particular ESE selected for rainfall simulation would have the lowest highest runoff potential at this site, and confirms that the various ESE’s here have distinct infiltration curves (parallel, with little, if any overlap). In fact, assessment of the error bars through the replicates of the dominant ESE and the crust removed replicates indicate unequivocal separation between control and treatment.

In short, the limitations of the use of the handsprayer, as with Logumukum, at least if used uncritically, is revealed by the ESE with 90% sandwash over the erosion crust. From the handsprayer results this ESE is apparently a high infiltration surface, but once this ‘mulch’ is brushed away in the ‘crust removed’ treatment, as at Logumukum, the values drops dramatically. Conversely, when the erosion crust is removed, as with the rainfall simulation, there is a great increase in infiltration, confirming a surface (and specifically crust) control, but the infiltration curves of the crusted and crust removed treatments on that ESE do not, unlike with the rainfall simulator, converge over time. This may be due to an insufficient wetting volume but almost certainly due to the lack of energy to seal the soil. As such, this confirms the conceptual model of a Stage 1 energy control in the case of an ‘antecedent crusting = zero’ initial surface state scenario.

In terms of the potential for discriminating between hydrologically distinct surfaces on a spectral basis at Eldume, it is clearly promising if the spectral resolution of the data available were commensurate with the scale at which the ESE’s vary, which is approximately 900 cm². If, on the other hand, only coarser resolution spectral data are available, then there will clearly be considerable variability in runoff potential within one pixel, as demonstrated from the handsprayer investigations of the constituent ESE’s at this site. If the net runoff potential from this Etats de Surface, however, is sufficiently different from that of another Etats de Surface, then
the internal variability within each will not pose any operational barriers in a suitability
assessment procedure for water harvesting.

At Site 9.6 the non crust surfaces of a cattle track and grassy area can be distinguished from the
crusts but not from each other, on spectral criteria, as can be seen from Figure 9.8. The
differences between the crusted ESE’s, as observed in the field can be extremely subtle. In
hydrological terms the dominant ESE, the interrill area selected for rainfall simulation, is
confirmed to have the highest runoff potential and removing the crust confirms the crust control
evident form this same treatment under rainfall simulation. Runoff potential (from greatest to
least) is: interrill (the dominant surface on which rainfall simulation was carried out) and rill (very
close), then grass, then crust removed, then cattle path. This trajectory indicates the importance
of crusting at this site in reducing infiltration / promoting runoff. The effect of grass and cattle
trampling on overland flow (as opposed to runoff generation) are more complicated and cannot be
assessed with the handsprayer.

It is interesting to note at this site that using the MMR at 50 cm and 150 cm, increasing the field-
of-view by three times, had no impact on the spectral curves, indicating that a change in spectral
resolution has no effect, over this reasonable range, due to the subtle differences between the
ESE’s. This is a typical area of the central Flats where, in both spectral and hydrological terms,
for the dominant rill-interrill land system, the ESE’s should be upscaleable to ES’s and therefore
are assessable at various resolutions) with little difference in results. This is in marked contrast,
for example, to the case of Eldume, described above. In fact, it was found that the error bars of
the rill and interrill ESE’s replicates’ handsprayer values at Site 9.6 completely overlap: from a
hydrological point-of-view, and taking a functional definition of crusting surfaces, they can for
practical purposes be defined as the same ESE.

(9.4.2)
Comparisons between hydrological and spectral variability between representative
sites

A comparison can also be made between the three sites described above in terms of  a) the
variability between handsprayer replicates at the dominant ESE’s at each site and b) the
variability in reflectance between the ESE’s comprising each site. In these comparisons Site 9.6
is chosen to represent the central Flats, Eldume a distinctive highly eroded area and possible
Figure 9.8
Spectral and hydrological characteristics of ESE's at site 9.6
preview of the future of other sites if they are not managed properly, and Ongata Mara, a clay rich low angle alluvial fan, a common land unit in the study area. The ability to separate these three sites, which have been shown on the basis of rainfall simulation to have distinctive hydrological behaviour, can be seen from Figure 9.9 to be promising, according to handspraying across multiple replicates of the dominant ESE at each site. The range of variability between three replicates at each site shows a marginal amount of overlap between sites, and more so at the beginning of the spraying than at the end. The greater spread of values at the end of the handsprayer cumulative infiltration curve reflects true differences between replicates, as the initial infiltration volume is limited not so much by the infiltration capacity of the surface so much as by the speed at which the spraying can physically be maintained. By the end of the spraying the various moisture dependent swelling and sealing processes have been largely activated, and differences in the texture and chemistry of the top few mm of the surface at different spots likely accounts for the different curves. The range in total volume infiltrated between replicates at any one site increases proportionately to the average total volume infiltrated for all replicates at that site; the reason for this is not known.

In spectral terms, it is apparent from Figure 9.10 that Eldume can be separated from the other sites on the basis of albedo, but the error bars around the five replicates (various ESE’s) at that site excessively overlap those of the other sites to separate them. The range of reflectance values over the first four TM bands across five ESE’s at each of the three rainfall simulation sites shows a large range in spectral values but a similar trend for virtually all ESE’s; increasing reflectance towards the warmer end of the spectrum. In a general sense, therefore, these sites should be distinguishable from satellite imagery on the basis of albedo, but their classification in multispectral space would not likely greatly enhance the classification accuracy. If this is in fact the case, then there is little to be gained by automated classification over visual interpretation of the imagery, where the latter has the advantage of taking into account complex properties such as texture, pattern and shape which are not readily assessed in an automatic classification. The area which can be manually interpreted, however, is limited for practical reasons, and the consistency of the interpretation undermined by subjectivity where multiple interpreters are employed. The overlap between ESE’s at the three sites is such that Ongata Mara could, in principle, be unambiguously distinguished from the other two sites. There is some isolation of the Site 9.6 surfaces in bands 1 and 2.
Figure 9.9
Discrimination between rainfall simulation sites using handsprayer values

Intra and intervariability in handspray curves, rainfall simulation surfaces, Eldume, site 9.6 and Ongata Mara

Lines demarcate zones of scatter, similar to error bars, around the average total infiltrated volume, denoted by the large white circle, for each site.
Figure 9.10 Discrimination between rainfall simulation sites using MMR values

The range of reflectance values over the first four TM bands across five ESE’s at each of three rainfall simulation sites with distinctive runoff behaviour.
In short, the separation of ESE's on hydrological criteria, by either rainfall simulation or handspraying, is more promising than on spectral criteria, a fact also evident at the resolution of the Etats de Surface by the frustrating experiences attempting supervised classification. As such, field spectroradiometry can serve to alert one to the potential to and at what resolution one can hope to distinguish between surfaces. If one cannot distinguish, on spectral grounds, between ESE's, then there is no disadvantage to the 'coarse' resolution of satellite imagery, and the question becomes how to upscale only the hydrological values.

de Jong (1994) exposed five Mediterranean semi-arid soils to laboratory rainfall simulations to induce crusting and then a 63 channel spectroradiometer was used to assess the spectral separability. Only two of the soils could be separated by absorption phenomenon (iron and calcite) and even using a complex correspondence analysis on the 63 bandwidths only albedo was able to identify a progression in the degree of crusting, which correspond to findings from the present study and offer a possibility for monitoring of crust transitions from remote sensing. The crusting process induced by the simulations caused an increase in albedo of 12 – 15%; still fairly subtle. If a cycle of wetting and drying had been allowed, however, as with the work of Courault (1993), then the changes would likely have been greater. It is hypothesised that these changes are due to a reduction in surface roughness, decreasing scatter and causing the surface to act more and more like an idealised Lambertian surface. The surfaces assessed in Baringo with the field spectroradiometer were not carried out on the actual rainfall simulation spots; they were 'natural' crusted surfaces, having been subject to crust evolution processes over wetting and drying cycles and yet were still problematic to distinguish on spectral criteria.

As such, it may prove more practical to accept the spectral resolution of the principal data source (the satellite imagery), plus an allowance for georeferencing errors, as an 'effective pixel' and work with this minimum resolution in an attempt to distinguish on a spectral basis between sites known to have distinctive hydrological behaviour. In other words, instead of carrying out investigations at a subpixel level, to work at a higher level of aggregation, as the unsupervised classifications reported above displayed a spectral classification of the landscape which corresponded with the drainage systems. In essence, by operating at this scale, one is really mapping spectral differences between physiognomic units, naturally occurring soil-vegetation-topography associations, rather than attempting to isolate the crust from them. This may prove more successful, as it is reasonable to assume a relationship between crust type and/or extent and other variables in the environment. In other words, it may be more practical to take an indirect
A physiognomic approach to mapping crust crusting, so that variables in the environment which are more ‘visible’ in terms of remote sensing can be used to map those variables which are more subtle. This approach was taken with a reasonable degree of success by Puech (1994) in the Sahel, using the variables ‘soil type’, ‘vegetation cover’ and ‘cultivated / uncultivated’. A similar approach will be presented in the following section, but using a general physiognomic approach using an unsupervised classification on the Orstom Tunisia indices, described above, which was found to be meaningful in the study area on the basis of knowledge of the area.

(9.5)

A physiognomic approach to landscape mapping of runoff potential; assigning rainfall simulation values to 200 x 200 m mixels

Attempts described above to use 25 x 25 m units of secondary ‘ground verification’ data to train an image classification procedure did not prove to be very successful. Various possible explanations were proposed for this, including georeferencing errors and the low threshold of vegetation cover at which the signal becomes dominated by tree cover. That approach involved ‘starting from the ground’ and then attempting to relate the sample site data to the continuous spectral areal coverage of the study area in the form of a satellite image. Another approach would be to ‘start from space’ and work down to the ground. The advantage of this approach is that the ‘natural’ variability in spectral properties at the geometric and spectral resolution available are the starting point. This was done with the unsupervised classifications described at the beginning of this chapter, both directly using the bands and on indices of these bands found to be useful for demarcation of the landscape into hydrologic units in Tunisia and the Sahel. The problem of trying to relate these units to ground verification of runoff potential has been described above; namely the small number of sample sites which are possible with the time consuming rainfall simulations, which are nevertheless preferred as reference values because of their relatively good kinetic energy reproduction.

Similarly, the possibility of assigning the values of these rainfall simulation sites, which are generalised to 200 x 200 m units to account for potential georeferencing errors, to the spectral clusters in an unsupervised classification on the Orstom Tunisia indices has been introduced above. This will now be pursued here. The methodology employed will be briefly described and the results presented in the form of a classified image of runoff potential across the entire study area.
area. As such, this is a supervised classification, albeit on the basis of relatively few training sites, but as the unsupervised classifications showed a consistent correlation between the distribution of spectral clusters and the facets or zones around the main drainage channels in the landscape, it is believed that there is good potential to relate spectral and hydrological properties in this area at a relatively coarse resolution. Again, as hypothesised above, it is believed that this relationship is evident because there are certain typical, recurring associations in the landscape between soil, vegetation and topography, essentially catena at various slopes.

In short, the organisation of this landscape is driven by differences in potential energy, along the path of least resistance, a landscape shaped by the drainage system. Furthermore, this seems to be confirmed by the fact that this pattern is readily apparent at whatever resolution / scale of observation was attempted; be it at the finest scale in the subtle patterns of rill / interrill at Site 9.6 on the central Flats, using the handsprayer and spectroradiometer, at the scale of the 1.3 m resolution digital aerial photography (obtained too late to be employed), or at the scale of the satellite imagery. In short, the study area strongly appears to be a ‘fractal landscape’. The implications of this in terms of the potential to bridge changes in scale will be discussed in the concluding section of this chapter.

Following the approach of Lamachere and Guillet (1996), presented along with other options for linking hydrological and spectral measures discussed in Chapter 5, and as explained above, an attempt was made to map (relative) runoff potential over the entire study area on the basis of the rainfall simulation sites. No attempt was made to quantify runoff values because of a) the relatively small number of rainfall simulations vis-à-vis the area of the image b) the variability within the Etats de Surface at each rainfall simulation site, demonstrated with the handsprayer, and c) because of the potential Partial Area Contribution phenomenon which led to errors in a similar attempt in Mali (Ben-Asher and Humborg 1994, Tauer and Humborg 1992). Rather, a more modest attempt was made to rank spectral clusters in terms of their relative runoff potential, based on the proportions of each cluster corresponding to each generalised rainfall simulation site.

(9.5.1)
Assigning hydrological values to spectral clusters
In Table 9.1 the calculation of the relative runoff potential of each cluster, from by the classification of the Orstom Tunisia indices, is based on the premise that the value of each cluster is proportional to the percentage area of a given rainfall simulation site (200 x 200 m) occupied by that cluster, multiplied by the relative runoff ranking of that site. When this procedure is repeated for every rainfall simulation site for every cluster, the result is a map of relative runoff potential. The resolution of Landsat TM is not sufficiently fine and the georeferencing not sufficiently accurate and the dominant ESE on which rainfall simulation was carried out is not sufficiently homogenous over a sufficiently large area and the vegetation cover not sufficiently low to directly relate the imagery to the ESE for which the runoff value which is known. Hence this procedure is implicitly a multiscale linking of the ESE to pixels covering the area around it on the hypothesis of reasonable homogeneity in infiltration values, as indicated by the handspraying.

The table sequence should make the logic of the ‘a posteriori training’ runoff value assignment procedure clear. Ideally a ‘standard’ training procedure would have been employed, identifying large homogeneous areas, but the sites were chosen on the basis of various criteria, and in any case the MMR results indicated that the dominant ESE in many cases could not be distinguished in spectral terms from the surrounding ESE’s. The Potential runoff ranking in Table 9.1 for each site is simply an ordinal ranking based on steady state infiltration values. The Runoff weight is simply this order reversed (this is not intended to generate quantitative predictions of runoff but rather as an example of a possible approach). The Proportions table quantifies the proportion of each spectral class occupied by each rainfall simulation site (the non rainfall simulation sites are ignored). The Proportions weighted table then weights these by the Runoff weight, and the sum is considered to be a relative runoff potential value for each spectral cluster.

From the results it can be seen that cluster of runoff ‘Class’ 4 has the highest relative runoff potential according to this procedure and Class 3 the least, which makes sense upon examination of their distribution throughout the image, as will be seen. Recall that these ‘runoff’ classes are simply the clusters identified by unsupervised classification of the reference TM image using the Orstom Tunisia indices. In Figure 9.11 the proportions of each ‘runoff class’ in terms of the contributing area from each rainfall simulation site is presented. On the X axis a description of the Etats de Surface or landscape unit typically associated with each ‘runoff class’ (i.e. spectral cluster) is provided. This follows a logic proposed by Puech (1994), in associating runoff values with soil, vegetation and topographic properties of the landscape, as the latter are ‘visible’ at the
Table 9.1
Runoff potential assigned to each cluster in the classification based on the Orstom Tunisia indices, as an illustration of the type of approach which could be taken when training site surfaces of interest are too small / heterogeneous to use a conventional training procedure.

The Potential runoff ranking for each site is simply an ordinal ranking based on steady state infiltration values. The Runoff weight is simply this order reversed (this is not intended to generate quantitative predictions of runoff but rather as an example of a possible approach). The Proportions table quantifies the proportion of each spectral class occupied by each rainfall simulation site (the non rainfall simulation sites are ignored). The Proportions weighted table then weights these by the Runoff weight, and the sum is considered to be a relative runoff potential value for each spectral cluster.

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<th>Runoff weight (inverse of runoff potential ranking)</th>
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<th>Class 5</th>
<th>Class 4</th>
<th>Class 2</th>
<th>Proportion of each remote sensing class made up of each site</th>
<th>Proportion weighted by runoff potential of rainfall simulation site</th>
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</tr>
<tr>
<td>Lameluk</td>
<td>6</td>
<td>1</td>
<td>Lam (1)</td>
<td>0.00</td>
<td>0.00</td>
<td>0.29</td>
<td>0.14</td>
<td>0.00</td>
<td>0.00</td>
</tr>
</tbody>
</table>

Final order of runoff potential for each remote sensing class:

```
Class 4  Class 2  Class 5  Class 3
```

376
Composition of each remote sensing class in terms of hyrological classes
(from 6 = highest) [based on the proportion of each rainfall simulation site area classified as each remote sensing class]
resolution of TM or Spot imagery. In that research, however, a separate classification was carried out for each constituent and then associated with runoff, whereas here it is done on 'net' classification without distinguishing between the landscape features contributing to the spectral values. The only surprising result in Figure 9.11 is the composition of Class 3; Site 9.6 would not normally be associated with 'medium vegetation, linear features', however it is true that large areas of the central Flats do include these features. The resultant distribution of relative runoff values will be presented in the next section in a side-by-side comparison with an independent assessment of the same issue.

(9.6)

Comparison with an independent assessment of runoff potential on the basis of relative runoff potential

In order to 'validate' the relative runoff potential map created by assigning runoff simulator site relative rankings to spectral clusters, described above, an independent assessment of runoff potential is necessary. Fortunately The GTZ survey of Baringo, part of a larger study on the rangelands of northern Kenya, was published in electronic form in Arc export format, based on fieldwork utilising a 1976 MSS hardcopy image of the region for a paper publication scale of 1:500,000. The principal coverage of direct interest is the runoff map, but other variables are also relevant in assessing water harvesting suitability at this (reconnaissance level) scale. The Arc polygons were imported into Idrisi and georeferenced, over a TM89 band 2/3/4 image. As the GTZ approach is physiognomic and used satellite imagery to stratify sample sites, the match to the image is good in spite of differences in date and resolution between the TM and the MSS source image. The GTZ classification accords the central Flats a rating of 29 (moderate; locally very high) and Eldume 40 (high) but also, bizarrely, groups that region with the swamp area south of the Lake.

In order to compare the GTZ map of runoff potential is compared to the map of runoff potential created by assigning the relative rankings of the rainfall simulation sites to the spectral clusters in the study area, as explained above, the runoff values of the former first need to be converted to a relative numeric scale equivalent to that of the latter so that they can be compared on the same scale. The GTZ coverage for 'runoff losses' was rasterised in Idrisi from vector coverage polygons exported from Arc Info. The use of a legend where classes are coded on a non gradient
scale, i.e. the lowest number representing the lowest value and the highest the highest, restricts the possibilities for image algebra by overlay, which is the central logic in a raster GIS as used in this study. Therefore the code values have been subjectively translated into an ordinal scale of 1 to 5 in which 1 represents the lowest runoff value class (apart from zero, absence of the variable) and 5 the greatest, without pretending to be a ratio scale (the values of class 2 being twice those of class 1). The reclassification thus results in a new image on the 'same' scale of relative runoff potential as that generated by the present study, which allows for direct comparison between them.

Relative runoff for April 1993 for the area southwest of Lake Baringo is presented in Figure 9.12 to highlight the difference in level of detail (but not necessarily accuracy) between the two runoff potential assessments. On the left the GTZ relative runoff potential map is overlain against the rainfall map for April 1993 presented in Chapter 7 and (right) the 'map image' produced for this research overlain on the April 1993 rainfall distribution. The absolute amount of runoff yield cannot be calculated from the data available, but, for example, for a water harvesting system with a given runoff: runon area ratio and a monthly raindepth of 30 mm at that location, the runoff yield will be proportional to the relative runoff potential, as per the maps below. The actual runoff yield will depend on the absolute difference in runoff coefficient (here based on final infiltration rate) between the runoff units, the time to runoff for each unit, the duration and intensity and intensity pattern of each storm making up the monthly total. Time of day of each rain event and the rate of infiltration behind the bund (= evaporation loss) will also influence net runon yield. In short, given the variety of factors to consider, runoff maps should have the modest objective of indicating relative differences and, with sufficient field data, runoff coefficients under a set of specified assumptions / conditions. Ultimately, however, the most limiting data set is the spatial distribution of rainfall, a typical problem in semi-arid environments due to their low economic potential. The difference in the maps is a kind of 'sensitivity analysis' (non quantitative) of the GIS based spatial 'model' described in the next section to differences in the relative and absolute values of the input factor map 'runoff potential'.
Figure 9.12
Comparison of runoff maps for April 1993

(Left) GTZ relative runoff potential map overlain on April 1993 rainfall distribution using the RAE fields’ rainfall gauges, for a detail of the southwestern Njemps Flats

(Right) Same, but using the relative runoff potential map produced in this research by assigning rainfall simulator values to spectral clusters
The GTZ data set was imported from ArcView export coverage format to Idrisi and recombined for a different objective from that originally intended, which was a suitability assessment or carrying capacity for livestock (Herlocker et al. 1995). This is a good example of the power of GIS (geographical information systems). The constituent inputs into an map can be disaggregated, if available as individual coverages, and recombined for novel applications, including applying differential weights to each layer. Indeed, sensitivity analysis can be carried out by applying different weights to each input and identifying which input has the greatest impact on the final analysis when changes are made to that input. This signals that care must be taken to ensure that the values of that particular input are accurate. As the key variable for the purposes of a suitability assessment for water harvesting is the runoff potential of the surfaces, two input maps of runoff potential were tested with the GIS ‘model’ developed; the GTZ map and that developed by this research, compared above as Figure 9.12. A comparison of the effects of substituting one runoff potential map for the other is discussed below. First, however, the construction of the GIS ‘model’ will be presented.

(9.7.1)

The logic of land evaluation and the structure of the GIS based model developed for assessing suitability for water harvesting

The basic logic employed is the following: the final map, Suitability for Water Harvesting, is produced from factor maps (Runoff Potential, Runon Potential, Constraints on Runon Potential, Potential Water Demand), each of which in turn is derived from ‘contributing’ maps. The ways in which a map is created from constituent maps is a subjective process, based on the nature of the data, the objective, and an understanding of the processes / relationships involved and of the study area.

The factor maps, which can be thought of as ‘land qualities’ within the ‘FAO’ (Food and Agriculture Organisation of the United Nations) land evaluation framework tradition, are complex attributes of the landscape derived from ‘land characteristics’ or measurable attributes of the landscape. The landscape is mapped in terms of land characteristics according to classes defined using class limits, or threshold values of the characteristic being measures, which have some real world significance in terms of the distinction between classes. Maps of land characteristics can be thought of as contributing maps in the creation of maps of land qualities. The land quality maps derived from maps of land characteristics are combined in turn, as here,
algebraically, taking advantage in the case of the present study of the power of a GIS. The objective in this case is to produce a 'higher level' land quality, 'Suitability for Water Harvesting'. Water harvesting, again within the FAO tradition of land evaluation, is a 'land utilisation type', having a specific set of requirements for suitability having been defined on the basis of 'expert' knowledge (literature and / or interviews of experts).

Note that the final product of the GTZ study were paper maps (Herlocher et al, 1995), and only the final maps (as opposed to maps of the constituent data) were presented. To be of use to the present study, however, that data was obtained in Nairobi in digital form, complete with contributing maps, however certain variables of interest linked in a database to each polygon had to be extracted and mapped specifically for this work.

(9.7.2) The development of and results generated by an hierarchical, GIS based, water harvesting suitability assessment procedure

In Figure 9.13 three input maps, Soil Depth, Available Water Capacity (AWC) and Relative Fertility, each on a scale of classes 1 – 5 (5 = maximum, white), reclassified thus for this study in a manner analogous to the reclassification of the GTZ Runoff Potential map, described above. For the present study these particular coverages were added together to create the Runon Suitability map layer within the Suitability Assessment for Water Harvesting GIS model. Soil Depth class limits range from < 20 cm to > 80 cm, and was reduced by the surveyor in proportion to the volume of coarse fragments as well as for high salinity. AWC was derived from the soil texture after Landon (1991). The Relative Fertility classes were based on field observations, as laboratory analyses were not yet available at the time. The contributing maps are combined with an algebraic overlay operation in Idrisi, as presented in Figure 9.13, with a weighting applied to the AWC map, due to significance of this attribute for the application being assessed.

The final product is considered to represent the relative suitability of each polygon in terms of suitability as an area for 'runon', in other words for cropping (using runoff water). Therefore for a mapping unit to be considered suitable as a potential runon area, it must exhibit attributes or 'Land Qualities' (FAO 1976), including 'ability to provide nutrients' and 'ability to provide water'. In a water harvesting system relatively large volumes of water in the form of runoff are directed from a runoff producing area to an adjacent 'runon' receiving area. Therefore, in order
Figure 9.13
Creation of Runon Suitability factor map layer

Each of the three contributing maps have been reclassified on a scale from 1 to 5, with 5 being white, meaning greatest relative value of the mapped attribute. The scale of the final map reflects the mathematical combination of the contributing map, as presented. Black dots = RAE water harvesting fields. Source data, GTZ Range Management Handbook (Herlocker et al 1994).

Runon suitability map for water harvesting, or ‘production potential’
for an area to be considered suitable for runon it must be able to accommodate a reasonable depth of water and to hold onto that water against gravity and to make it available to the plant roots at a tension at which they can extract it from the soil. As such, the GTZ coverages 'Soil Depth' and 'AWC' were selected as most relevant to this assessment criteria.

Turning now to potential obstacles to cultivation, a 'Constraints' map was also produced for the present study from contributing maps. Figure 9.14 presents the creation of a 'Constraints on Runon Suitability'. Constraints due to rockiness is a function of the percentage of the surface area covered by stones, boulders and/or rocky outcrops, with class limits ranging from < 20 % (black) to > 40 % (white). Constraints due to rockiness is more heavily weighted in the calculation due to the widespread rockiness and the fact that gullied areas have been shown to be successfully utilised in water harvesting systems in the area. Class limits for topography range from <15% slope to > 30% and/or frequent gully / river incisions. Note that the scale for the Runon Suitability runs in the case of the data employed from 0 to 18, whereas that of the Constraints on Runon Suitability map from 0 to 9. These are not necessarily the maximum theoretical values; as the scales are relative, that is not of concern here. The higher maximum for the Runon Suitability map is due to the fact that there are three contributing maps as opposed to two, and as each runs from 0 to a potential maximum of five (and one map is further multiplied). This is not necessarily problematic, as the relationship between the factor maps can be manipulated at a later stage, and in any case the final result is expressed in terms of relative suitability, so the least suitable land units would not be recommended, no matter what the numbers happen to work out to be.

The Potential Water Demand map (Figure 9.15) was created from a Settlement Density and a Range Utilisation map, both based on systematic reconnaissance flights flown for UNEP. The sampling scheme is grid-based accordingly; note the resultant difference in spatial unit boundaries from the GTZ maps presented to date, which are also based on remote sensing (satellite imagery), but on 'naturalistic' boundaries in accordance with a sampling scheme based on physiognomic units. The UNEP based contributing maps have a maximum of 3 classes, as opposed to a maximum of 5 for the GTZ maps, in spite of the larger mapping scale of the UNEP study (Ottichilo et al. 1990). For the Settlement Density map a survey flown in 1987 was used to count structures (houses, sheds, bomas etc) in rural areas. Class limits for this map are: 0 (black) = 0 - 10; 1 = 10 - 20; 2 = > 20 (maximum of 32). For the Range Utilisation map, the same class limits are employed, but refer to Tropical Livestock Units. The range in this case is greater (a
Figure 9.14
Creation of Constraints factor map layer

Each map is on a relative scale from 0 to 5; see text for details of criteria and class limits. Lighter colours mean greater constraints.

Figure 9.15 Creation of the Potential Water Demand factor map layer
See text for details of the sources of the data for the contributing maps

Settlement Density map

Range Utilisation map

Potential Water Demand map

Legend:
- 1 - low
- 2 - medium low
- 3 - medium
- 4 - medium high
- 5 - high

Scale: 1 Km N
maximum 136). The aerial survey was flown in September 1987, the peak of grass cover and hence representing the maximum herd density.

Figure 9.16 presents the overall combination of Factor maps, each of which was developed from contributing maps, as described, map by map, above. If one substitutes the GTZ runoff map in that figure for the runoff map produced in the present study, the difference in the resultant suitability assessment is presented in Figure 9.17. The range of values is similar, as is the spatial distribution; this is not surprising, as all the other factor maps are the same between in both combinations. One cannot use this directly as a sensitivity analysis, as the values of the other maps would also have to be altered and the results compared. The actual runoff values to be expected are likely the most sensitive element in such an analysis, as a notional multiplicative factor would be assigned to each runoff unit in the Runoff Potential map. For a quantification for actual planning purposes, one would require a greater number of rainfall simulations. As this is unlikely in practice to happen because of their time consuming nature, it can be concluded that the GIS ‘modelling’ approach presented is a powerful tool but is naturally subject to the representativity, accuracy, precision and density of sampling upon which the contributing maps are based. There is, of course, a danger, as in any GIS analysis, of error propagation, and the effects of this may be revealed in validating the analysis by carrying out actual water harvesting experiments at various units in the classification, observing the success of each experiment. Unfortunately, this was beyond the scope of this study.

It is possible, however, to overlay the location of successful water harvesting fields. This has been done in Figure 9.16 (white spots represent fields of the successful RAE project). Most RAE water harvesting fields, significantly, are located in zones considered on the basis of these classifications to be non suitable for water harvesting, and yet this is the only water harvesting project to have proven sustainable. The FAO and World Bank sites are located principally in the high potential area of the Flats, as would be expected from these classifications, and were largely successful on technical criteria, yet have proven socially / economically unsustainable, as evidenced from low adoption and from the abandonment of these schemes after funding ceased. For the sake of simplicity Figure 9.18 displays the runoff potential alone rather than against water harvesting suitability per se, which involves multiple variables. Most of the RAE fields are located in areas which, according to this classification, do have a reasonably high runoff potential. There are also quite a few sites, however, located in the ‘lowest’ category, in the hills, but the rationale for site location of the fields was not made purely or even principally on the
The Runoff Potential map used in this case is the GTZ map. The legend scale is relative (darkest least suitable to lightest most suitable) and varies in numeric range depending on the particular map.
Figure 9.17
Comparison of water harvesting suitability classifications based on different runoff factor maps

The map on the left is the water harvesting suitability resulting from the use of the GTZ runoff potential factor map, whilst the one on the right is the result of an identical process but using the classified image-map generated by this research. The final scale is in relative units, and have been adjusted on a sliding scale on the basis of the Runoff Potential factor map, to account for the differences in the amount by which rainfall would be translated in to runoff yield. As such, the scale is relative and is for illustrative purposes.
Figure 9.18
Comparison of choice of location for the RAE water harvesting fields and the runoff potential assessment generated by this study

The RAE water harvesting sites (white dots) found in the north, central and southern Baringo lowlands are displayed over a supervised classification of runoff potential in the study area. Note that black denotes unclassified areas, which correspond mainly to the hill areas, as the spectral signatures were developed on training areas found in the Flats. The Lake is displayed in a natural colour for aesthetic reasons.
basis of runoff potential, but rather on the basis of the condition of the community into which water harvesting (and the associated scarce resources like employment and cash) were to be introduced (Roberts, Pers. comm. 1997). Thus it can be seen that factors such as the degree of social cohesion are a critical ingredient for macro water harvesting, as with the RAE fields, which require labour and local management co-operation. It is not common, and probably very difficult to map such factors, but they could potentially be mapped in a GIS and introduced as a suitability requirement. This is an exciting area for future research in the area of land evaluation in general and for the development of methodologies for mapping suitability for water harvesting in particular.

(9.8) Conclusions and possible ways forward

The key question being addressed here is how to determine whether the demarcation of the landscape on spectral terms corresponds to the demarcation of that same landscape in terms of units which are hydrologically distinct. Due to differences in scale between the hydrological and spectral measures, however, one is essentially comparing point measurements of infiltration with a continuous surface of reflectance properties. Therefore it is necessary to implicitly or explicitly extrapolate from the point values to an area around in order to compare a common dimension. The validity of this extrapolation (or, if the point density were sufficiently great, interpolation) could be assessed in a number of ways. One potential source of data in this respect were runoff plots which were set up on short slopes to answer another question, that of the conveyance loss which might be expected, however this cannot be directly used to infer the degree of hydrological variability over the sample strips (some 15 m long), as only the uppermost meter is subject to the kinetic energy of simulated rainfall and therefore inducing sealing processes whilst the rest of the slope is subject only to an infiltration reduction due to surface storage capacity.

Another approach to assessing the geostatistical nature of the variability in infiltration would be to have a large number of infiltration tests over a relatively small area, which is largely impractical with rainfall simulation due to the time consuming nature of this protocol, particularly if replication is to be carried out at each site for purposes of assessing the statistical validity of apparent differences between points. Therefore one could turn to a less time consuming measure to provide an indication of variability, and to do so along what is believed to be the maximum
axes of variability, in this case, from an understanding of the processes involved, along catenas. This last strategy was employed and a sample result using the handsprayer reported above. In short, at a very fine scale (within several meters) of a particular point there is a relatively high degree of variability in infiltration, due to the centimetric scale at which the ESE's are distributed spatially along microcatena in this fractal landscape. However, for the same reasons, namely the reproduction of the topographic patterns across scales, *this variability is mitigated* when, for example with the transect mentioned, the survey covers an area of several kilometers.

What readily became apparent from a combination of fieldwork and both visual and digital image analysis with a remote sensing products of various resolutions was that a basic hydrological logic exists which recurs at certain scale intervals. Whilst the quantitative nature of these intervals are the subject of future of further research, it is apparent that they are the result of self-similar or self-reproducing patterns of runoff producing and runoff transition (during large rain events) or receiving (during small events) areas over a range of scales. Furthermore, these areas had subtly but distinct differences in albedo, due both to the selective removal and deposition of certain grain sizes at various points along the catena, as well as differences in slope. As the scale of investigation becomes coarser, albedo becomes increasingly dominated by slope, as the differences in slope between production and transition areas becomes more dramatic, moving in scale from microsteps to gullies. In addition, at the coarser end of the scale axis, vegetation becomes, as we shall see with the supervised classifications, a dominant factor in the spectral constitution of the linear (gullied) land systems, where soil moisture is concentrated. This phenomenon was found to facilitate the visual interpretation of the imagery but complicate the digital analysis.

In short, at each stage and/or scale in the assessment of runoff potential and water harvesting suitability, a different approach may be best. This confirms the finding of Puech (1997) for the Sahel, after some 10 years of attempts to map runoff using both aerial and satellite imagery. The domination of the spectral response by vegetation found in the supervised classification using satellite imagery, even at low average coverage makes sense given that the satellite sensors utilised were developed largely for crop monitoring purposes, and as such vegetation sensitive spectral windows dominate the band selection. As such, one alternative for the purpose of mapping runoff potential in crust dominated areas with reasonably high degrees of vegetation would be to use higher resolution panchromatic imagery, which mitigates the problems of
vegetation dominance by using albedo over the full visible spectrum and using a spectral mapping unit closer in scale that at which the crusting varies.

Although not the focus of this research, a couple of ideas will be presented in conclusion which point to possible improvements in the way in which runoff potential could be mapped more accurately when working with crusting soils in semi-arid environments. In the light of the findings above, one can compare an area well known from fieldwork in terms of the accuracy with which the spectral demarcation of the landscape in high resolution digital aerial imagery and in Landsat TM imagery corresponds to the hydrological demarcation. In the case of the panchromatic (representing net albedo in visible spectrum) the aerial digital imagery the resolution (1.3m pixels) is so close to the scale at which the crusts vary spatially that with some familiarity with the study area they can substitute for ground verification. With respect to the Landsat TM images, as expected, the infrared bands, which are more vegetation sensitive, revealed a more subtle vegetation pattern than the bands in the visible spectrum. It was also discovered that the infrared bands provided a better overall picture of the distribution of crusts. The reason for this is not known, however in the case of the digital aerial imagery the near infrared band (results not elaborated here) was sometimes found to offer a more accurate image, whilst the panchromatic was superior in other cases, depending on the site. Given the relative dearth of studies of the spectral characteristics of physical degradation crusts, this offers an important area of further research.

The digital equivalent of this same comparison might also be considered. In this case (not shown here), there are distinct patterns or digital image textures which correspond to different ESE's in the image, in both the high resolution and low resolution remote sensors. Such an examination appears to confirm the potential usefulness of these sorts of 'textural' signatures. In short, one has evidence of a meaningful correspondence between the 'picture' of the landscape according to reflectance characteristics and according to what is known about the crust distribution and hydrologic units present in this image. This implies that the quest to map the latter from the former is promising, but may rely on a combination of spectral and textural analyses rather than simply the former. Furthermore, even with the loss of resolution with the TM imagery as compared with the digital aerial photography, three distinct digital image textures are readily apparent in each, with a greater subtlety or precision within each pattern with aerial imagery being commensurate with its greater resolution.
In conclusion, then, it may yet be possible to bridge to leap in scale between the most widely available spectral maps of the crusting surfaces in semi-arid areas, medium resolution satellite imagery, and the hydrological phenomenon which operate at a subpixel level. The key to this, however, may be to focus more on texture than on the multispectral nature of the imagery, which windows for which were selected primarily for mapping vegetation, not soils. As such, one can be optimistic about the prospect of utilising remote sensing for the purpose of assessing runoff potential as an input into a methodology for identifying promising areas for water harvesting, however more research is required in this area. Another ‘leap’ to be made is that between the environmental and social sciences, as seen from the fact that the project with the fields in the least promising areas and yet has had the greatest success, there are many socio-economic variables which need to be incorporated in land evaluation, but how to do so in a GIS based analysis is not always self evident. This is an area of great potential for future research.
Chapter 10

Conclusions

- Summary of each chapter
- Possible ways forward
- General conclusions

Chapter Overview

(10.1) Overview of Chapter

(10.2) Summary of each chapter

(10.3) General conclusions
Overview of Chapter

This chapter begins with a summary of the main ideas and/or findings of each chapter, and then concludes with a discussion of the most important results of this study and the implications thereof. The summary of Chapter 2 is essentially a review of the main issues related to water harvesting. The summary of Chapter 3 is a reminder of the main conclusions of the review of the phenomena of crusting and sealing carried out in that chapter. The summary of Chapter 4 recalls the key points regarding the methodology employed and particularly caveats regarding the appropriate use of rainfall simulators. The summary of Chapter 5 explores the options identified in that review for applying point measures of infiltration to map runoff potential across a landscape. The summary of Chapter 6 then goes on to remind one of the sampling strategy employed and the challenge of applying it in the study area, given the resultant mixels.

The summary of Chapter 7 begins the 3 chapters devoted to the result of the methodologies as applied to the study area described in the previous chapter. This summary refers to the results of the hydrological investigations, and in particular the finding of the rainfall intensity dependence of the steady state infiltration rate and the implications for assessing runoff potential. The summary of the next chapter, Chapter 8, which is a discussion of the results of the rapid low-cost tests of runoff potential, and a comparison with the runoff rankings of the study sites using rainfall simulation. The appropriate conditions under which the most successful of the simple tests, the 'handsprayer', can be utilised are reviewed. Finally, Chapter 9 is reviewed, reminding one of the main findings of the attempts in this study to map runoff potential across the entire study area on the basis of the 'point' measurements of infiltration using rainfall simulations. The experience with the approach taken is reviewed, and a brief discussion of possible alternative approaches engaged in. The question of the 'fractal' nature of the landscape is broached, and the implications for bridging scales introduced. The results of the GIS based analysis are summarised, and in particular the implications of the findings regarding social factors, are highlighted.

This is followed by a general discussion of the main conclusions arrived at in this study, the novel findings of this work and the relationship between this work and the literature reviewed, and the implications of the findings for the objectives of the study, which is to assess relevant methodologies for determining runoff potential in the context of a suitability assessment for water
harvesting. A two stage model of seal development is elaborated to explain the findings of the rainfall simulations and the model / method dependence of the ranking of runoff potential using rainfall simulations is emphasized.

(10.2)

Summary of each chapter

(10.2.1)

Chapter 2

- An introduction to Water harvesting

It was seen from this chapter that, in terms of the physical effectiveness of water harvesting, this has been established beyond a doubt both by the use in semi-arid and arid areas around the world for at least 10,000 years, and by modern studies of soil water balance and yield improvements vis-à-vis in situ rainfall receiving controls. For the purposes of this particular study, a working definition of water harvesting was proposed which is based not on a description of particular systems but on common physical bases underlying their operation, which are common to most if not all practices covered by the term. Such a process-based approach, it is hoped, can relate water harvesting to a land suitability assessment methodology, which itself is predicated on an understanding of the environmental requirements necessary for the successful (on technical criteria) implementation of a water harvesting programme.

Given that runoff efficiency is not normally subject to alteration at an economic cost, the prediction of runoff from small surfaces throughout a study area is essential for planning micro water harvesting. The determination of both the fact of and relative degree of runoff and possibly (at a detailed stage in the suitability assessment procedure) the absolute amount of runoff are components in predicting runoff. Ways to determine these parameters have been discussed throughout this study.

(10.2.2)
Chapter 3

- A review of crusting and sealing in semi-arid areas

In this chapter it was argued that crusting soils, particularly those resulting from physico-
chemical degradation, are widespread and very important for the surface hydrology of semi-arid
areas. As water harvesting is potentially very attractive in these same areas, it is very relevant to
the overall goal of assessing suitability for water harvesting to develop a methodolog(ies) by
which to determine the runoff potential of these soils. This objective, however, is complicated by
a number of considerations raised in this review of the literature on the phenomena of crusting
and sealing. First of all, the method dependence of assessing crusting became apparent from this
review of the literature; the preferred approach in this study is a functional approach, or ability to
restrict infiltration. Secondly, the definition dependence of crusts means that two studies may
actually be referring to two different phenomena when reporting results of work on ‘crusted’
soils. Finally, and particularly significant for this study, crusting and sealing phenomena vary at
a relatively fine scale over space and time. Together, these complications revealed by the
literature review imply the necessity of establishing a consistent classification system, the
inventorying of those crusts occurring in a study area, and a mapping of the distribution of their
occurrence over the entire study area. Those issues were then addressed in Chapter 5 in the
context of methodological options for achieving these objectives.

(10.2.3)

Chapter 4

- Methods used in the hydrological investigations

A number of conclusions regarding the instruments employed in the hydrological investigations
were arrived at in this chapter:

a) The use of rainfall simulation results as reference values against which to interpret or
calibrate simple tests, the basic strategy proposed by the research design, may be misleading
in so far as the relationship appears to be dependent on the type of simulator chosen as the
reference value. There are multiple factors of error and variability inherent in the various
attempts to replicate different aspects of rainfall and to combine these with other
considerations such as logistics in the field. Therefore, it is acceptable to compare the results
of the simple tests to those of a simulator, however only one design should be selected for
this purpose, which will be assigned the role of a standard reference value. It should not be assumed, however, that this reference value represents the ‘real’ values under natural rainfall, but subject to an awareness of the degree to which the characteristics of natural rainfall known to influence the response of interest have been mimicked in the simulator design, the simulator will be taken to be more accurate than the simple tests, in so far as they lack a reasonable kinetic energy reproduction, amongst other limitations.

b) A research approach based on the triangulation between simple tests appears to be promising, or at least much more promising than relying on just one or two such tests. Laboratory data, where available, are a useful but not essential aid in the interpretation of the runoff potential of the surfaces assessed.

c) Amongst the tests previously employed and newly developed, the handsprayer appears most promising, as it replicates the an in situ response controlled natural process, that of infiltration of the top 5 mm of crusted soil, albeit without energy application. As such, the ‘final infiltration rate’ obtained using this tool (which is predicated upon assumptions about the effective wetted area) should be close to the saturated hydraulic conductivity of the crust and represents the wetting effects of rainfall on sealing.

The systematic calibrations and error assessments carried out on the rainfall simulator lead to a number of discoveries about the design chosen, amongst which are:

a) Considerable variability over the field season in the calibrated apparent intensities, in spite of very little variability between replicates during calibrations at the beginning of the season, which would otherwise inspire confidence about the precision of this instrument. The reason for this variability is not known, but on the basis of other calibrations and the monitoring of behaviour over the field seasons, could include:

- Temperature effects
- Changes in air pressure
- The intensity dependence of the spatial distribution of rainfall
- Clogging of the drop formers
- Differences in parallax between users of different height
- A failure to seal the system
• Differences in the hydraulics of two boards/simulators
• The board not being properly levelled (though carefully checked)

b) The implication of this variability is the necessity of discounting differences in runoff response as a function of differences in (apparent) intensity of, say, less than 15 - 20 mm/hr, if the intensity has not actually been measured in a study for every simulation.

In spite of these caveats, the rainfall simulator is still considered to be the most reliable tool for characterising infiltration (as it reproduces the kinetic energy believed to be responsible for sealing), but its use introduces a fundamental dilemma. As only a few rainfall simulations can be carried out per day as a practical matter in the field, the opportunity to develop statistically meaningful relationships is unlikely in most cases. Therefore, the results of a long campaign of rainfall simulations such as summarised in the inventory of Casenave and Valentin (1989) for the Sahel, are a rich and rare resource, but it was found that the direct application of these relationships to another semi-arid area (Baringo) has not been unproblematic, as will be discussed in the general conclusions. The implications of this are critical to the theme of the study: for any given area, a new set of relationships needs to be developed, and then related to the spectral characteristics of that same area.

(10.2.4)
Chapter 5
• Options for applying point measures of infiltration to map runoff potential across a landscape

This chapter identified key studies of relevance to the objective of mapping the distribution of runoff potential in areas of crusting soils, inevitably from remote sensing, in arid and semi-arid environments. These studies were reviewed for the purpose of identifying their advantages and limitations with respect to the objectives of determining runoff potential within a suitability assessment procedure for water harvesting. The fact that the French researchers working in the Sahel had access to a catalogue of established relationships between crust morphology and infiltration meant that their studies started ‘on the ground’ and at the scale of the rainfall simulator plot and then various attempts to upscale to the size of a pixel were attempted. A similar approach was the primary approach in this study, again because the primary instrument
employed was a rainfall simulator utilised on a small plot and because the conceptual
classificatory principles in describing crusted surfaces developed by Casenave and Valentin
(1989) was also utilised in this study. Differences between the crusts occurring in the Sahel and
in the study area and differences between the infiltration values of the same crusts and the
implications thereof are returned to in the general conclusions, below, when drawing general
lessons about the applicability of the ‘Valentin Catalogue’ of morphology-runoff relationships to
areas outside the zone in which it was developed.

Unlike the work of Orstom, the present study also attempted to determine the degree of variability
around the dominant ESE in each Etats de Surface investigated using field spectroradiometry, in
order to determine whether the dominant ESE could be considered representative of the mixel
corresponding to the Etats de Surface. The results of those investigations were reported in
Chapters 8 and 9. Similarly, details of the procedure developed to assign the values of the
dominant ESE in each Etats de Surface (or local, narrowly defined physiognomic unit), which is
the surface on which the rainfall simulation was carried out, to the corresponding spectral clusters
were described in further detail in Chapter 9.

(10.2.5)

Chapter 6;

• Sampling strategy, applied to the study area

The selection of sample sites involved trade-offs between achieving representativity on
hydrological and spectral criteria. For the former, it was important to ensure that a range of crust
types found across the area were included in the selection of sites, while for the latter one should
ideally select large, homogenous sites on spectral criteria, in order to avoid the problem of
‘mixels’, or pixels containing different spectral surfaces over the corresponding area on the
ground, making it difficult to establish a one-to-one relationship between spectral and non
spectral characteristics of the landscape. The problem in the study area, and which is likely
widely true of semi-arid environments, is that the crusts vary at a finer scale than that of the
minimum resolution of the imagery, particularly if the effective resolution is taken to be a pixel
+/- two or three pixels to account for georeferencing imprecision on the ground (GPS with +/- 85
m precision) and during image processing at the stage of ‘rubber sheeting’. This ‘problem’ was
exacerbated by the desire to carry out simulations at sites where secondary data were available for
comparison / verification, due to the difficulty of comparing the results to runoff under natural
rainfall, and therefore the site selection was not done purely on the basis, for example, of ensuring clearly differentiated clusters on an unsupervised classification.

In short, the problem of mixels is almost inevitable, which is rooted in the difference in scale at which hydrological and spectral characteristics vary. This is really, however, an issue of a difference in precision between the instruments used to assess hydrological and spectral characteristics. This in turn is due to the impracticality of carrying out rainfall simulation on large plots and the expense of high resolution imagery. For these reasons a parallel investigation was also carried out at the rainfall simulation sites, using a simple test of water acceptance as a proxy for runoff potential and a spectroradiometer at the same resolution as the scale at which the crusts vary (approx. 20-30 x 20-30 cm for the *états de surface élémentaires*).

In addition to site characteristics and their relationship to the sampling strategy chosen, this chapter also described what is known about the rainfall characteristics of the study area. This is obviously very relevant to accurate rainfall simulation, and these data were taken into account when determining the protocol to be used.

(10.2.6)

Chapter 7

- Results of the rainfall simulation campaigns and implications in terms of determining runoff potential of crusted surfaces across a landscape

One of the outstanding results presented in this section is the rainfall intensity dependence of runoff potential (when using the steady state infiltration rate as the measure of runoff potential) across all sites and for all treatments and at all intensities. This indicates the predominance of this factor as a control on runoff, but by way of the surface, of course, through a reorganisation thereof. It is hypothesised that high intensity storms inhibit seal formation through turbulence effects of the impact energy, combined with the energy of the movement of a depth of water accumulating on the surface resulting from the high wetting rate. This confirms the findings of Bowyer-Bowyer (1993) in Swaziland using *in situ* simulations, who noted this phenomenon and contrasted it to the ‘classic’ model developed for temperate soils of equifinality, but without elaborating upon the mechanisms responsible. A similar finding was first reported (it is believed) in an important study by Romkens *et al.* (1990) using laboratory simulators in the U.S., who found that final seal conductance was a function of rainfall intensity.
This phenomenon also relates to the findings of Patrick and Berliner (1993) in the Negev, where a crust specific threshold intensity was discovered above which runoff yield declined under micro water harvesting systems, which was attributed to crust 'breakage'. Romkens et al. (1985) postulated that at higher rainfall intensities there is a higher rate of removal of detached particle, resulting in greater infiltration. Working with laboratory simulations, they found that for the same cumulative rainfall energy, the hydraulic conductance was greater at greater rainfall intensities. At higher rainfall intensities, however, there is of course a greater rate of energy application, which is almost certainly the cause of higher infiltration rates, for reasons described above. Furthermore, such an experiment does not allow one to separate the energy and wetting effects of the rainfall, as both the rate of moisture and rate of energy application to the soil surface vary together with changes in rainfall intensity.

Where crusts are not disturbed, the cumulative energy of the rainfall rather than the wetting rate has been postulated in this study, on the basis of the literature, to be the key control on the runoff yield. In short, one would expect to see a rainfall intensity dependence with both the crusted and crust removed treatments, as indeed was found to be the case for the Baringo data across all treatments. The reasons for this intensity dependence, however, analysing the results from this study in the light of findings with other crusting soils, was concluded to be different between the treatments. For the crust removed treatments, this was postulated to be due primarily to wetting effect, at least over the first part of the simulation, but with crusted controls due primarily to the rate of kinetic energy application. The wetting effect is believed to be a particularly important contribution of a raindrop in crust formation in the case of the crust removed treatments because the aggregates must first slake before the particles detached in the collapse of the aggregates can be made available to clogging fine pores in the surface of the soil. The interactions between the chemistry of the rainwater (natural or under a simulator) and the soil surface are likely significant at this stage of crust formation, but even with undisturbed soils chemical aspects are believed to be a factor where the clay content is high, such as at Marigat.

Through the conception and use of a handsprayer this study has allowed for the separation (in an indicative manner) of the effects of wetting from the effects of energy, by comparing the runoff rankings as measured on the same surface using a rainfall simulator and a handsprayer (which measures crust-controlled reduction in water acceptance due to wetting effects). This distinction can also, however, be examined by analysing the results of the rainfall simulations alone. A
significant finding of this study was that, contrary to steady state infiltration, there was no rainfall intensity dependence on the time to runoff. This implies that the initial state of the surface, rather than rainfall (be it through the wetting or energy effects thereof) controls this parameter. This initial state is quite variable, depending on its ‘history’ since the last rainfall, but may also involve wetting effects such as satisfying the clay demand for moisture before runoff can occur, as consistently observed on cracking surfaces. In the case of short rain events, where the steady state infiltration may never be reached, the proportion of rainfall ‘taken up’ getting to the point of runoff initiation is very important in terms of runoff yield for water harvesting systems. This parameter seems to be surface controlled and therefore requires a study of the variability in surface response to rainfall.

A practical implication of the phenomenon of rainfall intensity control on steady state infiltration rates, in terms of the use of rainfall simulation to determine rank surfaces in terms of runoff potential as part of a water harvesting suitability assessment exercise, is that these simulations should be carried out within a narrow intensity range in order to isolate the effect of the surface response. Another important implication in terms of water harvesting is that, to the degree that rainfall intensity controls the infiltration rate across a particular set of surfaces being compared, so much less important are differences between the surfaces in determining runoff yield. At high intensities, the effect of differences in steady state infiltration between surfaces, however, is diminished, due to the low proportion of potential runoff yield (rainfall) lost to infiltration. At low intensities, however, differences in infiltration rate between surfaces will be very important and thus the rainfall intensity dependence of infiltration is particularly important to investigate in low intensity simulations. This is particularly true where rainfall occurs, as in the study area, in many smaller and low intensity storms.

This is why, from the point-of-view of assessing water harvesting potential, the finding, for the study area, of the rainfall intensity dependence of the response of the surfaces assessed is very significant. The actual impact of this phenomenon, however, is also a function of the proportion of runoff lost to infiltration, the rate of decay of the infiltration curve, the time and depth to runoff and the duration and intensity patterns of the rain events in the study area and not just of the steady state infiltration rate, attractive as that may be as a ‘standardising’ and ‘natural’ parameter. In addition, it is important to remember when thinking about the rainfall intensity dependence of the steady state infiltration that this state may never, in fact, be reached with many of the smaller storms; in which case it is rather parameters such as depth and time to runoff and the rapidity of
the decline in infiltration ('Horton's alpha') which are the most significant factors. As demonstrated by the comparison of rankings using different measures of runoff potential, and tying this in to the present discussion, an understanding of both the pedo-hydrological processes and the implications thereof in terms of runoff yield are necessary to assessing water harvesting suitability.

This discussion returns one to broader issues addressed in Chapters 3, 4 and 5:

a) the data dependence (local rainfall, in this case) of rainfall simulation and
b) the measurement and definition dependence of the analysis (in this case, of the results of rainfall simulation). This became particularly apparent when attempting to determine the most relevant amongst the many parameters related to runoff potential by which to rank the surfaces.

Having studied many possible parameters and parameter combinations by which to describe both the infiltration behaviour and the runoff yield, it is concluded that it is not possible to adequately describe the surface – rainfall interactions for the purpose of water harvesting suitability with any single parameter. This revisits the issue of the complexity of the infiltration phenomenon with these soils, largely on account of the complex and still little understood processes of sealing and crusting, combined with the lack of data on rainfall characteristics in the study area, together with the inherent variability in rainfall simulation, not to mention the definition and method dependence of the results.

(10.2.7)

Chapter 8

- Results using low cost, rapid measures of runoff potential
- Comparison to the results of the rainfall simulations in terms of ranking runoff potential

In this chapter it was seen that sites which have an initial wetting control on infiltration, such as Logumukum (which has a gravel mulch, protecting the surface from the impact energy of raindrops), will be less successfully characterised with the most successful simple test, the handsprayer, than those, like Eldume, which require a threshold instantaneous kinetic energy to
overcome the organisation of the soil surface before runoff will occur. In the latter case the handsprayer, though assessing sealing according only to wetting, obtains a closer response to that of rainfall simulation than with surfaces where there is a change from a wetting to an energy controlled response over the course of a rain event. This is because there is an insufficient application of water using the handsprayer to satisfy the initial wetting demand of surfaces such as at Logumukum, resulting in a great overestimate of the infiltration rate.

For crust removed treatments, the relationship between the total volume infiltrated with the handsprayer and the final infiltration rate with the 3.5 m rainfall simulator was found to be $r^2 = 0.65$. With the surface intact, no statistical relationship was found, confirming the hypothesis of a change in control in a two stage model at some sites but not others, described above. With the surface removed there are 'constant' conditions across all sites. In the case of the crust intact treatments, however, there is a great variability, as those surfaces not protected by a mulch are the expression of the history of rain events at each site, where the organisation of the surface is the product of the cumulative energy imparted over that series of rain events. If Logumukum and Ongata Mara (which has a very high clay content, creating a very high wetting demand) are removed from the crusted treatments, the $r^2 = 0.67$ for the handsprayer, but at a lower degree of freedom ($n = 6$). This indicates that, hydrologically, Logumukum and Ongata Mara stand out from the other sites, which is accurate, indicating the potential usefulness of the handsprayer.

The parameter of 'total volume infiltrated' groups the values of the three Lameluk sites more closely (apparent runoff potential) with the handsprayer than 'final infiltration rate' (using an ascribed wetting area). The final infiltration rate, however, gives a closer fit to rainfall simulation rankings for initially wetting (swelling, in this case) and later energy dominated responses at clay rich sites such as Marigat, as the effect of the swelling is discounted when only the last point on the handsprayer's infiltration curve is used. This revisits the issue of measure dependence, which has been a consistent theme throughout this study.

Based on findings from this research, it has been concluded that soils which are clay rich or which have clay enriched crusts (for example, sedimentary crusts with many fine layers) result in the greatest discrepancy between handsprayer and rainfall simulation results. These discrepancies, however, are not, however, believed in the case of such surfaces to be due primarily to differences in energy between the two modes of water application, but rather due to absolute amount of water which can be absorbed / adsorbed by clays before the storage-excess
component of the runoff controls is satiated. In the case of the handsprayer the relative runoff potential is underestimated, as the infiltration rate and infiltrated volume is still great by the end of the two minute test, when in fact it rapidly falls off after a threshold volume of rainfall, as indicated by rainfall simulation on the same soils. The same is true in soils with a gravel cover over a less permeable layer. Therefore a combination of factors must be considered when interpreting the results of the handsprayer for rapid assessment purposes. It does, however, remain valid as an approximation of trends in runoff potential when such caveats are borne in mind, both in terms of the logic of the hydrology of the study area and when compared with the results of the rainfall simulations.

(10.2.8)

Chapter 9

- Linking point (rainfall simulation) and area (satellite imagery) data for mapping runoff potential over an entire landscape
- Possible ways forward
- The use of GIS in the analysis of suitability assessment for water harvesting

The key question addressed in this chapter was how to determine whether the demarcation of the landscape on spectral terms corresponds to the demarcation of that same landscape in terms of units which are hydrologically distinct. This was assessed in two ways; at the level of the Etats de Surface Elementaires, and at the level of the Etats de Surface, which is an association of ESE’s. The former corresponds to the ‘fundamental’ runoff producing surface, using the ‘Valentin’ conception of crusting soils, which is effectively defined by the use of a rainfall simulator and the lm2 plot used by the Orstom simulator. The relationship between hydrological and spectral characteristics were assessed at that scale around each 200 x 200 m ‘effective’ pixel (really a mixel) around each rainfall simulation site. Furthermore, the differences between mixels were assessed in terms of whether the variability between sites was greater than the variability within sites.

To summarise the results of these efforts, it was found that the separation of ESE’s on hydrological criteria, by either rainfall simulation or handspraying, is more promising than on spectral criteria, a fact also evident at the resolution of the Etats de Surface by the frustrating experiences attempting supervised classification. As such, field spectroradiometry can serve to
alert one to the potential to and at what resolution one can hope to distinguish between surfaces. If one cannot distinguish, on spectral grounds, between ESE's, then there is no disadvantage to the 'coarse' resolution of satellite imagery, and the question becomes how to upscale only the hydrological values.

In practice, at the level of the Etats de Surface, due to differences in resolution between the hydrological and spectral measures, one is essentially comparing point measurements of infiltration with a continuous surface of reflectance properties. Therefore it is necessary to implicitly or explicitly extrapolate from the point values to an area around in order to compare a common dimension. The validity of this extrapolation (or, if the point density were sufficiently great, interpolation) could be assessed in a number of ways. One potential source of data in this respect were runoff plots which were set up on short slopes to answer another question, that of the conveyance loss which might be expected, however this cannot be directly used to infer the degree of hydrological variability over the sample strips (some 15 m long), as only the uppermost meter is subject to the kinetic energy of simulated rainfall and therefore inducing sealing processes whilst the rest of the slope is subject only to an infiltration reduction due to surface storage capacity.

Another approach to assessing the geostatistical nature of the variability in infiltration would be to have a large number of infiltration tests over a relatively small area, which is largely impractical with rainfall simulation due to the time consuming nature of this protocol, particularly if replication is to be carried out at each site for purposes of assessing the statistical validity of apparent differences between points. Therefore one could turn to a less time consuming measure to provide an indication of variability, and to do so along what is believed to be the maximum axes of variability, in this case, from an understanding of the processes involved, along catenas. This last strategy was employed and a sample result using the handsprayer reported above. In short, at a very fine scale (within several meters) of a particular point there is a relatively high degree of variability in infiltration, due to the centimetric scale at which the ESE’s are distributed spatially along microcatena in this fractal landscape. However, for the same reasons, namely the reproduction of the topographic patterns across scales, this variability is mitigated when, for example with the transect mentioned, the survey covers an area of several kilometers.

What readily became apparent from a combination of fieldwork and both visual and digital image analysis with a remote sensing products of various resolutions was that a basic hydrological logic
exists which recurs at certain scale intervals. Whilst the quantitative nature of these intervals are
the subject of future of further research, it is apparent that they are the result of self-similar or
self-reproducing patterns of runoff producing and runoff transition (during large rain events) or
receiving (during small events) areas over a range of scales. Furthermore, these areas had subtly
but distinct differences in albedo, due both to the selective removal and deposition of certain
grain sizes at various points along the catena, as well as differences in slope. As the scale of
investigation becomes coarser, albedo becomes increasingly dominated by slope, as the
differences in slope between production and transition areas becomes more dramatic, moving in
scale from microsteps to gullies. In addition, at the coarser end of the scale axis, vegetation
becomes a dominant factor in the spectral constitution of the linear (gullied) land systems, where
soil moisture is concentrated. This phenomenon was found to facilitate the visual interpretation
of the imagery but complicate the digital analysis.

In short, at each stage and / or scale in the assessment of runoff potential and water harvesting
suitability, a different approach may be best. This confirms the finding of Puech (1997) for the
Sahel, after some 10 years of attempts to map runoff using both aerial and satellite imagery. For
example, the domination of the spectral response by vegetation found in the supervised
classification using satellite imagery (not reported, as it was not successful) even at low average
coverage, means that for the purpose of mapping runoff potential in crust dominated areas with
reasonably high degrees of vegetation it may be better to use higher resolution panchromatic
imagery.

In conclusion, then, it may yet be possible to bridge to leap in scale between the most widely
available spectral maps of the crusting surfaces in semi-arid areas, medium resolution satellite
imagery, and the hydrological phenomenon which operate at a subpixel level. The key to this,
however, may be to focus more on texture than on the multispectral nature of the imagery,
windows for which were selected primarily for mapping vegetation, not soils. As the basic logic
of landscape in the study area is that of rill – interrill alternations, across a range of scales, and as
this produces a distinct pattern, or texture, various texture measures might prove to be promising.
As such, one can be optimistic about the prospect of utilising remote sensing for the purpose of
assessing runoff potential as an input into a methodology for identifying promising areas for
water harvesting, however more research is required in this area.
Another 'leap' to be made is that between the environmental and social sciences, as seen from the fact that the project with the fields in the least promising areas and yet has had the greatest success, there are many socio-economic variables which need to be incorporated in land evaluation, but how to do so in a GIS based analysis is not always self evident. This is an area of great potential for future research. A GIS based analysis of suitability for water harvesting using secondary data for the inputs apart from rainfall and runoff, as an illustration of what is possible. This, however, is quite a theoretical exercise, rife with assumptions and simplifications. As a type of validation of the results, however, it was possible to overlay the location of successful water harvesting fields. This revealed that most of the RAE water harvesting fields, significantly, are located in zones considered on the basis of the GIS classification to be non suitable for water harvesting, and yet this is the only water harvesting project to have proven sustainable. The FAO and World Bank sites were found to be located principally in the high potential area of the Flats, as would be expected from these classifications, and were largely successful on technical criteria, yet have proven socially / economically unsustainable, as evidenced from low adoption and from the abandonment of these schemes after funding ceased.

On the criteria of runoff potential alone, most of the RAE fields were found to be located in areas which, according to the classification produced by this study, do have a reasonably high runoff potential. The maps of runoff potential produced by this study and by the GTZ (Herlocher et al. 1995) proved to be quite similar, which was taken to be a validation of the accuracy of the output of this study, at least on purely 'technical' criteria. However, it was curious to note that there were also quite a few RAE fields located in the 'lowest' runoff potential category, in the Tugen hills. Upon investigation it was learned that the rationale for site location of the fields was not made purely or even principally on the basis of runoff potential, but rather on the basis of the condition of the community into which water harvesting (and the associated scarce resources like employment and cash) were to be introduced (Roberts, pers. Comm. 1997).

Thus it can be seen that factors such as the degree of social cohesion are a critical ingredient for macro water harvesting, as with the RAE fields, which require labour and local management cooperation. It is not common, and probably very difficult to map such factors, but they could potentially be mapped in a GIS and introduced as a suitability requirement. This is an exciting area for future research in the area of land evaluation in general and for the development of methodologies for mapping suitability for water harvesting in particular.
General Conclusions

In semi-arid lowland Baringo rainfall simulation was utilised together with the Valentin catalogue as a conceptual framework in order to determine the relative runoff potential of various crusted (and non crusted) surfaces around the study area. For those rainfall simulation sites where 'Valentin-type' crusts could be identified, for example, for the crust type 'Erosion' (as at Eldume), the catalogue gives a runoff threshold (antecedent dry) raindepth of 2 to 6 mm; in the case of the study area, it was found to be 3.5 mm on a crust of this type, and using a lower rainfall intensity than in the Orstom research. Average infiltration, antecedent dry, to a raindepth of 50 mm is given as 15 to 30% in the catalogue for this crust type; in the case of the Baringo site, over a 20 mm rainstorm depth, an average of 15 to 20% was found. In short, the difference in protocol between the two rainfall campaigns makes direct comparison problematic, but the values are close. It is important to note that the 'average' value given in the catalogue is an average across a range of intensity-duration combinations of simulated rainfall.

Another surface (not crusted) type ESE which could be identified from the catalogue in the study area was the 'Gravel' type (at Logumukum), with catalogue values of 1.5 to 5 mm threshold depth and 5 to 20% average runoff, as opposed to, for the study, 3 to 5 mm and 40 to 50%. Although not a very good relationship to the catalogue values, the calculation of 'average' infiltration is clearly dependent of the length of the simulation, quite apart from the effect of intensity, and thus a more standardised measure is preferable, a parameter which is a function of the surface itself such as the steady state infiltration rate. Such a measure, however, whilst not dependent (within reason) on the duration of the simulated rain event, would still be strongly affected by different protocols with respect to the target intensity (rate of kinetic energy application) (Bowyer-Bower, 1993). Thus, for a true comparison, one would require a) similar levels of kinetic energy (drop height and mass and whether the drop exits the simulator at a velocity, as discussed in Chapter 4), b) similar rainfall intensity and c) similar antecedent moisture conditions. Failing this, local rainfall simulation would be advised instead of attempting to apply values from a generic catalogue developed for conditions elsewhere.

In the case of the most common crust type in Baringo, a 'Sedimentation crust' (due to the wide, flat, low friction surfaces ideal for the particular grain size sorting which is the genesis of this
type of crust, and which is evidence of classic Hortonian overland flow as the dominant hydrological process in the study area), the catalogue values are a 4 to 10 mm threshold and 20 to 35% average infiltration. In Baringo, the equivalent ranges are about 2.5 to 8 mm and 50 to 70% for the replicates carried out at the main site (Lameluk), although this site has the highest infiltration amongst the Sedimentation crusts; to a 1.5 to 4 mm threshold and 25 to 45% infiltration at Marigat, having the highest runoff potential of the Sedimentation crusts in the study area. In the case of Marigat there is clearly a surface enrichment of oriented clay, which probably accounts for the lower infiltration rate there; both the wetting (swelling) and energy effects of a raindrop are effective under such conditions in inducing sealing.

As can be seen from the example of the Sedimentation crust in Baringo, the variability in the average infiltration range of a single crust type (25 to 70%), means that one has to further discriminate on the basis of site characteristics and rainfall protocol, and not just on the basis of crust type, a point not emphasised by Casenave and Valentin (1989). This also implies that one catalogue is inadequate; local rainfall simulation or some other form of assessment of runoff potential is necessary, and with a sampling strategy which includes a number of locations manifesting each crust type. As infiltration is a function, amongst other factors, of rainfall intensity with degraded surfaces in semi-arid areas (Bowyer-Bower 1993) - due to the energy of the rainfall, which reorganises the soil surface during the storm - it is important to specify these conditions, ideally simulating rainfall across a range of the intensities (where data are available) found in the area being assessed for water harvesting potential.

The implication of such an approach, however, if one wants to be able to discriminate between runoff surfaces with a given statistical confidence level, is replication, and given the time consuming nature of rainfall simulation, a data collecting development agent would ultimately have to choose between certainty at one or two sites, or a lower level of certainty but a larger number of surfaces (greater representativity of the variability) in the area under consideration. If the runoff potential of a each crust type always fell within a narrow range, then it would be sensible to carry out many replicates on a few widespread crusted surface types, but judging from the results of the present work, there is too much intersite variability within each crust type to make this useful. Furthermore Puech (1994), using the catalogue within the zone in which it was developed and the same simulator and protocol found discrepancies of up to 400% from the catalogue values.
Hence, whilst the crust typology approach and associated rainfall simulation derived runoff values are an important theoretical advance, a practical shortcut, and a useful model with which to approach the problem of the spatially distributed nature of infiltration in semi-arid environments, the variability between sites of the same crust type / ESE still implies a very large number of rainfall simulations to properly characterise this variability. Thus a simpler, cheaper, and more rapid approach is required with which to assess relative runoff potential, ideally calibrated to rainfall simulation at these same sites in order to link qualitative or semi-quantitative and qualitative measures. In the case of the present study, the strategy decided upon was to select ‘key’ sites across a range of surface types, with multiple sites for the most common crust type (for example, Sedimentation; at sites Lameluk, 9.4, 9.5, 9.6, and Marigat), where rainfall simulations were carried out.

Of the rapid tests developed and employed, the most promising was shown to be the ‘handsprayer’, and the success therewith ascribed to the emulation of a natural process; maintaining incipient ponding so as to describe the infiltration curve of the undisturbed crust in this layered and surface controlled infiltration system, albeit without the application of energy. Essentially, therefore, within the limitation of an energy-free method, the resultant curve describes the infiltration characteristics of the crust and the final infiltration rate approximates, it is hypothesised, the hydraulic conductivity of the crust due purely to the sealing effects of wetting. [In fact, the hydraulic conductivity, technically, refers to the movement of a liquid through a porous medium in any direction, whereas with infiltration this is clearly movement preferentially in a vertical orientation].

As infiltration and therefore runoff is believed with crusted soils to be surface controlled, if tests can be devised which assess only crust behaviour, if those tests are quicker than those which assess the behaviour of the entire upper profile of the pedon, then this should provide both a practical and satisfactory indication of relative runoff potential. As mentioned above, however, just such a test which would otherwise qualify, the handsprayer, fails to reproduce one of the key controls on sealing, that of kinetic energy. In such a case, however, using the logic of ‘triangulation’ described in Chapter 4 and which was chosen as the analytical interpretative framework for the environmental data collected, this liability becomes an asset, as it may allow one to isolate and therefore separate the wetting and energy effects of sealing and runoff for a particular surface and to determine differences in the relative importance of these two mechanisms at various sites, which has both theoretical and practical implications.
It was found that surfaces such as Logumukum or Eldume (for the latter, this comment applies to a subdominant ESE: an exposed 'b' horizon overlain with a fine gravel wash), which have some form of surface ‘mulch’, or soils with a high clay content or (as with many sedimentary crusts) or clay enriched surface, give misleading results with the handsprayer. This alerts one not only to the limitations of this instrument, but also inspired, amongst other observations, the development of a ‘two phase’ within-storm conceptual model of seal (as opposed to crust) development with which to explain the results of the surface responses to rainfall within the context of the various mechanisms and models of sealing and infiltration reviewed in Chapter 3.

This conceptual model was progressively developed in interpreting the results particularly of the rainfall simulations but also of the simple tests; as the experimental design employing these instruments allowed one to vary the rainfall and surface treatments to isolate the effects of instantaneous kinetic energy (two drop heights), rainfall intensity (particularly in the first field season), undisturbed surfaces (one target intensity in the second field season, partly frustrated by the variability in the calibrated intensity of the rainfall simulator), the presence of a crust (removing the crust for comparison), amongst others considered subject to a smaller population of runs, such as the effects of vegetation cover and antecedent moisture. As a result, a conceptual model was conceived which appears to best explain the various responses to these various treatments and which draws upon the, ideally, advances the literature on crusting and sealing soils reviewed in Chapter 3.

This model postulates that, for a soil where the crust has been disturbed (as through the common occurrence, in the study area, of livestock trampling the generally fragile crusts), which was simulated by disturbing and even totally removing the crust, that the energy effects of rainfall dominate the runoff response, largely irrespective of rainfall intensity. The response to a given rainfall treatment, however, across a range of crust removed surfaces, or for a particular surface (with the crust removed) across a range of rainfall treatments (= wetting rate, instantaneous energy), was found to be much less ordered and therefore predictable than for crust-intact surfaces. This is believed to indicate a surface control on runoff, even for non crusted surfaces (such as Logumukum), albeit in a different manner than for crusted surfaces (likely surface rugosity / surface storage rather than porosity / structure).
It was also found, however, that although the parameters time / raindepth / cumulative energy to incipient runoff varied greatly, that once this threshold was reached the response was consistent across all surfaces: a 'classic' Horton-like decay curve, but parallel (rather than converging) curves, as a function of rainfall intensity and instantaneous kinetic energy. As the 'wetting effects' such as crack swelling are fully manifest by the point of ponding (as, by definition, the upper part of the surface is saturated – without getting into the storage excess vs. rate of intake debate – both are undoubtedly operating at the level of the crust layer), any further decline in infiltration is believed to be an energy controlled response, even for low intensity storms, and which appears to be borne out by the experimental results.

Furthermore, given that, by definition, at the point of incipient runoff the surface has reached a particular, natural, process based threshold, that the initial state of a surface, be it crusted or crust disturbed, might be elucidated from and defined in terms of the time / depth / energy required to reach this point. Indeed, these are some of the parameters chosen when exploring possible measures of runoff response, however, no relationship could be found to rainfall characteristics, leading to the conclusion of a surface control in this first stage of the soil response to rainfall, and dependent no doubt in part on the history of the surface at that point in time. In addition, the much greater differences between sites, or within one site, of crust removed than crusted treatments confirms the hypothesis that crusts mask variability in the underlying soil from which they were formed, which indicates the strong rainfall induced surface structural control on the runoff response, which is expressed not so much within one storm, but from the cumulative effect of several events and the cumulative energy which organises the surface over time from a non crusted state to, as in the case of Eldume, a very dense crust several cm thick. This also indicates that the relative importance of the surface response to wetting decreases as the surface becomes more and more impermeable over the course of crust development from a crust removed initial state. This is not to imply, however, that this is a linear process.

Considering now crust, as opposed to seal, development, which occurs in conjunction with wetting and drying cycles and in a non linear fashion on a between storm basis over the rainy season (as confirmed by monitoring plots under natural rainfall on the basis of energy free water acceptance as an indication of crust porosity) the cumulative energy of rainfall over a longer period is believed to be the operative variable in crust development. Note, however, that surface sealing cannot be unequivocally predicted from crust morphology, but must be measured locally as a functional response and displays considerable variability, as illustrated above for the crust.
type classified as ‘Sedimentary’ in the ‘Valentin’ system, at least in the case of the Baringo study area. This has important implications for the extrapolation of morphology – infiltration relationships identified in one crusted semi-arid environment to another. In short, it is recommended that a local campaign be developed if possible, at least to calibrate the relationships established elsewhere to local conditions.

In the case of crust-intact surfaces, it is postulated that the sealing and consequently the runoff response is a function primarily of rainfall energy, but specifically with an intensity-dependent response. In the case of low intensity events (= a low rate of both energy and moisture imparted to the surface), even with a sound reproduction of the kinetic energy of natural rainfall, the rapidity of the infiltration decline (‘Horton’s alpha’) was found to be much less than with higher intensity events. This is believed to be the result of the failure to exceed a threshold instantaneous energy required to overcome the effects of the energy imparted to the surface over the history of that surface, which is manifested as the structure of the crust, which is resistant to re-organisation. This was clearly illustrated in this study by the results of low drop height simulations and necessitated the development of the 3.5 m simulator.

Unlike with the ‘initial state = no antecedent crust’ scenario, in this conceptual model crust development does not continue in a progressive fashion consonant with cumulative energy over time; rather, from a given state of crust development, the relative impermeability of the surface may very well have substantially decreased by the end of a particular phase in the wetting-drying cycle, due to the reorganisation of the surface possible above a threshold energy. This threshold energy is undoubtedly a function of the surface (both the type of crust and the history thereof), however it was not possible to quantify this in the present study, but which would present a profitable opportunity for further research. As such, it is argued that the ‘wetting effect’ of the co-quanta of moisture-energy delivered to the surface as a raindrop of a given size and from a given height will dominate the runoff response for low intensity storms, whereas the instantaneous and to a lesser degree cumulative energy of rainfall dominate for higher intensity storms. Indeed, even after a considerably higher cumulative energy application, the maximum runoff yield at a given rainfall intensity on a given crusted surface with the 40 – 50 % instantaneous kinetic energy reproduction 1.5 m simulator rarely approached that of the 70% instantaneous kinetic energy reproduction 3.5 m simulator.
It is noted, however, that from the perspective of runoff, the response of interest in this study, the higher infiltration rate (maintained along the entire decay curve) at higher intensities for a given instantaneous energy, which is presumed to be due to the higher rate of energy application to the surface over time, ‘breaking’ and eroding the crust, and the accompanying loss of rainfall to a water harvesting system, is more than compensated for in terms of the absolute runoff yield compared to lower intensity storms, as the absolute quantity of rainfall input per unit time is much greater for higher intensity events (whilst the proportion of runoff per unit depth, or runoff ‘efficiency’, may be lower compared to an event of equivalent depth spread over a longer period at a lower intensity, as the surface remains largely undisturbed in such events). Thus it is important to know not just the spatial distribution of rainfall in an area under consideration for water harvesting, but also the temporal distribution, both within and between storms. Unfortunately, these data are rarely available.

Again, in terms of implications of this study for runoff yield, in the case of a short duration storm (or a short, intense, runoff producing burst), the time to runoff is important and this was observed to be strongly controlled by the time to sealing of the ubiquitous cracking in the surface area, which is characteristic of clay enriched sedimentary crusts (cracking is not observed below the crust layer). Thus, the dominant influence on runoff yield on such crusts may in fact be the rate of wetting rather than energy application in such a scenario; in short, a description of interest both in theoretical terms and in terms of the implications for water harvesting has been favoured in this study. This explains the recommendation of this study for the identification and use of a ‘hybrid’ parameter such as absolute infiltration rate / proportional instantaneous runoff at a common, process determined threshold such as the point of (approximate) steady state infiltration. In short, in order to manage runoff in crusted semi-arid environments for the purpose of water harvesting, both the dominant processes at work and a consideration of the use of the data collected must be considered when identifying relevant data collection and interpretation protocols.

Along the line of this argument, the ‘relative proportionality’ measure was used in Chapter 7, which is a measure of the degree to which the measured, subjective point of equi-finality (for logistical reasons, using rainfall simulation) approximates the theoretical end point at 10 hours of rainfall using the Phillips equation. These two measures of runoff potential were shown to be highly correlated, even though the rainfall simulations never exceeded 3 hours. As such, it can be confidently concluded that the finding of the non convergence of steady state infiltration holds true even after 600 minutes of rainfall at a variety of intensities, and thus that both the initial and
particularly final points on the infiltration curves are intensity dependent, in addition to being specific to the state of the surface at the time (literally, *etat du surface*). This was confirmed by the fact that the crust removed treatments rarely reached the same (as low) steady state infiltration rates as the crusted controls on the same soil type and location, even for the most intense events. Referring back to the proposed conceptual two stage within-storm model of seal development, hypothesised to explain these findings, the first stage is mainly surface controlled whilst the latter stage is mainly rainfall controlled.

The theme of the method, measure, model and observer dependence of the results of environmental investigations is a theme which has been repeatedly returned to over the course of this study. For example, in Chapter 4, in the systematic calibration of the principal instrument employed in this study, an 'Amsterdam-type drip-type' rainfall simulator, which has been widely used for soil erosion and related research, it was shown to have a much lower precision than appears to be assumed on the part of the user community. This, of course, can lead to misleading assessments of the runoff potential of a given surface (particularly in the case of the lack of substantial replication, as is typical with rainfall simulator usage in the field due to the time-consuming nature of this instrument). Two surfaces which appear to respond very differently to a standard rainfall treatment may in fact be responding to two different rainfall treatments.

Similarly, in Chapter 3, pains were taken to emphasis the great diversity and often contradictory findings with respect to the behaviour of the crusting and sealing soils most promising for water harvesting, and the definition (implicitly model) dependence of the results offered as an explanation above and beyond simple diversity in the physical environment to explain this. A good example of method dependence in the area of crust investigations was given by Bresson (1995) concerning the erosion crust evolutionary end-state almost inevitably induced by lengthy laboratory rainfall simulation studies in a quest to achieve a point of theoretical equi-finality in terms of infiltration. In reality, as was seen from the validation experiments carried out in the present study, crust and runoff inducing rainfall events are more typically short and of variable intensity. Whilst a constant intensity event renders more tractable the analysis of rainfall simulation results, and whilst one logical parameter with which to describe the interactions between rainfall and the soil surface is steady state infiltration, the point to be noted here is the observer dependence of both.
As such, the review of crusting and sealing soils in Chapter 3 was organised on the basis of the instrument type involved, be it a visual observation of structure or a "functional" approach (favoured in this study) using rainfall simulation. Indeed, it is precisely the linkage between process and pattern at a microscale and the parallel at field (several m²) scale which led Valentin, Boiffin and others to a realisation of the possibilities of characterising the former from the latter. The development of these ideas was reviewed in Chapter 5 together with extension thereof, with mixed results, to the scale observable (again, 'observer' dependent, in this case expressed as scale/resolution dependence) with satellite imagery.

An important example of method dependence which became apparent in the present research is the rainfall intensity dependence of runoff rankings of surfaces in the study area, clearly demonstrated in Chapter 7, which leads one to question the ability to separate the treatment from the response when a wide range of surfaces are to be evaluated in surveys for water harvesting assessment, when agricultural-station like replication is not likely to be carried out. In such a case the introduction of rapid tests which allow for replication is advocated, given a calibration against a reference value such a rainfall simulator with a sound reproduction of (instantaneous) kinetic energy might be an option, if an understanding of the limitations of the instrument are borne in mind.

In the face of the issues of both the instrument, treatment and parameter dependence of soil behaviour and the inherent complexity of the interactions between rainfall and the soil surface, both apparent from the preceding discussions, the triangulation interpretative framework proved useful in a number of ways. First-of-all, the use of a range of simple tests helped facilitate the development of a simplistic conceptual model which aims to render intelligible the complex responses of the surfaces assessed in terms of runoff potential. Secondly, these same tests allow us not just compared with a reference value, but the reference value itself in terms of the representativity of and variability around the dominant ESE (the ESE on which rainfall simulation was carried out) in the 200 x 200 m États de Surface around it. This allows for an assessment of the error bars in terms of the variability in infiltration characteristics at each site and hence the overlap and thus separability from the error bars at another site deemed, on the basis of the dominant ESE alone, to have a different runoff potential.

This in turn then facilitates the assessment of whether and to what degree each site can be considered, and over what area of integration, to be an internally homogenous hydrological
response unit at the resolution (including georeferencing errors) of a satellite pixel, for the purpose of upscaling from point hydrological measurements to runoff potential surfaces over an entire study area. No claim is made in the case of the present study of having achieved this with any degree of accuracy; indeed, this is difficult to validate. The final ranking of runoff potential over a landscape determined thus depends, of course, on many factors. These include (each related to various findings of the present work):

- the parameter chosen on which to compare runoff potential, which was shown to strongly influence the apparent runoff potential of any surface

- the type of rainfall simulator used, its precision, the protocol employed, the degree of replication

- the resolution of the imagery employed, the bands included and the classification algorithm and indices employed

- the density of observations in terms of ground verification

- the time the data are collected (due both to vegetation cover and to the less obvious effects of the history of each surface, where the crust is modelled to be a transient entity)

- the complementary data available with which to cross-check the findings (referring both to simple tests and to secondary data, where the latter, may in fact contradict each other due to the definitions and class limits employed, the scale and date of the survey, amongst other reasons)

- various other unexpected factors, such as baboon attacks on the validation plots, which influence the experimental results

In short, due both to the transient nature of the subject of study – the surface of the soil – and the sensitivity of this surface which renders it (to a much greater degree than with a traditional soil survey of subsurface properties) subject to the phenomenon of the ‘observer dependence’ of what is seen, the mapping of the spatially distributed nature of runoff potential in semi-arid environments must be approached with modest objectives. Modesty is important both
in terms of any attempt to quantify runoff yield, which must be accompanied with rigorous specification of the assumptions and conditions under which these values would hold true, and in terms of the temporal validity of the survey results. With respect to the latter, remote sensing offers a tantalising promise as a possible monitoring instrument, but the feasibility of this proposal is contingent both on the gap in (effective) resolution between the spectral unit and hydrological unit surveyed measured. From the findings of the present study, it can be concluded that, at the scale of *les Etats de Surfaces Elementaires*, one cannot clearly distinguish between hydrologically distinct surfaces on the basis of their spectral properties. At a coarser resolution, however, and in conjunction with an understanding of the topographically controlled distribution of *les Etats de Surface* and of the relationship between the ES’s and their constituent ESE’s, satellite imagery is extremely useful in painting a broad picture of the physiognomic units or (with sufficient resolution) the land facets therewithin.

There are many ways of linking a classification of a semi-arid landscape in hydrological terms to a classification of the same landscape in spectral terms; the relationship between them and the most suitable approach is related to the difference in resolution between the resolution of the instrument used to collect data on each. As such, a multi or trans scale approach based on the availability of low cost digital consumer cameras is suggested as a bridge between ground based and space based observations of the surface, and whilst relatively expensive to fly the equipment, offers the promise of a calibration between the high spatial resolution digital photography and the high spectral and temporal resolution satellite imagery, where the latter may then be used for monitoring purposes.

The likelihood of such an approach actually being taken up in a survey context for determining runoff potential for assessing water harvesting suitability, however, is subject to whether or not a ‘politically enabling environment’ exists for expensive environmental research. As such, it is not possible to divorce ‘purely’ ‘technical’ studies or interventions, such as maximising the availability of rainfall for some productive purpose in semi-arid areas, from the socio-economic and political realities within which this work takes place.


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