Geomorphic Response to Environmental Change: The Imprint of Deforestation and Agricultural Land Use on the Contemporary Landscape of the Pleiser Hügelland, Bonn, Germany

Dissertation

zur

Erlangung des Doktorgrads (Dr. rer. nat.)

der

Mathematisch-Naturwissenschaftlichen Fakultät

der

Rheinischen Friedrich-Wilhelms-Universität Bonn

vorgelegt von

Nicholas James Preston

aus

Wellington, New Zealand

Bonn, Mai 2001

Angefertigt mit Genehmigung der Mathematisch-Naturwissenschaftlichen Fakultät der Rheinischen Friedrich-Wilhelms-Universität Bonn

1. Referent: Professor Dr. Richard Dikau
2. Referent: Professor Dr. Armin Skowronek

Tag der Promotion: 11. September 2001

Preface

The submission of a doctoral dissertation represents the culmination of a period of often intense intellectual and personal development. Although personal, this development rarely occurs without substantial input from others. The document at hand, and the experience of the last 3½ years that it represents, are no exception, and I wish to take this opportunity to acknowledge the many people whose support and assistance I have been fortunate to receive.

Firstly, I wish to express my gratitude to Professor Dr. Richard Dikau. During the time I have spent as a member of his research group, I've learnt a great deal. I am grateful not only for his supervision of my doctoral study, but also for his making it at all possible. This dissertation represents part of a *Sonderforschungsbereich* research project – *Jungholozäne Reliefentwicklung in lößbedeckten Einzugsgebieten und ihre Modellierung*, aka "B15" – financed by the German Research Foundation. Employment within a research project of this nature is not common in New Zealand, and it provided me an opportunity for doctoral study that I might not otherwise have had. This, and the various other opportunities that Richard has offered me have been far greater than I could reasonably have expected when I first came to the European "unknown". My horizons have been expanded, and my appreciation of the nature of academic research has been greatly increased.

This dissertation represents only a small part of the research that was carried out within the B15 project. I have been fortunate enough to share the work with a number of students and research assistants involved in this project at various stages. My thanks to Marc-Oliver Löwner, Anja Feise, Thomas Parkner and Patrick Pilger, who chose to conduct their Diplom research within this project. My own work benefited immensely from their input. Thanks especially to MarcO for the stimulating discussions – I wish him all success with the continuation of this work. In addition, my thanks to Georg Pfeffer, Thomas Hoffmann, Ursula Davertzhofen, Marco Danscheid and Robert Jaksch for their various efforts in both field and/or laboratory. These last were employed within the B15 project; an extra vote of thanks is due to Kirsten von Elverfeld, Rainer Bell and Kalle Reitz who contributed to fieldwork "just for fun". And, of course, my thanks to Frau Mainz and Frau Schäfermeier – not only did they perform some of the laboratory analyses themselves, they also made it possible for those mentioned above to do so.

Luminescence dating was performed by Dr. Annette Kadereit at the Max-Planck-Institut für Kernphysik in Heidelberg, and by Dr. Barbara Mauz at the University of Bonn. My particular thanks to Barbara for delivering results under considerable time pressure, despite dealing with all the teething troubles inherent in the establishment of a new laboratory facility. ^{137}Cs concentrations were measured by Dr. Annette Kadereit, Dr. Regina Kalchgruber and Susanne Lindauer of the Max-Planck-Institut für Kernphysik in Heidelberg. ^{14}C ages were provided by Dr. Bernd Kromer of the University of Heidelberg.

There are a number of people to whom I wish especially to express my gratitude:

Firstly, Dr. Andreas Lang. My early discussions with Andreas struck a chord; his ideas both confirmed and further inspired my thoughts on the importance of human influences on the geomorphic landscape. His thorough understanding of the erosional history of this part of the world greatly contributed to my own. He was the ideal person with whom to discuss the relevant issues, and the influence of this is clearly reflected in this work. Beyond that, I value his friendship, and wish him all success with his future research – and hope to be involved with it!

My particular thanks to Jochen Schmidt, my colleague and contemporary within the *Sonderforschungsbereich* research programme. Without his considerable assistance, all of those little logistical details would have been infinitely more difficult. Although I suspect he doesn't realise how much, that assistance contributed a great deal to the maintenance of my sanity. Doctoral study is sometimes a lonely and introspective experience. Discussions with Jochen provided an opportunity to think beyond the confines of the task at hand, and to gain a better perspective of what we were doing, and why we were doing it. I wish him much success in the completion of his current research. I look forward to working further with him, and perhaps thereby having the opportunity of repaying his assistance in kind.

A special thanks to Dr. Thomas Glade for all his support, both professional and personal. Thomas, Ule, Christoph, Jona and Hannah helped to make my introduction to a new culture less traumatic, and provided a genuine sense of continuity and family during my first months in Bonn. I will always be deeply indebted to them.

Over and above the various other lessons and experiences I have learnt and gained in the course of the last 3½ years, meeting Anja Feise has been one of the highpoints. Geomorphology is interesting, but there is more to life than slopes and sediment storages. That has been perhaps one of the more important lessons I've learnt here. Her support and patience is very much appreciated – and I sincerely hope the late nights in the office are behind us.

My thanks to Andreas Lang, Anja Feise and Thomas Glade for their constructive criticism of the numerous versions of this manuscript. Their comments have greatly improved the text. The German language sections of this text were translated by Anja Feise, Andreas Lang and Barbara Mauz – and in no way reflect my own capabilities! Naturally, the responsibility for their correctness is mine however.

In addition to those already mentioned, I wish to thank all the members of the working group of Professor Dikau. Not only was this an intellectually stimulating environment in which to work, it was also *sehr gemütlich*. Meeting new people, learning about a different culture and gaining new perspectives was a valuable part of my time in Bonn. I thank the various people with whom I have had the privilege to know both professionally and privately. In particular, my thanks and appreciation for your patience with regard to language; more than three years later, and I'm still not a fluent German speaker. Your acceptance and understanding of my sometimes poor attempts at communication is very much appreciated – and I apologise for the terrible liberties I took with your language! During the time I spent in Germany a number of representatives of this working group travelled to New Zealand for various study-related purposes; I sincerely hope that this exchange programme continues, and I look forward to contributing to it from the "other side".

The support I received from family and friends in New Zealand is much appreciated; knowing that support was there was an inspiration. Thanks to Colin Walker for the happy coincidence of being in Europe for those times when I needed someone from "home" who understood how it is to be on the other side of the world and in an unfamiliar environment. My thanks to Mike Crozier, Professor of Geomorphology at Victoria University, for introducing me to the science of geomorphology, which has allowed me to both indulge and further develop an appreciation of natural landscapes. It was he and Dr. Kath Dickinson, formerly lecturer in Plant Ecology at

Victoria University, who first led me to believe that I could in fact undertake doctoral studies. And, at the other end of the process, my thanks to Dr. Noel Trustrum, of Landcare Research, who encouraged me with the thought that there might even be a tangible reward for the effort, thus inspiring me to get this thing finished!

The people mentioned here, and many more, have together contributed to what has been for me an immensely valuable experience, and there is therefore a degree of sadness in leaving. But, I will take with me many happy memories of my time in Bonn – it is not only geomorphic systems that retain the imprint of their past conditions.

My sincerest thanks to you all.

Vorwort

Die Abgabe einer Dissertation stellt den Höhepunkt einer Phase von häufig intensiver intellektueller und persönlicher Entwicklung dar. Obgleich persönlich, vollzieht sich diese Entwicklung selten ohne erheblichen Input von anderen. Das vorliegende Dokument und die Erfahrung der letzten 3½ Jahre, das es darstellt, sind keine Ausnahme, und ich möchte diese Gelegenheit wahrnehmen, den vielen Leute zu danken, von denen ich freundliche Hilfe und Unterstützung erhalten habe.

Als erstes möchte ich meine Dankbarkeit gegenüber Professor Dr. Richard Dikau ausdrücken. Während der Zeit, die ich als Mitglied in seiner Forschungsgruppe verbrachte, habe ich sehr viel gelernt. Ich bin ihm nicht nur für die Betreuung meiner Promotion dankbar, sondern auch dafür, daß er diese überhaupt möglich gemacht hat. Diese Dissertation stellt einen Teil des Forschungsprojektes des Sonderforschungsbereichs – Jungholozäne Reliefentwicklung in lößbedeckten Einzugsgebieten und ihre Modellierung, (oder einfach “B15”) – finanziert durch die Deutsche Forschungsgemeinschaft dar. Anstellung innerhalb eines solch Forschungsprojektes ist nicht etwas, das in Neuseeland üblich wäre, und sie bot mir die Möglichkeit zu einer Doktorarbeit, die ich anders nicht hätte durchführen können. Dieses und die vielen anderen Möglichkeiten, die Richard mir geboten hat, sind weit mehr als ich erahnen konnte, als ich vor 3 ½ Jahren dem europäischen “Unbekannten” zusteuerte. Mein Horizont ist weiter geworden, und meine Anerkennung für die akademischen Forschung ist gewachsen.

Diese Dissertation stellt nur einen kleinen Teil der Forschung dar, die innerhalb des Projektes B15 durchgeführt wurde. Ich schätze mich glücklich, die Arbeit mit einer Anzahl von Studenten und Forschungsassistenten habe teilen zu können, die in dieses Projekt in seinen verschiedenen Stadien beschäftigt waren. Mein Dank gilt Marc-Oliver Löwner, Anja Feise, Thomas Parkner, und Patrick Pilger die beschlossen hatten, ihre Diplomarbeiten innerhalb dieses Projektes zu schreiben. Meine eigene Arbeit profitierte unermeßlich von ihrem Input. Besonderen Dank schulde ich MarcO für die anregenden Diskussionen – ich wünsche ihm allen Erfolg mit der Fortsetzung dieser Arbeit. Außerdem gilt mein Dank Georg Pfeffer, Thomas Hoffmann, Ursula Davertzhofen, Marco Danscheid und Robert Jaksch für ihre verschiedenen Bemühungen im Gelände und/oder im Labor. Letztere wurden innerhalb des Projektes B15 als Hilfskräfte eingestellt; eine Extrastimme des Dankes geht an Kirsten von Elverfeld, Rainer Bell und Kalle Reitz, die freiwillig bei der Geländearbeit geholfen haben. Und, natürlich, meinen Dank an Frau Mainz und Frau Schäfermeier – sie haben nicht nur einige der Laboranalysen durchgeführt, sondern es auch einigen oben genannten Personen möglich gemacht, diese selber durchzuführen.

Die Lumineszenzdatierung wurde von Dr. Annette Kadereit am Max-Planck-Institut für Kernphysik in Heidelberg und vom Dr. Barbara Mauz an der Universität Bonn durchgeführt. Mein besonderer Dank geht an Barbara, die unter beträchtlichem Zeitdruck Ergebnisse bereitstellte, trotz der zeitraubenden Beschäftigungen, die bei der Einrichtung eines neuen Labors anfallen. Konzentrationen von Caesium-137 wurden vom Dr. Annette Kadereit, Dr. Regina Kalchgruber und Susanne Lindauer am Max-Planck-Institut für Kernphysik in Heidelberg gemessen. Karbon-14 Alter wurde von Dr. Bernd Kromer der Universität Heidelberg zur Verfügung gestellt.

Es gibt eine Reihe von Leuten, denen ich speziell meine Dankbarkeit ausdrücken möchte:

Zuerst, Dr. Andreas Lang. Bei meinen ersten Diskussionen mit Andreas platzte der Knoten; seine Ideen haben mich sowohl bestärkt als auch meine Gedanken zu der Bedeutung des menschlichen Einflusses auf die geomorphologische Landschaft weiter befruchtet. Sein profundes Verständnis der Erosionsgeschichte Mitteleuropas hat zu einem großen Teil zu meinem eigenen beigetragen. Er war ein geschätzter Gesprächspartner, um wissenschaftlich relevante Themen zu diskutieren und meine Arbeit hat sicherlich nicht zuletzt von diesen Diskussionen profitiert. Er ist aber weit mehr als das für mich – er ist zu einem guten Freund geworden. Ich wünsche ihm viel Erfolg für seine zukünftigen Forschung – und hoffe, in sie mit einbezogen zu werden!

Ein besonderer Dank geht auch an Jochen Schmidt, meinen Kollegen und Zeitgenossen innerhalb des Sonderforschungsbereichs. Ohne seine beträchtliche Hilfe wären all jene kleinen logistischen Details unendlich viel schwieriger gewesen. Obgleich ich vermute, daß er nicht weiß wieviel, hat diese Unterstützung sehr zur Wahrung meines Verstandes beigetragen. Eine Doktorarbeit ist manchmal eine einsame introspektive Erfahrung. Diskussionen mit Jochen boten eine Gelegenheit, über die Grenzen der anstehenden Aufgabe hinaus zu denken, und eine bessere Perspektive von dem zu gewinnen, was wir taten und warum wir es taten. Ich wünsche ihm viel Erfolg für den Abschluß seiner laufenden Forschung. Ich würde mich freuen, weiter mit ihm zusammenzuarbeiten und möglicherweise dabei die Gelegenheit zu erhalten, mich für seine Unterstützung zu revanchieren.

Ein spezieller Dank an Dr. Thomas Glade für seinen ganzen Support, sowohl professionell als auch persönlich. Thomas, Ule, Christoph, Jona und Hannah halfen, meine Einführung in eine neue Kultur weniger traumatisch zu gestalten und mir ein echtes Gefühl der Kontinuität und der Familie während meiner ersten Monate in Bonn zu geben. Ich werde Ihnen immer tief verschuldet bleiben.

Über die Erfahrungen der letzten 3½ Jahre hinaus, war mir am schönsten Anja Feise kennenzulernen. Sicher ist die Geomorphologie interessant, aber es gibt mehr in diese Welt als Hänge und Sedimentspeichern. Von was ich hier gelernt habe, ist das vielleicht am wichtigsten. Ich bedanke mich bei Anja für ihre Geduld und Unterstützung – ich hoffe wirklich, das die „Büroabends" sind jetzt vorbei.

Mein Dank an Andreas Lang, Anja Feise und Thomas Glade für Ihre konstruktive Kritik zu den zahlreichen Entwürfen dieses Manuskriptes. Ihre Kommentare haben viel zur Verbesserung dieses Textes beigetragen. Die Übersetzung der deutschsprachiger Teile dieses Manuskriptes wurden von Anja Feise, Andreas Lang und Barbara Mauz gemacht (aber, leider nicht ein paar von der Absätze Sie jetzt lesen!) – und sollen auf keinen Fall als Zeichnung meiner Fähigkeit in diese Sinne zu sehen! Natürlich, aber, bleibt die Verantwortlichkeit für den Inhalt bei mir.

Zusätzlich zu den bereits erwähnten Personen, möchte ich allen Mitgliedern der Arbeitsgruppe von Professor Dikau danken. Es war ein nicht nur intellektuell anregendes Klima zu arbeiten, es war auch sehr gemütlich. Neue Leute zu treffen, das Lernen über eine andere Kultur und die Gewinnung von neuen Perspektiven waren ein wertvoller Teil meiner Zeit in Bonn. Ich danke den verschiedenen Leuten, mit denen ich das Privileg hatte zu arbeiten und zu feiern. Insbesondere gilt mein Dank und meine Anerkennung Eurer Geduld hinsichtlich der Sprache; mehr als drei Jahre später und ich bin noch immer kein fließender Deutschsprecher. Eure Akzeptanz und Euer Verständnis für meine manchmal schwachen Versuche zu kommunizieren habe ich sehr geschätzt – und ich entschuldige mich für die schrecklichen Freiheiten, die ich Eurer Sprache angetan habe! Während der Zeit, die ich in Deutschland verbrachte, reisten eine Anzahl von Vertretern dieser Arbeitsgruppe nach Neuseeland aus den verschiedensten studienrelevanten Gründen; ich hoffe aufrichtig, daß dieses Austauschprogramm fortdauert, und ich freue mich, hierzu von der "anderen Seite" beizutragen.

Die Unterstützung, die ich von der Familie und Freunden in Neuseeland erhalten habe, wurde hoch geschätzt; das Wissen, daß dieser Support da war, war eine Inspiration. Danke dem Wanderer Colin für die glückliche Übereinstimmung seines Aufenthaltes in Europa während jener Zeiten, in denen ich jemanden "von zu Hause" benötigte, der verstand, wie es ist auf der anderen Seite der Welt und in einer nicht vertrauten Umgebung zu sein. Meinen Dank an Mike Crozier, Professor für Geomorphologie an der Victoria University, der mich in die Wissenschaft der Geomorphologie einführte, was mir erlaubt hat, mich dafür zu begeistern und eine größere Anerkennung für die natürlichen Landschaften zu entwickeln. Es waren er und Dr. Kath Dickinson, frühere Dozentin für Pflanzenökologie an der Victoria University, die mich zuerst überzeugten, daß ich tatsächlich eine Doktorarbeit aufnehmen könnte. Und, am anderen Ende des Prozesses, endet mein Dank bei Dr. Noel Trustrum (Landcare Research), der mich durch die Vorstellung, daß es sogar eine reale Belohnung für die Anstrengungen geben könnte, ermutigte und mich so anspornte, diese Sache zu beenden.

Die Leute, die hier erwähnt werden, und viele mehr, haben gemeinsam zu einer für mich unermeßlich wertvollen Erfahrung beigetragen, und ich bin daher etwas traurig jetzt Abschied zu nehmen. Aber, ich nehme viele glückliche Erinnerungen an meine Zeit in Bonn mit – es sind nicht nur geomorphologische Systeme, die ihre Vergangenheit widerspiegeln.

Meinen herzlichen Dank an alle!

Table of Contents

List of Figures

List of Tables

Chapter 1
Introduction

1.1 Background and Rationale

The fertile loess-covered hill country of central Europe has in many areas been subjected to continuous agricultural land use for several millennia (e.g. BORK *et al*. 1998, LANG & HÖNSCHEIDT 1999, LANG *et al*. 2000, in press). Deforestation and the introduction of agriculture to a previously undisturbed environment represented not only a perturbation to the physical landscape system, but a shift to a qualitatively different landscape system, one in which the inadvertent and unintentional production and redistribution of sediment has consequences for both further land use and for the morphological development of the landscape.

HOOKE (2000) argues convincingly that humans have become significant geomorphic agents, moving considerable volumes of material, both intentionally through mining and engineering, and inadvertently through agriculture. As the proportion of the global population dependent on agriculture increased from the beginnings of the Neolithic agricultural revolution, the generation of sediment per capita has steadily increased. To some extent this has decreased again in the last two millennia as alternative economies have developed. This has been especially true in recent decades with improved agricultural techniques – at least in the developed world. Nevertheless, with absolute population increases and the extension of agricultural activity into degraded and unsuitable areas, the total volume of sediment generated by agriculture has increased exponentially (HOOKE 2000). VAN ROMPAEY *et al*. (in press) have investigated the effects of 250 years of variation in land use in the central Belgian loam belt, and concluded that even relatively limited land use change can have a significant effect on regional soil erosion rates and sediment delivery to channels.

PHILLIPS (1997) discusses the significance of human agency – specifically, deforestation and land use change – as a landforming factor. He concludes that rates of sedimentation on the coastal plains of North Carolina following land use change are orders of magnitude greater than background Holocene rates, and that therefore this sedimentation is a phenomenon that should be considered independently of variation in Holocene rates. The geomorphic impacts of deforestation are fundamentally different dependent on what happens next. If there is no subsequent land use change, and the landscape is allowed to naturally revert, PHILLIPS (1997) defines the deforestation event as an external perturbation, and the system quickly relaxes in terms of a return to previous runoff and erosion rates. Alternatively, if agricultural land use follows deforestation, this represents a fundamental internal change to the system, which does not – or is not allowed to – relax.

The introduction of agriculture represents a fundamental change to the landscape through the removal of protective forest cover, altering its internal structure and its potential for response to external impulses or forcing processes, i.e. perturbations. Two significant geomorphic consequences follow from this change. Firstly, the sensitivity of soils to erosion induced by rainfall-runoff events is altered and the rainfall threshold for erosion initiation is considerably reduced. Thus, although the frequency/magnitude distribution of rainfall itself does not change, the relationship between rainfall and runoff, and, more importantly, the geomorphic effectiveness of these events is affected. Secondly, agricultural land use itself, i.e. tillage, represents a new geomorphic process operating on the soil system. These two principal process types to which the soil landscape is subject following environmental change are of a fundamentally different nature and produce different process responses. Application of the plough is a regular perturbation, and results in the mechanical displacement of surface soils. Although of high frequency, the magnitude of the perturbation and process response is low, with small volumes of material moved over short distances. Unprotected ploughed surfaces can also experience low magnitude process responses to rainfall events, in the form of rainsplash displacement. Tillage thus produces, both directly and indirectly, diffusive soil erosion and redistribution. While rainfall-runoff events are not uncommon, most are of low magnitude and have minimal geomorphic effect. Of greater significance are the less frequent high magnitude events that generate surface runoff and process responses in the form of rilling and gullying. These different process responses – diffusive soil erosion and linear erosion – produce different morphological responses. Nevertheless, the overall effect is the generation and redistribution of sediment.

This response to environmental change – put very simply, the increase in erosional redistribution of sediment throughout the landscape – has important implications for the sustainability of land use, for the design of engineering infrastructure, for contamination of waters and aquatic environments through sediment itself and as a result of associated particulate fluxes, for landform development, and for prognoses of all of these phenomena under changing climate and land use scenarios. Of particular interest, therefore, is a greater understanding of the relative significance of climatic and anthropogenic influences on the behaviour of geomorphic systems. This is important as we attempt to manage and to modify our activities so as to avoid, or at least minimise, adverse impacts on the landscape. The need to determine the relative contributions of climate and land use in influencing the condition and behaviour of the physical environment is thus a contemporary research issue (WASSON 1996).

Research in Germany into soil erosion phenomena has a long history, dating back to at least the 19th century. PENGNAN (1994) provides a comprehensive review of this research. In particular there has been extensive discussion of the significance of land use in comparison to extreme meteorological events in producing enhanced rates of erosion (e.g. HARD 1970, BORK 1983, 1989a,b, BLAIKIE & BROOKFIELD 1987, BORK *et al*. 1998). Looked at from one perspective, this discussion might be seen as one of two competing hypotheses – one arguing that climate has been the strongest influence on rates of erosion, the other that anthropogenic landscape modification is of greater significance and must be taken into account. These are in fact not competing hypotheses; there is room for both to be accepted. While there is impressive evidence linking catastrophic erosion events to meteorological events, it is also undoubtedly true that human agency has influenced erosion rates and has had a clear morphological impact on the physical landscape. Indeed, small-scale landforms that are typical of anthropogenically dominated areas have been extensively documented (e.g. HEMPEL 1954a, RICHTER 1965, RICHTER & SPERLING 1967, LINKE 1976). However, considerably less attention has been given to systematic investigation, i.e. the consideration of geomorphic responses to environmental change within the framework of a geomorphic systems analysis. In part, at least, this is a reflection of the dominance in the latter half of the 20th century of process-oriented studies within geomorphology.

Much recent and contemporary research into erosional phenomena and their likely future behaviour has focussed on model development, and especially on the physical process itself (see, for example, BOARDMAN & FAVIS-MORTLOCK 1998a). However, the relationship between process behaviour and morphological response is far from simple. Issues of landform scale (spatial and temporal), landscape sensitivity and variation in frequency/magnitude/effectiveness of process behaviour influence the behaviour of the sediment flux and thus of the various phenomena that it in turn controls. It is thus important that we learn to interpret landscapes in an historical sense, so that we may gain some understanding of their possible future behaviour (WASSON 1994).

SEMMEL (1996) dismisses the view that only through sophisticated understanding of processes, and their representation in models, can we address applied issues. He argues that understanding of temporal development is also essential in this regard, and advocates the "historic-genetic" approach as an often easier and cheaper means of understanding landscapes than measurement and modelling exercises. Both the so-called historic-genetic approach and modelling approaches have their virtues. Although "real" and empirical, the evidence available in the landscape is almost never complete, and is susceptible to subjective interpretation. Because system behaviour does change through time it is important that we gain some understanding of how this happens. On the other hand, if we wish to speculate about future behaviour or extrapolate past trends into the future, we need some model on which to base this. Thus, placing landforms in an historical context is important, as is understanding of the processes that are active in the landscape (or have in the past been active!). It is important to model process behaviour – *but this must be consistent with the behaviour of landscapes as geomorphic systems*. This implies not only an understanding of the issues referred to in the preceding paragraph, but also – as this thesis attempts to demonstrate – more recently recognised phenomena relating to the spatial aspects and configuration of geomorphic systems.

1.2 Hypotheses and Aims

This work deals fundamentally with questions that relate to the behaviour of geomorphic systems in response to environmental change. The relevant questions can be summarised as:

- What was the nature of environmental change?
- How has this changed the landscape system?
- What has been the geomorphic response to environmental change?
- Given that there has been the introduction of a new process, i.e. tillage, to the landscape system, what are the implications of the interaction between processes for system behaviour? In other words, what is the implication of environmental change for longer term landform evolution?
- Has environmental change caused a shift in the nature of landform development?

This thesis investigates geomorphic responses to land use change in loess-covered agricultural hill country. The response to land use change is characterised for three sites within the Pleiser Hügelland study area that represent different system scales (i.e. a zero order single slope, an unchannelled first order basin, and a second order headwater catchment). The initial aim is to identify and distinguish between geomorphic responses to climatic and land use perturbations. The extent to which these morphological responses remain as a part of the contemporary landscape should enable assessment of the relative contributions of land use and climate to landform development, and an elucidation of the geomorphic response to environmental change.

Specific aims include:

- the development of a sedimentation chronology on the basis of a range of dating techniques, i.e. optical luminescence and the use of the radionuclide Caesium-137 as a temporal marker
- the use of this temporal information in the development of historical sediment budgets for discrete spatial landscape elements

In pursuit of these aims, a number of hypotheses will be tested:

1. *That two different processes have been active in the landscape, and have left morphological evidence of their occurrence*. It is not necessary to demonstrate that these are the result of environmental change – only that there have indeed been different processes.

2. *That human influences, i.e. tillage, dominate the landscape*. This hypothesis is based on the speculation that the frequency/magnitude spectra of the two dominant processes is such that the less spectacular but more frequent tillage process is more geomorphically effective.

3. *That characterisation of geomorphic response to environmental change depends on systematic scale*. An important point is that a systematic perspective must be retained, including the influence of time and – especially – space. Thus, based on the concept of system configuration clearly expressed by LANE & RICHARDS (1997), there will be different geomorphic responses in different parts of the landscape, and their characterisation needs to explicitly recognise this.

A supplementary aim relates to the development of models for both assessing the behaviour of geomorphic systems and for reconstructing landform evolution. The development of a numerical model itself is beyond the scope of this work. Nevertheless, an important aspect of model development is the establishment of a genuine empirical database (DIKAU 1999). This study aims to provide at least the beginnings of this. Secondly, and more importantly, models need a sound conceptual base; it is thus an aim of this work to demonstrate the appropriate direction in which modelling efforts might most profitably continue.

1.3 Thesis Structure

The conceptual and scientific foundations of this work are introduced in Chapter Two. The nature of environmental change is described, both in general and in systematic terms. This is followed by a selected review of international and German research into historical erosion phenomena. The various aspects of geomorphic theory that are relevant to this work are reviewed. These provide the framework for the concluding section of Chapter Two, in which their application in addressing the aims of this work is assessed – and specifically the theoretical basis of this work is presented. The study area is described in Chapter Three, with a focus on characterising the Pleiser Hügelland region (i.e. climate, geology and landforms, soils). The history of human occupation is discussed, along with the evidence for deforestation and the introduction of agriculture. Previous research into the historical soil erosion phenomenon within the study area itself is also reviewed here. Chapter Four focuses on methodology. The research design employed in this work is outlined, and specific descriptions of the techniques applied are given, including the use of ^{137}Cs and a brief review of optically stimulated luminescence as a technique for the dating of sedimentary phenomena. The individual study sites (Auf dem Scheid, Forstbach, Heiderhof) are described in more detail in Chapter Five, and the results of investigations in each, ordered geographically, are presented. Discussion of these results follows in Chapter Six. The principal focus is on the importance of the interaction between the frequency/magnitude/effectiveness of process behaviour and the role played by configurational aspects of geomorphic systems. The implications of results are assessed and conclusions drawn in Chapter Seven, and the hypotheses are evaluated. Following this, there is a brief discussion of further research needs that can be identified as a consequence of the conclusions drawn here. Particular emphasis is given to the need for modelling the regional sediment flux, rather than individual processes, and with a strong focus on landscape configuration.

Although this research was conducted in Germany and addresses issues that have, at least in some respects, been dealt with extensively in the German language literature, this dissertation is written in English by a native speaker. It is therefore appropriate to make some brief comment concerning terminology. With respect to erosional phenomena, there are a number of terms that appear similar or identical in both German and English, but are attributed with subtle – and sometimes not so subtle – differences in meaning. Terms such as *erosion* and *colluvium* are used essentially in the English language sense. In the interests of avoiding confusion, their usage in this text is defined as follows:

Erosion:	The entrainment and transport of soil and sediment. This may occur through a range of different geomorphic processes, any of which can be used to qualify the word erosion, e.g. rainsplash erosion, gully erosion, mass movement erosion, ... Tillage therefore also causes erosion, but will be referred to here as *tillage translocation* simply for consistency with contemporary geomorphic literature. *Water erosion* is used here to refer to the combined erosional effects of diffusive water impact and flow.
Denudation:	This is specifically independent of process, and describes the combined effect of all erosional processes that have occurred. It is thus generally applied more in a regional context.
Deposition:	The settlement of material out of transport.
Accumulation:	The effect of deposition.
Colluviation:	Strictly speaking, this term is more appropriately used only for gravitational processes that *may* involve water. However, much of what is described in this text as colluviation actually refers to either or both water erosion and tillage translocation. The key implication of its use is the distinction between slope derived material and channel derived material. Hence, the appropriate definition here is: the combined effect of erosional processes transferring material *within and from slopes*. [also: colluvium, colluvial]

Specifically, the use of none of these words is intended to imply human causation, as with the German *Bodenerosion*. In all cases, these terms relate simply to the physical fact of sediment movement. Where human agency is to be invoked, the adjective *anthropogenic* (or similar) is used. The term *soil erosion* is avoided, other than in the review of literature, principally for this reason.

The Anglo-Saxon usage of commas and periods for separation of numbers has been applied, e.g.:

One thousand is expressed as:	1,000
One thousandth is expressed as:	0.001

I realise this may lead to some frustration among readers more familiar with the European system. But 1.234,56 just doesn't seem right within an English language text. Sorry!

Chapter 2

Geomorphic Response to Environmental Change

2.1 Introduction

This chapter outlines the conceptual and theoretical context of this study. In its first section, the nature of the environmental change is described, both specifically and in terms of the landscape as a system. The remainder of this chapter deals with the geomorphological analysis of environmental change. Selected studies of geomorphic response to environmental change are reviewed. While much research focuses on the landforms that have eventuated as a result of erosional processes, consideration must also be given to the long-term geomorphic consequences of these for the whole landscape. This is a different issue and requires consideration of various aspects of geomorphic theory; issues pertinent to systematic geomorphological analysis are discussed. Conventionally geomorphology has sought to characterise geomorphic response to changes in environmental conditions through the identification of equilibrium landforms associated with characteristic controlling conditions. In this context, the investigation of geomorphic response to change in controlling conditions seeks to identify whether a landscape is in equilibrium with contemporary controls or, if this is not the case, to assess how far it is from an equilibrium state. In recent years, however, a number of authors have argued that this paradigm is perhaps somewhat simplistic, if not in fact obsolete. Non-linear dynamics and configurational issues are becoming increasingly important in attempts to gain deeper understanding of the behaviour of geomorphic systems. Both traditional equilibrium theories and the newer ideas are reviewed here. The concluding section of this chapter builds on the concepts previously introduced, and defines the theoretical and conceptual tools that are developed and applied in this study.

2.2 Geomorphic Landscapes and Environmental Change

In this section the nature of environmental change is described in systematic terms. Firstly, systematic conceptions of geomorphological phenomena are briefly reviewed. The "natural" condition of the landscape system is then characterised, followed by a description of the way in which this system was changed. Lastly, the consequences of that change are outlined, and a revised characterisation of the post-environmental change landscape system is presented. (A detailed description of the study area follows in Chapter Three.)

2.2.1 The Landscape as a System

Geomorphic landscape systems comprise a number of physical components, including their underlying lithology, soils, vegetation, water, fauna, and the landform assemblage that these form in their entirety. Depending on the scale of interest, various of these components may be considered as dynamic elements of the system, subject to variation, and others as external boundary conditions (SCHUMM & LICHTY 1965). In addition, landscape systems are subject to energy inputs and the application of force through a range of geomorphic processes. As with the physical components of the landscape, some energy inputs may be regarded as a part of the system's boundary condition, while others act dynamically within the system. Given sufficient time, the internal elements of the system may achieve an equilibrium state in which the form of the internal physical components is adjusted to the prevailing energy regime. CHORLEY &

KENNEDY (1971) present a scheme for the conceptualisation of systems relevant to physical geography (Fig. 2.1). The simplest of these – the *morphological* system – is defined by the correlation between material and morphological properties. A higher level of complexity is represented by *cascading* systems, which are characterised by the transfer of mass and/or energy through a series of sub-systems. The scale of cascading systems is extremely variable; the hydrological cycle in its entirety, for example, is a cascading system, as is a simple headwater basin comprised of a series of colluvial storage sites. Cascading systems have both inputs and outputs, and generally involve some form of decision regulator which determines the manner in which input is transformed into output (e.g. storage of matter or energy within the sub-system, or its diversion to one of various alternative downstream sub-systems). Of greatest importance at landscape scales are *process-response* systems – defined as the combination of morphological and cascading systems, i.e. morphological systems linked by their throughput of mass and/or energy. The common link is generally in the form of an element of a morphological system that operates as a decision regulator within a cascade. An important aspect of process-response systems is the feedback between individual properties or components, and the degree to which change in one element of the system demands corresponding adjustment in others. Finally, *control* systems can be defined as process-response systems in which certain key elements exert considerable control over system behaviour. A further system type within this framework was introduced by SLAYMAKER (1991) as a *morphologic evolutionary* system. Time is inherent in such a system, which is defined as the transition of a morphological system from one state to another. While landform development is clearly such a transition, some mechanism is still required to effect that transition. It is thought that the typology offered by CHORLEY & KENNEDY (1971) is sufficient for representing the change in landscape resulting from environmental change as discussed here. The nature of the landscape system and the significance of environmental change will be discussed within this systematic context in the following sections.

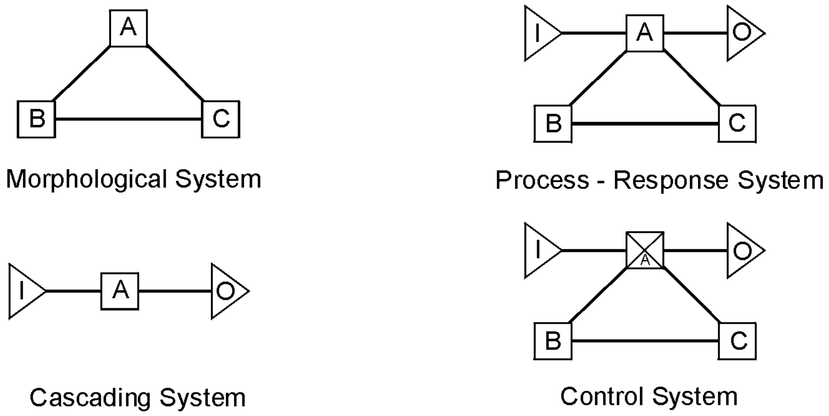


Figure 2.1: Schematic representation of system types (CHORLEY & KENNEDY 1971).

2.2.2 The Undisturbed Landscape

This study focuses on an anthropogenic change to the landscape system that occurred at least ~1,200 years ago, and possibly as much as ~4,000 years ago (see Chapter Three for discussion of land use change in the Pleiser Hügelland). The period covered is thus the late Holocene, with a temporal scale on the order of several thousand years. Although the environmental change dealt with here was regional in its extent, for pragmatic purposes the spatial scale is limited to landscape elements characterised as low order drainage basins (zero to second order). More pertinently, this spatial scale is considered to be appropriate for assessing the effect on landform of an environmental change over this temporal scale. There is a strong correlation between landform magnitude and both its duration/persistence/longevity and the time over which it develops (AHNERT 1981, BRUNSDEN 1993a). The landforms that are sensitive to processes that vary over this time period – and especially, that are influenced by a change in vegetation cover – are the slopes and channels of low order drainage basins (Fig. 2.2).

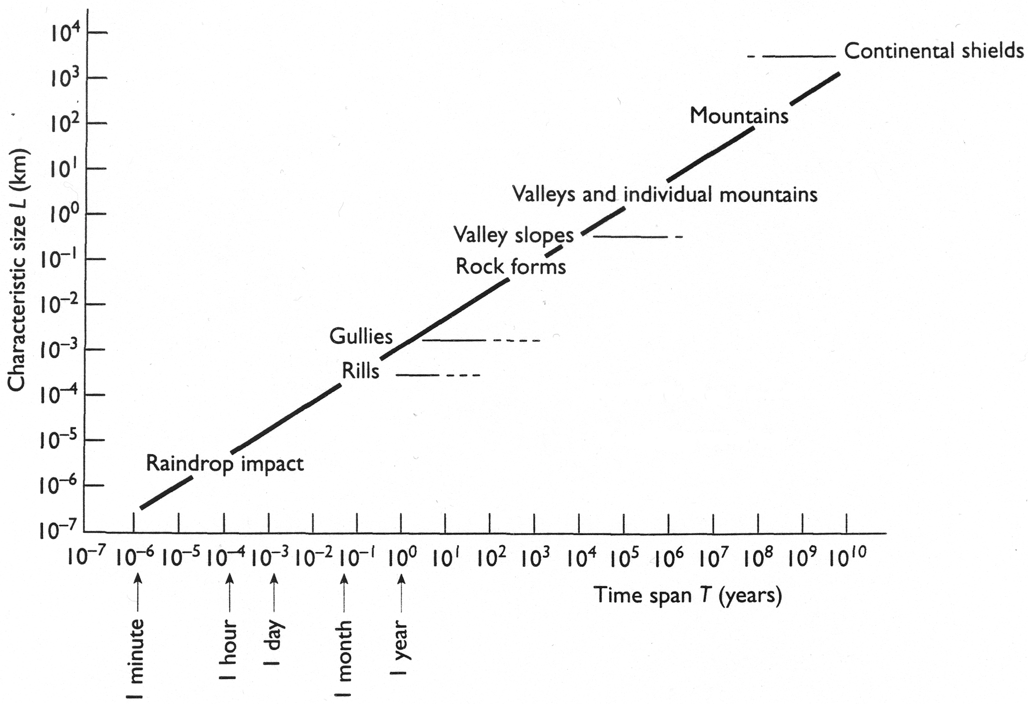


Figure 2.2:. Spatial and temporal hierarchy of landforms (adapted from AHNERT 1996).

Changes in the landscape as a result of the temporal variation in lithology and tectonic activity are not considered. Lithology varies in space, even within such small areas, but it is not subject to variation within the period of interest. While tectonic activity may certainly occur within a period of some thousands of years, its effects are considered to be uniform for all elements of a low order drainage system. Nor is the effect of climatic change as represented by the transition from the colder Pleistocene to the warmer and humid Holocene included. While climate exhibits natural stochastic variation, this is about constant mean values. These factors – geology and a humid temperate Holocene climate – are considered to be part of the system's external boundary conditions. The physical components that are internal to this system thus include soils, vegetation and the landform itself. Two sources of energy are available within this system. The relief of the landscape represents an inherent source of potential energy capable of driving gravitational processes. Kinetic energy is derived from meteorological phenomena (principally precipitation, but also wind) which act as forcing processes for both gravitational and aquatic processes. The material and morphological properties of the individual landforms represent a series of morphological systems, formed by and linked by the transfer of energy and matter (both water and debris) through the drainage network cascade. Because it is the transfer of matter and energy through this cascade that determines the morphological and material properties of the landforms, this landscape is clearly a process-response system. The role of decision regulators within this system is played by spatial properties such as drainage density, basin storage potential and slope/channel coupling (see below). Within this mature natural landscape system vegetation, soils and landforms were more-or-less in dynamic equilibrium with the existing energy regime. The late Holocene – prior to human changes – was a period defined by ROHDENBURG (1971) as one of geomorphic stability, with relatively low rates of geomorphic process behaviour. The forest vegetation played an important role in maintaining this period of quiescence. Vegetation provides both mechanical stability to soils and slopes and has an ameliorating and damping effect on the hydrological cycle through interception and evapotranspiration (SIDLE 1985, GREENWAY 1987). The forest vegetation was therefore an integral component of the system, influencing pedogenesis and providing resistance to both gravitational and aquatic geomorphic processes, and in fact can be seen as a key variable within a control system.

2.2.3 Environmental Change and its Consequences

The primary anthropogenic change to this system (i.e. not counting more recent engineering works) was the widespread removal of forest vegetation. Lithology and geological structure were not themselves changed, and tectonic activity continues at the same average rate. Nor did anthropogenic change involve direct modification of the prevailing Holocene climate which remains the same, notwithstanding natural stochastic variation. The external physical components of the system thus remain as boundary conditions, as does the energy inherent within and entering the system. However, deforestation represented a significant change in the state of one of the system's internal components, the consequences of which are reflected in changes in those other system components that are related to it.

The process of deforestation itself involves a degree of mechanical displacement of soil, and may indeed also involve burning of large areas with a consequent impact on soil properties. From a longer temporal perspective, this change has more pervasive effects on the nature of the landscape system. With deforestation the protection from direct precipitation receipt afforded to soils by a dense forest cover is no longer present. A direct consequence of this loss of interception potential is that the energy contained within rainfall impacts directly on bare soils, inducing mechanical displacement, i.e. splash erosion. Further, the reduction in both interception and evapotranspiration means that more moisture enters the soil hydrological cycle. Precipitation receipt may exceed the soils' infiltration capacity, resulting in surface runoff and thus a greater likelihood of linear erosion (rills and gullies). Surface sealing can also result from direct raindrop impact with similar consequences for enhanced overland flow. Increased receipt of precipitation at the soil surface alters the soil hydrological system and has an influence on subsequent pedogenesis. Where volumes of water entering the soil exceed its drainage capacity, saturation and the development of pseudogley soils can occur. This reduces infiltration and drainage capacities still further, ultimately also leading to increased surface runoff. Alternatively, where soils are well-drained and able to absorb increased volumes of infiltrating water, with certain conditions of soil texture and throughflow velocity the development of subterranean pipes can occur, potentially leading to gully formation. Through enhanced erosional and fluvial activity, the expected effect of deforestation for the morphological landscape is thus an increase in drainage density, an increase in both slope and channel gradients, but – after initial local increases – a general decrease in relief. STRAHLER (1958) demonstrated that when such a transformation is complete, and if a new equilibrium state is achieved, this will be characterised by a different set of landforms adjusted to a greater flow of energy and matter.

Environmental change did not involve only the removal of forest vegetation; the purpose of deforestation was the introduction of agriculture. Forest was replaced by grassland and especially by crops. The change in vegetation was thus a lasting alteration to the system. In particular cropland is maintained in a constant state of renewed disturbance. In this respect, vegetation is clearly a controlling variable, and agricultural landscapes are control rather than process-response systems. More importantly, the regular application of the plough represents an entirely new process and source of energy that had not previously been a part of the system (Fig. 2.3). The importance of tillage as a medium of sediment generation and redistribution is emphasised by, for example, GOVERS *et al*. (1994, 1996) and QUINE *et al*. (1997). The post-environmental change landscape is thus characterised by two different processes, that occur with fundamentally different frequencies and magnitudes (Fig. 2.3). Tillage occurs regularly, with little variation in magnitude, which is low for individual events, but may be quite significant when the cumulative effect of many events is considered. By contrast, the second process – rainfall-runoff – varies markedly in its frequency/magnitude spectrum. Many small events will have no effect, while some very large events may move more sediment in a single event than the cumulative effect of years of tillage.

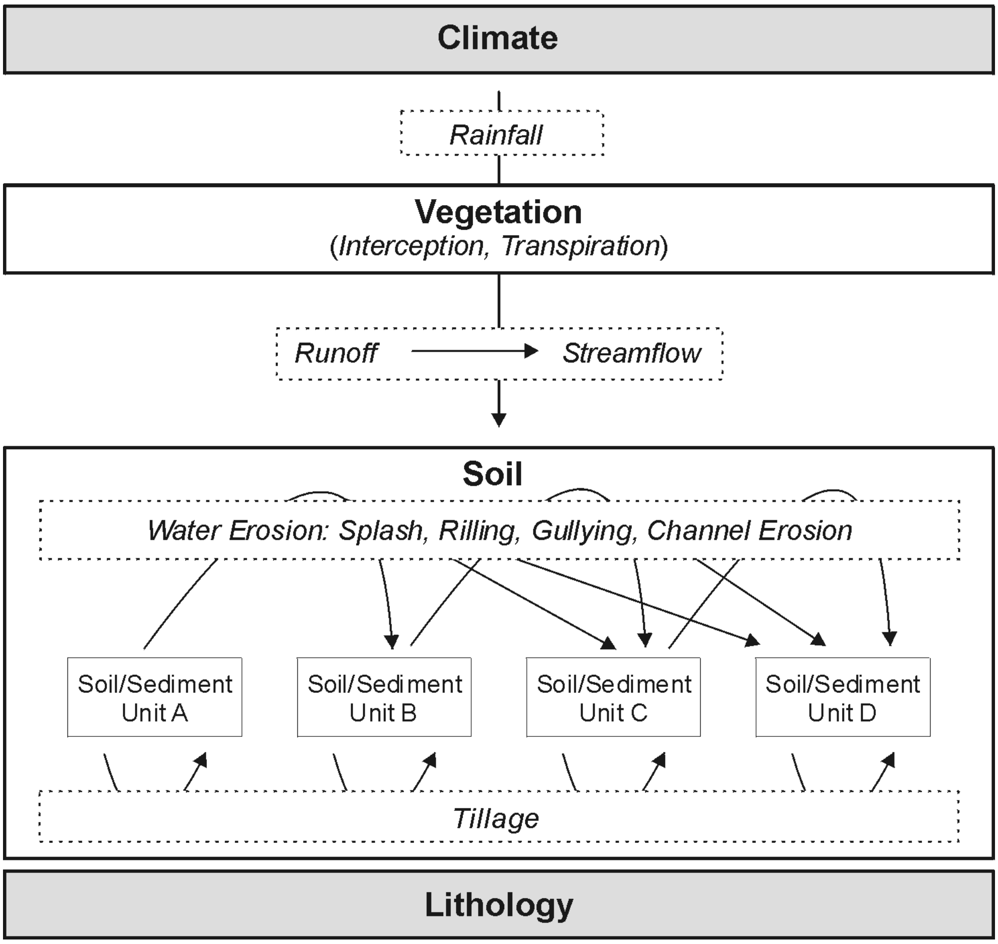


Figure 2.3: Flow chart representing the principal processes involved within the landscape system. Physical components of the system are in solid rectangles, while dashed line rectangles represent processes, which are also italicised. Lithology and climate play an external role within the soil system at this scale of consideration. Vegetation plays a crucial role in regulating the relationship between rainfall and runoff/streamflow. Arrows within the soil system represent the combined action of sediment entrainment, transport and deposition. Water erosion processes are capable of entraining material from all soil/sediment units and transporting this to any of multiple downstream depositional sites. Tillage is causally independent of the climate/vegetation/soil complex, and itself usually redistributes material within the same soil/sediment unit.

Together, these changes lead to increased generation of sediment, and the redistribution of this throughout the landscape. In turn this has consequences for the development of individual landform elements, and for the development of the landscape as a whole. The change in the system is summarised in Figure 2.4. Prior to deforestation slope morphology in many cases broadly reflected inherited Pleistocene forms, and exhibited a catenary distribution of soils which were largely undisturbed, reflecting a balance in the interaction between the various pedogenetic factors. After deforestation and the subsequent mobilisation of soils in the form of sediment, slope morphology has been altered. Relief has been reduced with the removal of soil from upslope areas and deposition of sediment in topographic sinks. This change is represented schematically in Figure 2.4(b) as a change in storage. Prior to change, the soil storage can be considered to have been full, i.e. the volume of soil represents the totality of potential storage of material. At the same time, there were topographically defined potential stores of material throughout the landscape. Although empty at that stage, such topographic lows represented potential sinks for deposition and storage. The redistribution of soil and sediment following deforestation has changed the relative distribution of material in these storage units. Where soils have been eroded, the volume of material in storage has decreased; where deposition has occurred, part of the available potential storage is now being utilised.

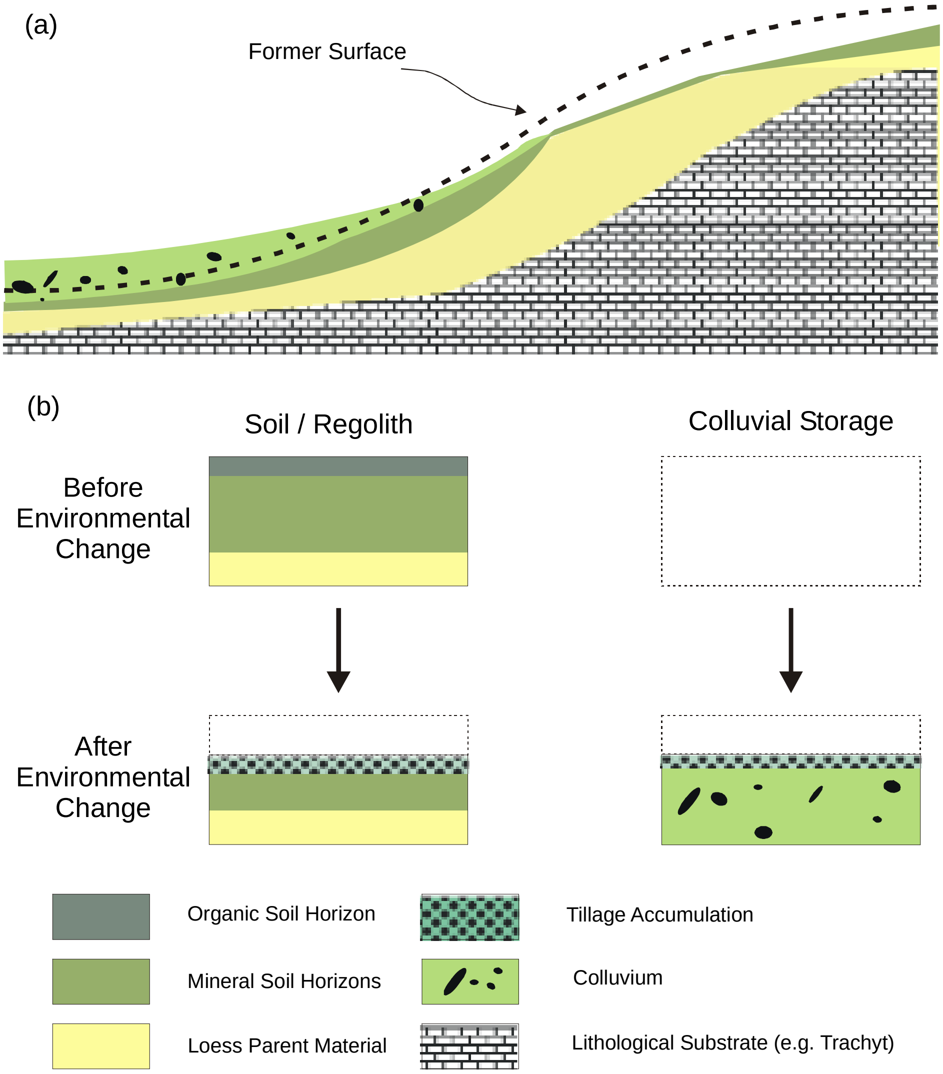


Figure 2.4: Schematic representation of the landscape system prior to anthropogenic change through deforestation, and as it exists now. (a) Two dimensional representation of late Holocene landform change. Soil and regolith material has been eroded from upper slope areas, and redeposited as colluvium in lower parts of the landscape. (b) Schematic representation of the change of storage in this landscape, comprised of two sediment storage units. Before deforestation and introduction of agriculture, the soil/regolith storage unit is characterised as a maturely developed soil formed in *in situ* parent material, e.g. a loess Luvisol, while potential colluvial storage remains unoccupied. After some interval of time, and as a result of anthropogenic influences, the soil/regolith unit has been partly evacuated, and part of the colluvial storage unit is now occupied. Note the change in the soil/regolith unit; the natural A horizon and part of the *in situ* B horizon have been eroded, and both this and the colluvial storage units are characterised by the presence of a plough layer.

2.3 *Historical Soil Erosion Research*

Research into the response to this environmental change and understanding the phenomenon of soil erosion has been extensive, and has been at two levels, which can be distinguished on the basis of their temporal perspective. The first of these focuses on the process itself, with the premise that if we understand the mechanics of the process we are in a better position to combat its effects. It was long ago recognised that erosion of productive soil is a threat to the sustainability of our land uses, and considerable research effort has been devoted both to the development of models to predict amounts of erosion and to the development of remediation measures and best land use practices. A good treatment of the phenomenon is given by MORGAN (1995), while a review of research is given by HIGGITT (1991) and BOARDMAN *et al*. (1990) is a collection of many examples. The second aspect focuses more on the understanding of soil erosion in an historical context, and there has also been a considerable body of research devoted to understanding and interpreting soil erosion in an historical context, e.g. BELL & BOARDMAN (1992) or BORK *et al*. (1998). Questions relate to the identification of the human role as a cause of erosion: what is natural, what is anthropogenic? How do current rates compare to those of the past?

Modelling of soil erosion began as an attempt to address soil erosion problems. Perhaps the most well known approach is the Universal Soil Loss Equation (WISCHMEIER & SMITH 1978). This and its numerous refinements are empirical models, i.e. they are based on observed statistically significant relationships. Input variables relate to rainfall, morphometry, soil erodibility, vegetation cover and land use factors. The driving force comes from water flow over the surface, although the detaching effects of raindrop impact may also be included, and the response variable is a volume of material eroded or a net surface lowering. These are simple models of long-term average surface erosion at plot or small slope scales, and at this level, their most useful application lies in the identification of best agricultural practices for individual plots.

Process-based models represent an increase in sophistication over empirical models. These are based on an understanding of the processes that underlie observed empirical relationships, and are often described as physically-based. Considerable knowledge has been gained in this respect, and at the field scale, at least, the physical basis of many erosional/depositional processes is well understood. More interesting from the perspective of landform development are spatially distributed models i.e. those that include a spatial dimension, using a continuity equation satisfying elementary physical principles regarding conservation of mass and energy. Examples include WEPP (NEARING *et al*. 1989), Erosion3D (SCHMIDT 1991, VON WERNER 1995) and EUROSEM (MORGAN *et al.* 1998). Discussion and assessment of these and other models can be found in BOARDMAN & FAVIS-MORTLOCK (1998a) and SIAKEU & OGUCHI (2000). They operate at sub-basin or basin level, subdividing space into discrete units (cells or modules), and modelling the movement of sediment between these units. Basin sediment outputs can be quantified, with applications for denudation and channel sedimentation studies. The more advanced are capable of elucidating within basin sediment redistribution, with resolution that is dependent on the scale of the internal unit. This approach is clearly a better representation of reality, and can provide further useful information for questions of applied geomorphology beyond the individual plot or slope.

More recently interest has turned to the use of soil erosion models for representing longer term rates of process behaviour, both with the objective of testing hypotheses about soil development (e.g. FAVIS-MORTLOCK *et al.* 1997) and of assessing possible future responses to climate and global change (e.g. FAVIS-MORTLOCK & BOARDMAN 1995, FAVIS-MORTLOCK & SAVABI 1996). Although not specifically designed for such a purpose, it is tempting to speculate as to whether process-based models might also prove useful for representing landform development. To the extent that sediment redistribution *is* landform development, such models do indeed serve this function, albeit on small scales. The spatial redistribution of material through erosional and depositional processes can be relatively simply converted into changes in elevation. However, use of these models for the purpose of landform reconstruction at a Holocene scale is problematic. Although it has been suggested that they in fact perform better over longer periods, with better results for continuous rather than event-based modelling (BOARDMAN & FAVIS-MORTLOCK 1998b), extensive parameterisation is required with attendant heavy computational demands. More importantly, many of the factors used in such models (e.g. those relating to vegetation properties and climatic factors) are subject to change over time. If these factors are treated as constant, i.e. part of model boundary conditions, then the period over which the model can be applied is determined by the frequency of variation in these factors. Therefore, although in principle they can model landform development, this can only be at limited spatial and temporal scales. The MEDALUS and MEDRUSH models (KIRKBY 1998, 1999, KIRKBY *et al*. 1998) represent an attempt to address this point.

Models need data, not only for their parameterisation, but also for both calibration and validation (e.g. see DIKAU 1999). In this respect, the second – historical – aspect of soil erosion research plays an important role. Environmental change of the nature discussed in the preceding section has been a common phenomenon in at least the temperate regions of the Earth. In New Zealand, where changes in land use have occurred both recently and rapidly, significant increases in sedimentation associated with anthropogenic land use have been recognised (PAGE & TRUSTRUM 1997, 2000, WILMSHURST 1997, TRUSTRUM & PAGE 1992). These provide clear evidence of the impact of human land use change on sediment generation and redistribution. On the other hand, for the same period and in the same landscape, GRANT (1985) identifies distinct periods of alluvial sedimentation associated with climatic fluctuation. In Germany, CLEMENS & STAHR (1994) estimated total soil loss since deforestation on the basis of various assumptions relating to soil profile truncation and soil type distribution, and compared this with rates of soil loss since 1950 derived from a range of geochemical tracers. They conclude that post-1950 soil loss represents a large percentage of the long term total, and that mechanisation and modern agrarian practices are a significant cause of soil erosion. Conversely, RICHTER (1981) suggests that the contemporary evidence is of historical process behaviour that was almost certainly stronger than today.

Historical rates of erosion in Germany are summarised in Figure 2.5. There have been two periods of greatly increased erosion during the Holocene (BORK & BORK 1987, BORK 1989a,b). Firstly, there was catastrophic gullying and extensive sheet erosion in the early 14th century, associated with a brief period of extremely heavy rainfall – possibly one single event. BORK & BORK (1987) dated the fill of these gullies to the 13th-15th centuries on the basis of archaeological finds. Then followed a period in which previously fertile land was abandoned and reverted to forest or was used as grassland. Filling of gullies occurred through slow sedimentation from these surfaces or more rapidly from scarp retreat. A second phase of gully erosion, also attributed to heavy rainfall, although related more to a longer duration phase of fluctuating weather, occurred in the 18th century. This phase of gully erosion was mitigated by erosion prevention measures and was not as extreme as the earlier episode. BORK (1989a) has calculated a mass balance that demonstrates that 65% of total late Holocene (~1,000 years) soil loss occurred in these two gullying episodes, and that approximately half of this was associated with the 14th century episode.

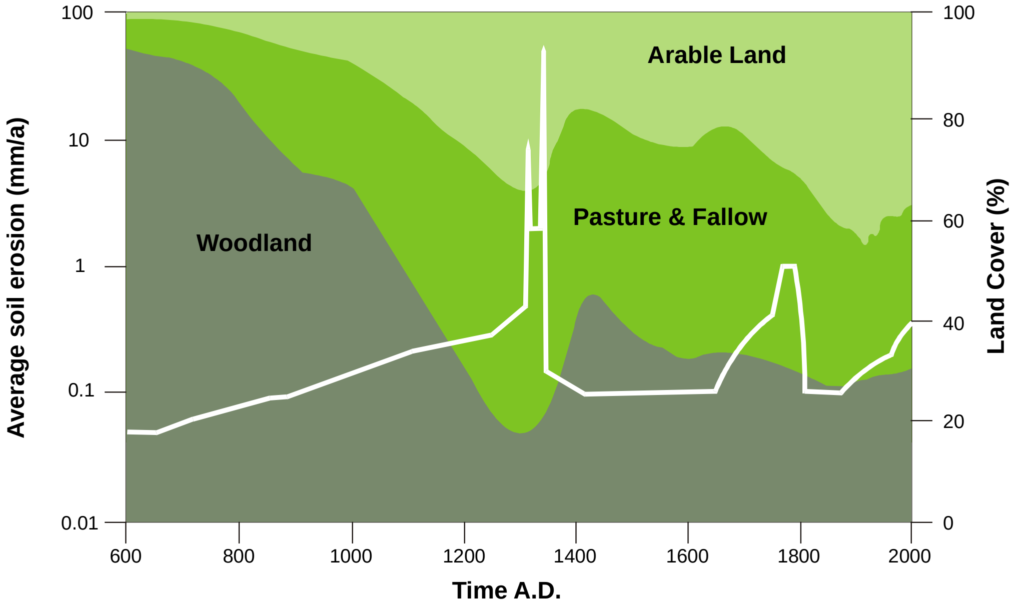


Figure 2.5: Historical rates of soil erosion (white line) and changes in vegetation cover through time for Germany (from LANG *et al.* (in press); soil erosion rates are based on BORK (1989a,b) and vegetation changes are based on BORK *et al.* (1998)).

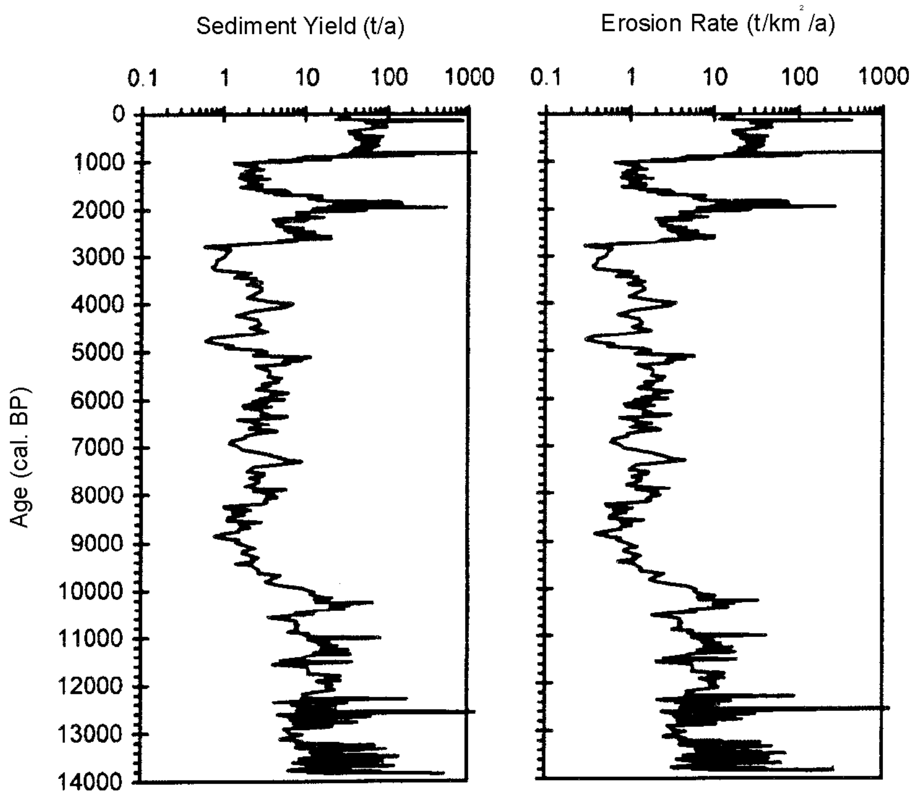


Figure 2.6: Late Pleistocene and Holocene sediment yields from Lake Holzmaar in the Eifel region (ZOLITSCHKA & NEGENDANK 1997).

This pattern of late Holocene erosion rates should be seen in the context of known/assumed erosion rates for central Europe, from which broad perspective they are clearly anomalously high. For example, a 14,000 year record of lake sedimentation from Lake Holzmaar in the Eifel region (Fig. 2.6) indicates high sediment yields in the late Pleistocene, decreasing by an order of magnitude with the transition into the Holocene (ZOLITSCHKA 1998, ZOLITSCHKA & NEGENDANK 1997). Sediment yields remained very low throughout the majority of the Holocene, during which time vegetation stabilised the landscape, leading to a period of geomorphic stability (ROHDENBURG 1971). BORK (1989a,b) maintains that there was no soil erosion during this period, which lasted until the anthropogenic deforestation of the early Middle Ages. As Figure 2.6 indicates, however, sediment yields increased again dramatically ~2,800 years ago with the onset of agricultural land uses, and again ~1,000 years ago showing the effect of deforestation. They have remained high since then, with pulses of higher rates reflecting the climatic influences evident in Figure 2.5.

The extent of arable land was at its historical maximum at the height of the Middle Ages (Fig. 2.5). However, while this might be seen as a precondition for an increase in erosion rates, BORK (1989a) argues that this did not itself directly cause soil erosion, attributing greater significance to the effects of climate in producing enhanced erosion rates. BORK (1989b) argues that there was no erosion in either the early Holocene or in the period between the 3rd and 6th centuries AD, and concludes that there were therefore no erosion-inducing rainfall events. While this may be the case, one wonders whether large rainfall-runoff events may have removed evidence of earlier events. Archival evidence confirms the widespread occurrence of flooding and erosion associated with climatic extremes in the early 14th century (WEIKINN 1958). In particular central Europe experienced extensive flooding in the summer of 1342 associated with a rainfall event with a supposed return period of greater than 1,000 years (FLOHN 1949, 1958, 1967, PFISTER 1980, 1985). It is certainly tempting to attribute the occurrence of the 14th century gullying to this event. However, the early 14th century was a time with many wet summers (FLOHN 1993), and it may be that the temporal occurrence of gullying was indeed narrowly restricted, although perhaps not exclusively due to this single event. In any case, it does seem reasonable to attribute this brief period of extremely high erosion rates to predominantly climatic causes.

While it appears that the gullying episode of the early 14th century was coincident with the beginnings of climatic deterioration towards the Little Ice Age, this was also a time when the extent of agricultural land use had reached its maximum (Fig. 2.5), and the effects of human land uses have been advanced as an alternative explanation for increased erosion rates. In emphasising the significance of climate, BORK (1989a) claims that earlier authors have mistakenly assumed unchanged rainfall and soil moisture conditions in attributing historical soil erosion to anthropogenic causes[1]. An anthropogenic cause for the 14th century gullying is rejected by BORK & BORK (1987) principally because of the evidence in support of a climatic trigger, and BORK (1989a) specifically rejects land use as a cause of the 18th century gullying episodes. He cites various authors as evidence that cereal cropping had given way to pasture and forest by the late Middle Ages, and argues that this would tend to decrease susceptibility to erosion. He rejects the hypothesis of catastrophic linear erosion being caused by soil exhaustion or impoverishment, quite reasonably asking how such a mechanism could cause widespread simultaneous gullying.

BROOKFIELD (1999) concurs with BORK (e.g. 1989a,b) that an extreme climatic event was sufficient proximate cause of the widespread 14th century mass wasting event, independent of the effect of agricultural land use as a preparatory factor. He maintains, however, that the agrarian

[1] BROOKFIELD (1999) denies this, and various other authors (e.g. HARD 1970) have certainly considered the role played by climate.

situation in the late 18th century was also a significant contributing factor to the occurrence of gullying in that period. There is support for the contention of significant influence of human activity from numerous other workers. For example, AMAYO (1979) attributes the greater part of Holocene erosion in the middle Rhine hill country to viticulture. BAUER (1993) found that gully systems in the Hessen Taunus are late Holocene forms, caused by "massive human impact", i.e. deforestation and agriculture. The thesis of climatic events as sole cause is specifically rejected, and it is maintained instead that these were superimposed on a background of both biophysical and especially land use factors. Working in the same area, SEMMEL (1995) found similarly that gullies were formed by land use.

In questioning the predominance given to climatic causes of erosion, RICHTER (1998) points out that gullying was not only associated with 14th and 18th century episodes, but has also been recorded for the 17th century (RICHTER & SPERLING 1967; SEMMEL 1995), 18th century (HEMPEL 1954b) and 18th-19th century (HARD 1970). Despite this, RICHTER (1998) maintains that gullying takes place rarely, and only when a certain combination of contributing factors occur. He argues, thus, that their significance should not be overestimated, and that over the long term other less catastrophic processes have greater effect. This is a direct appeal to the frequency/magnitude concept of WOLMAN & MILLER (1960) and especially the idea of a most effective formative event (WOLMAN & GERSON 1978) (see below).

According to HARD (1970) the high point of gully erosion in southwestern Germany occurred between 1760 and 1850. While perhaps not coincident with a peak in storminess (FLOHN 1993), this period was certainly in the middle of the Little Ice Age. Nevertheless, HARD (1970) discounts the significance of these climatic perturbations, arguing that these were at best a strengthening factor, but not a principal cause. He argues instead that this phase of gully formation was coincident with agrarian change – specifically the transition from an extensive alternating crop/pasture system to the three crop permanent rotation system – and that the gullying phase ended with the further transition to the use of a seasonal fallow system and permanent pasture as an explicit recognition of inappropriate land use. HARD's (1970) refutation of the climatic hypothesis has three grounds:

(i) the actual effectiveness of either strong or enduring rainfall varies greatly with factors such as soil texture, field size, crop type and field condition,
(ii) there is no (or a weak) spatial correlation between areas likely to receive high rainfall and areas that were gullied; the areas that received greatest rainfall were not gullied *because* they were not used for agriculture,
(iii) both the greatest likelihood of erosive rainfall (either amount or duration) in the area investigated and the observed periods of greatest erosional activity are in late autumn or early spring; this is precisely *not* the time when the characteristic weather pattern associated with the 18th century events occurs. In other words, [on the basis of modern observations], the weather pattern characteristic of the 18th century event does not produce the greatest erosional response.

None of these refutations of the climatic hypothesis are particularly strong. The first point is undoubtedly true, but does not of itself demand rejection of a climatic cause for gullying. The second objection, concerning the lack of correlation between rainfall magnitude and gully location, may simply reflect the dominance in those areas of other geomorphic processes (e.g. debris flows, rotational landslides), and the lack of appropriate sites for gully formation. The last point, comparing well-documented contemporary weather patterns and patterns of erosion under modern conditions with both climatic and land use patterns of two centuries ago is dubious to say the least. While the weather pattern supposedly characteristic of the 18th century storm events is not associated with maximum modern erosion rates, the nature and pattern of former land use may well have rendered the landscape susceptible to those weather conditions. On these grounds alone, it is difficult to reject outright the hypothesis of climatic causes for gullying.

Clearly climate has been a proximate cause of many individual erosional events. On the other hand, land use as a preparatory factor has also been important (as BORK indicates himself (BORK *et al.* 1998)), and over a longer temporal scale it is apparent that erosional response shows a strong correlation with land use change. A general picture of colluvium formation through time for southern Germany is shown in Figure 2.7 (LANG in press). Periods of colluvium formation broadly coincide with periods of human impact on the environment. Low rates of sedimentation are associated with initial Neolithic agriculture; the first significant impact occurs in the Iron Age, followed by higher rates in the Medieval and modern periods. The influence of climate is not reflected in the same way as indicated in Figures 2.5 and 2.6. Perhaps one of the strongest arguments in support of an anthropogenic influence on soil erosion is advanced by VAN VLIET-LANOE *et al.* (1992). These authors argue that erosion during the Holocene has been essentially associated only with human alteration of the soil system, i.e. agriculture. They acknowledge increased Medieval and Little Ice Age rates in response to climatic perturbation, but maintain that the effects of these climatic events were exacerbated by agricultural modifications. Further, they argue that modern agricultural practice has recreated a landscape that is in many respects similar to that of the last glacial, and it is hence not surprising that contemporary erosion rates are comparable to those pertaining at various stages of the last glacial.

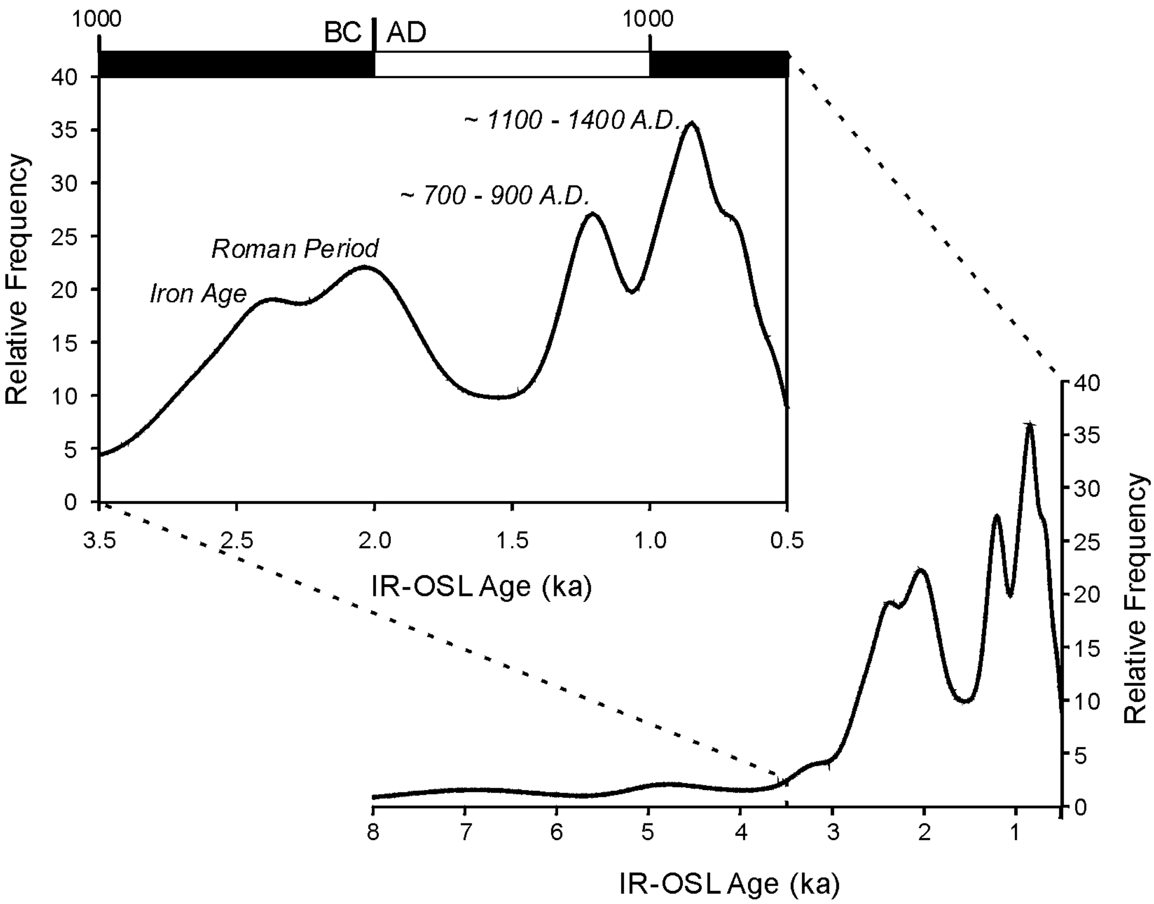


Figure 2.7: Relative frequency of colluvium ages from southern Germany (adapted from LANG in press).

Clearly, not only have both the extent and intensity of erosion changed through time, its principal causes are also open to debate. The different interpretations briefly summarised above can partly be attributed to the focus of investigation. For example, BORK was primarily interested in the widespread gullies, and sought some explanation for them. It is not surprising that he finds climate significant; gullies *are* triggered by climatic events. Alternatively, LANG, for example, has focused on the accumulation of sediment on and at the base of slopes, within research specifically aimed at human-landscape interactions. Because the focus is on sediments generated by an essentially human process, it is not surprising that strong emphasis is placed on human causes. In other words, the results, interpretations and conclusions of the various workers alluded to above (and numerous others) are not antagonistic. In fact, they are not really comparable at all. Rather, they can both contribute to the formation of hypotheses concerning geomorphic questions relating to landform behaviour and development. Specifically, both human agency and climatic triggers induce erosional responses. What is their relative contribution? Is this constant through time? On the basis of answers to these questions, how do we interpret the stratigraphic record and soil archives?

The examples of research referred to above, however, were principally soil erosion studies rather than attempts to characterise geomorphic response. In this last respect, there has also been a wealth of published work describing landforms that are characteristic of both natural conditions and the erosional processes that have followed deforestation. For example, NICKE (1989) provides an hypothesis for the natural Holocene development of a landform characteristic of the forested hill country to the east and north of Bonn. These are termed *Siefen*, and according to NICKE (1989) are small valley features formed under forest. The forest provided protection to the soils and there was thus minimal upland erosion. Nevertheless, precipitation did generate runoff through a variety of processes, and when this concentrated in drainage lines it had some erosive capacity. Thus, although uplands remained relatively stable, small channels were able to develop. These are the *Siefen*. Drainage typically followed the pre-existing pre-Pleistocene topography, which was thus rejuvenated. The typical landform complex was thus a series of small valleys incised into the Pleistocene fill of valleys formed in Tertiary or early Pleistocene basement. At the heads of these valleys in many cases, however, remained a body of Pleistocene valley fill that was unable to be entrained and transported under prevailing conditions, but which was ripe for redistribution when the controlling conditions of the landscape system changed.

RICHTER (1965) demonstrated that where agricultural land use in the upper part of a catchment supplies material, natural slope depressions – or dells – are naturally filled in. This is also true for rills or small gullies formed in arable fields, and in the absence of catastrophic gullying, the development of landforms is characterised by a smoothing of the landscape and reduction in relief. This may also be true of *Siefen*, formed as described above. However, as pointed out by RICHTER (1998), rilling on arable fields may develop into a gully system if not ploughed over. If this is sufficient to cause field abandonment – or indeed if this happens for other reasons – there will no longer be a supply of sediment to refill these features, and a form resembling a *Siefen* may be present. Indeed, this is typical of much of central Europe's loess cropland: where they have been forested following abandonment, Medieval gully forms are preserved (BORK 1989a, MACHAN & SEMMEL 1970). The cycle may repeat if agriculture is reintroduced, or if there is some other source of sediment capable of filling in the gullies, valleys or depressions.

There are thus characteristic landforms associated with agricultural land use. For example, HEMPEL (1954a) describes and compares the origins of forms known as *Tilken* and *Sieke* (Fig.

2.8). *Tilken* are small, flat-bottomed valleys formed by the deposition of agriculturally-derived material in previously notch-shaped drainage lines. It is this deposition and the flattening of the valley floor that is attributed to human activity; the form of the slopes, however, is not considered to have been altered by such activity. *Sieke* have a very similar contemporary appearance, i.e. they are also small, box-shaped valleys. Two origins of these forms are described, the first being essentially identical to that of *Tilken*. For the second origin, the contemporary form is more directly the result of human activity. Rather than being the result of deposition of material from a remote source, *Sieke* are formed by the direct modification of the slope by tillage, and anthropogenic alteration to the valley floor. The difference between the two thus relates to the proximity of agricultural activity, and the degree to which the form is directly (*Sieke*) or indirectly (*Tilken*) a result of this.

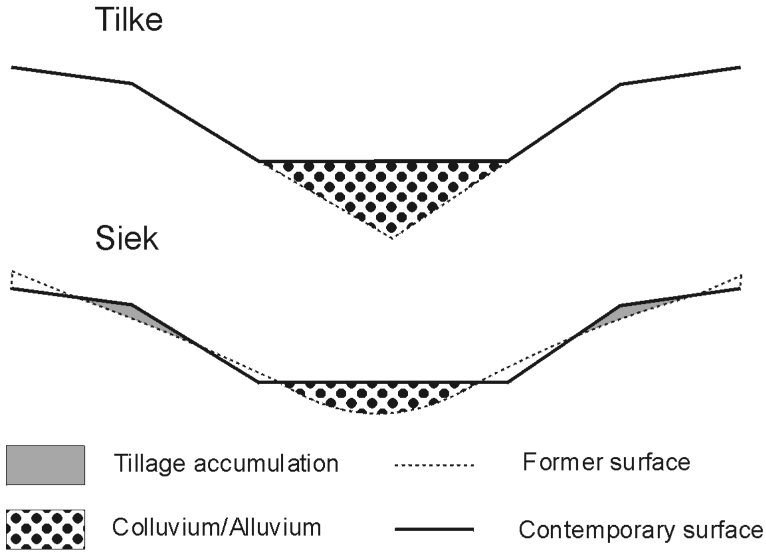


Figure 2.8: A comparison between *Tilken* and *Sieke* (based on HEMPEL 1954a).

To summarise, there has been considerable research into rates of erosion through time and discussion of the reasons why they vary. Furthermore, the morphological consequences of anthropogenic erosion have also been investigated, and characteristic landforms that result from human land uses have been identified. However, analysis of the geomorphic response to land use change has not been extensively investigated within a geomorphic systems context.

2.4 Equilibrium, Landscape Sensitivity and Frequency/Magnitude

In attempting to characterise geomorphic response to environmental change as described in the preceding section, consideration needs to be given to the concepts of equilibrium, landscape stability and sensitivity, and frequency/magnitude of geomorphic processes. These are reviewed here.

2.4.1 Geomorphic Equilibrium

Conventionally geomorphologists have sought to characterise the behaviour of landform in response to systematic perturbations in terms of equilibrium. Two broad concepts of equilibrium have dominated geomorphic thinking. These two approaches – often referred to for convenience as Davisian and Gilbertian – differ fundamentally in the way in which they conceive of equilibrium. The classical Geographical Cycle of DAVIS (1899) is inherently historic, and specifically treats time as an important variable determining the stage of landscape development. This approach is grounded in the 2nd law of thermodynamics, i.e. geomorphic change trends towards a state of maximum entropy with minimal flux of energy and matter. Equilibrium within this concept is achieved only after a measure of time in which the landscape has evolved through specific stages. DAVIS' cycle explicitly dealt with large spatial scales and long (geological) temporal scales. It described the evolution of a landscape following an abrupt rejuvenation through uplift and the creation of potential energy in the form of relief. While it can be argued that this concept is elegant and simple, it lacks a degree of practical value. We are interested not so much in the development of landscapes over geological time, as in the development of landscapes on much smaller scales – both spatially and more importantly, temporally. While we need to recognise the presence in the contemporary landscape of forms inherited from past environments or geomorphic regimes, recognition of contemporary process behaviour is also important. The contrasting Gilbertian approach involves this recognition that it is not simply the inevitable passage of time that determines landscape form, but the action of processes. Landform development is thus a far more complex phenomenon than simple decay to entropy, and by contrast, the Gilbertian approach focuses on the 1st law of thermodynamics, i.e. conservation of mass and energy. From this perspective, equilibrium is defined in terms of the relationship between form and process.

Since the 1950s and 1960s geomorphology has experienced something of a quantitative revolution and an emphasis on understanding of the processes that shape landforms. Perhaps showing a uniformitarian approach, the assumption has been that it is knowledge of the mechanics of the processes that form them that leads to greater understanding of landforms. The dominant paradigm has been one of *constant process-characteristic form*. However, in order to remain within this paradigm, it has been necessary to refine it and to invoke a number of supplementary concepts, as discussed below.

2.4.2 Sensitivity and Stability, Thresholds, Reaction and Relaxation

The idea of landscape sensitivity was first expressed within the geomorphological literature by BRUNSDEN & THORNES (1979). It encapsulates the notion that some landscapes are more resistant to change than others. Environmental change and perturbing impulses do not always elicit a geomorphic response, and if they do, that response may find different expression in different parts of the landscape. The idea of sensitivity is closely related to that of stability. A landscape that cannot absorb perturbations is sensitive to change in its controlling factors and forcing processes, and thus at least potentially unstable. Conversely, a landscape that can tolerate considerable variation in controlling factors and forcing processes can be considered by comparison as being relatively stable. The ability to resist change or absorb perturbations can be referred to as the buffering capacity. Buffering capacity – or buffers – mean that a landform or landscape is able to experience perturbation or change in some part of the system, i.e. an impulse of energy from an external forcing process or change in the condition of a controlling factor, without this being expressed externally as a morphological response.

An important part of the relationship between forcing processes or controlling factors and morphological response (i.e. form) is represented by thresholds (SCHUMM 1973, 1979). Thresholds may be internal to the system or external, and in neither case can stationarity or constancy of threshold values be assumed. External thresholds relate to the behavioural regime of external forcing processes, e.g. the amount or intensity of rainfall that is necessary to initiate overland flow (or rilling or mass movement etc.) represents an external threshold. In the simplest case, rainfall initiates a process or morphological response only when it exceeds a given magnitude – the external threshold. Although variation in precipitation is effectively independent of the other aspects of the soil or slope system, temporal variation in the condition of controlling factors internal to that system can influence its response. This can have the effect that the relationship between magnitude of external forcing process and the occurrence (or magnitude) of morphological response is not constant through time. Values of external thresholds are thus not constant (see below). Internal thresholds relate to critical values of internal system elements (controlling factors); geomorphic response follows if these values are exceeded. These thresholds are more likely to have constant values. However, in many cases they will be very much influenced by external processes and thus subject to temporal variation.

Importantly, because of buffers and thresholds, change in form does not always follow immediately after change in process, and in some cases detecting a connection between triggering process and morphological response may be difficult. There may be considerable time lags between perturbation and morphological response in systems with large buffering capacity and/or with large thresholds to overcome – termed “barriers to change” by BRUNSDEN (1993a). Indeed, some landforms may be so stable and insensitive, or so slow to react, that they are adjusted to a previous set of controlling conditions and forcing processes. Thus, characterisation of morphological response to environmental change or external perturbation must take into account the concept of reaction and relaxation times (BRUNSDEN & THORNES 1979; Fig. 2.9). Together, these define the response time of a landform or landscape to perturbing impulses. In turn, relaxation time needs to be considered in relation to the recurrence interval of the forcing process that produces the landform. The ratio between relaxation time and the recurrence interval of the forcing process is termed the transient form ratio (BRUNSDEN & THORNES 1979). If the recurrence interval of the perturbation is shorter than the time required for the landscape to relax from the last perturbation, the transient form ratio will be > 1.0. In such a case, the landscape is sensitive and unstable – at least with respect to that particular process. The converse is true if the transient form ratio is < 1.0.

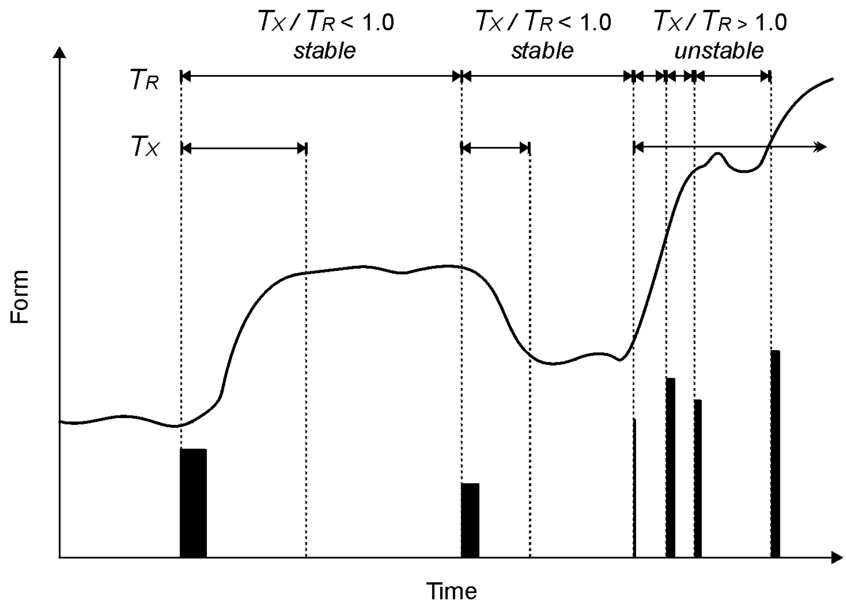


Figure 2.9: Stability and instability defined by transient form ratios, i.e. as a function of relaxation times (T_X) and recurrence intervals of perturbation (T_R) (adapted from BRUNSDEN & THORNES 1979).

2.4.3 *Frequency, Magnitude and Effectiveness of Geomorphic Processes*

WOLMAN & MILLER (1960) formalised the idea of frequency and magnitude of geomorphic processes, whereby it is recognised that low magnitude processes occur often, larger processes are less common, and truly extreme catastrophic processes are rare. Recognising this, one must take account not only of the magnitude of a process, but also how frequently it occurs. If the geomorphic work effected by processes of varying magnitude can be measured, and compared with the frequency of their occurrence, it is in principle possible to statistically infer the frequency and magnitude of process that is most effective in performing geomorphic work, i.e. in shaping the landscape. Thus WOLMAN & GERSON (1978) introduced the concept of a *formative event*, defined as the process magnitude (with a specific frequency) that is the most geomorphically effective, and therefore the event to which landforms should be adjusted. This represents one of the most pervading and characteristic aspects of the dominant geomorphological paradigm, i.e. the notion that there exists an idealised or characteristic landform which is adjusted to the most effective magnitude of process. As with DAVIS' Geographical Cycle, the notion has elegance, and intuitively seems reasonable; indeed it has met with empirical support. Fluvial geomorphologists, in particular, have been able to relate channel form to magnitude of stream discharge (e.g. ANDREWS 1980).

2.5 *A New Paradigm?*

The equilibrium paradigm which has been dominated by what might be more appropriately termed the formative event-characteristic form notion has not been unsuccessful. However, where it has found success has typically been for simple landforms that are clearly the result of one genetic process, e.g. channel reaches in equilibrium with discharge. But different individual landforms have different sizes and longevity (AHNERT 1981, DIKAU 1989, BRUNSDEN 1993b), and they represent morphological responses to different processes operating at different temporal scales. SCHUMM & LICHTY (1965) attempted to resolve this issue by appealing to relativity, i.e. the existence of equilibrium depends on temporal and spatial scale and how the system is defined. Nevertheless, one is still faced with the challenge of finding a consistent relationship between forcing processes and the morphological response (CROZIER 1999). One reason for this is the existence of thresholds, and especially their variability, and thus the varying effectiveness of similar process magnitudes.

Not only do thresholds vary in space with differences in internal system properties (e.g. GLADE 1998), they may also vary in time because of feedbacks within the landscape system. CROZIER (1989) introduced the term "event resistance" to refer to situations where landforms have become resistant to the occurrence of geomorphic processes, i.e. notwithstanding the occurrence of a forcing event that has in the past been capable of inducing a geomorphic response, such response does not occur. CRUDEN & HU (1993) used the term "exhaustion" to describe a similar phenomenon, i.e. the exhaustion of sediment supply. This concept was extended further by CROZIER (1996), using the term "ambient filters" to describe landscape phenomena that act as filters between initiating processes and the process response. PRESTON (1996, 1999, 2000) used these ideas to demonstrate changes in erosional responses to identical energy inputs as landscapes were modified through time. The operation of geomorphic processes introduces a feedback effect such that the relationship between forcing process and geomorphic responses is not constant in time. The presence of spatially distributed filters in the landscape thus influences geomorphic responses. The implications of this were explored by CROZIER & PRESTON (1999) with their postulated "Interrupted Relaxation" model, which is essentially a system trajectory plotting the hypothetical evolution of requisite rainfall thresholds for landslide initiation through time. The threshold varies not only as the system relaxes to a new stable state, but also due to sediment redistribution and the feedback effects of this on subsequent process behaviour. It is thus postulated that ambient filter phenomena, when their operation is considered at a regional scale, could influence system behaviour (Figure 2.10).

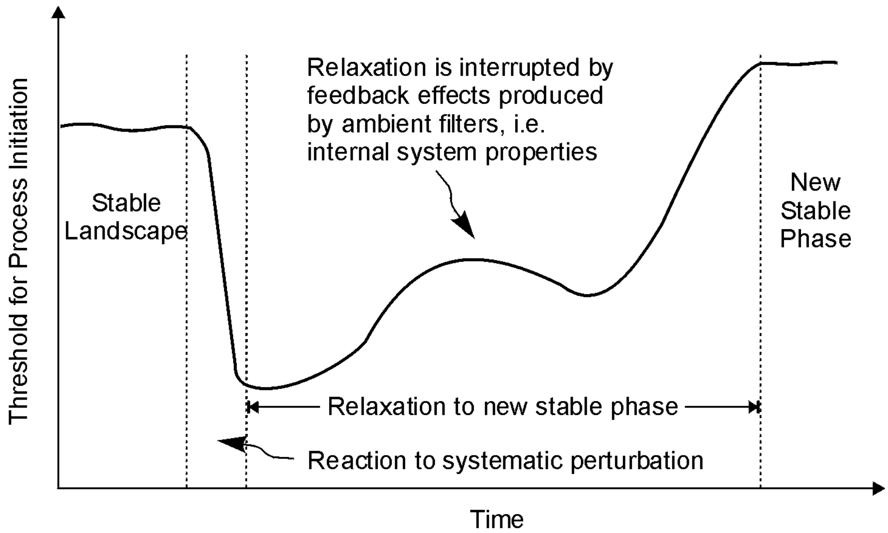


Figure 2.10: The "Interrupted Relaxation" model of CROZIER & PRESTON (1999). Environmental change resulted in a dramatic increase in susceptibility to landsliding, expressed here as a reduction in the requisite rainfall threshold that must be exceeded for landslide initiation. As the landscape adjusts to the new balance between external impulses and internal controlling conditions, i.e. relaxes, this threshold slowly increases. However, because of the effects of ambient filters, the relaxation trajectory is not linear.

When considering the landscape scale, i.e. a whole suite of landforms of different age and size forming complex open systems, both perturbations and geomorphic responses are complicated. For example, CROZIER & PILLANS (1991) found that regional landscapes respond to a multiplicity of processes that operate with markedly different frequency/magnitude distributions, and which leave varying imprints on the landscape. Clearly, reconstruction of landform development – or understanding of geomorphic response to environmental change – requires assessment of more than just one simple morphological measure responding to one simple defining process. The situation is summarised by CROZIER (1999:43): "the challenge now is to isolate and predict the landform product of intersecting process regimes, interrelated but all working to their own frequency and magnitude agendas." Landscapes are constantly being adjusted, and can often best be described as being in a non-equilibrium or metastable condition. In fact, the equilibrium paradigm can be characterised by the huge diversity of different concepts of equilibrium, and indeed the recognition that some, if not many, systems do not in fact exist in equilibrium (e.g. ABRAHAMS 1968, RENWICK 1992, MALANSON *et al.* 1992, AHNERT 1994, THORN & WELFORD 1994). Indeed, the validity of equilibrium as a unifying geomorphological paradigm has been questioned (e.g. PHILLIPS 1992, RICHARDS 1999).

RICHARDS (1999) has challenged the assumptions underlying the process-oriented study of landform change, and specifically the use of the frequency/magnitude concept to characterise dominant or most effective magnitudes of landforming processes. He rejects the notion of an equilibrium in terms of constant process and characteristic form. Landscape systems react to their stimuli, and their evolution is dependent on both initial conditions and history of change and perturbation. He argues that a new paradigm is needed, that on the one hand recognises and acknowledges the non-linear aspects of geomorphic system behaviour, and especially that has a spatial dimension, focussing on the varying relationships between sediment source areas and sinks. Spatial aspects of landscape systems have in fact long been recognised. WALLING (1983, 1999) has drawn attention to the problems involved in defining regular behaviour of sediment delivery. Routing of sediment through the landscape is influenced not only by the various issues of sensitivity, response/relaxation, complex response, thresholds etc. as described above, but also by the way in which these phenomena are filtered by spatial and topological relationships. An example is provided by the work of TRIMBLE (1993, 1999), which has demonstrated clearly that pulses of sediment generated by specific events take varying amounts of time to move through the landscape. The widespread occurrence of these so-called sediment slugs, at various spatial and temporal scales, has been summarised by NICHOLAS *et al*. (1995).

Increasing emphasis is thus being placed on issues of space. THOMAS (2001) argues that spatial sensitivity is as important as temporal, i.e. that it is equally as important to identify the sites within the landscape that are most sensitive to change as it is to identify the temporal frequency with which perturbations may occur. Time is clearly an important factor, although not in as simple or absolute a sense as in the Davisian approach; it remains a relative factor, rather than being an absolute determinant of system status. Perhaps more importantly, it is the interaction between time and space that is important. How long does it take for a storage to fill up? How long does it take for a pulse of sediment to move through a system? Clearly, the answers to these questions are not absolute. They are relative because they are principally influenced by the way in which a system is put together, i.e. its *configuration* (LANE & RICHARDS 1997, BROWN & QUINE 1999). Specifically, the configuration of the landscape relates to the spatial distribution of its various components and their topological relationships. LANG & HÖNSCHEIDT (1999) present a qualitative model of interim storage of sediment as it moves through the landscape (Fig 2.11). This model is inherently configurational: it consists of a series of storage units linked topologically, and interpretation of its “final” sedimentary column appeals to both the topology and the interaction of this with frequency/magnitude of redistributive processes.

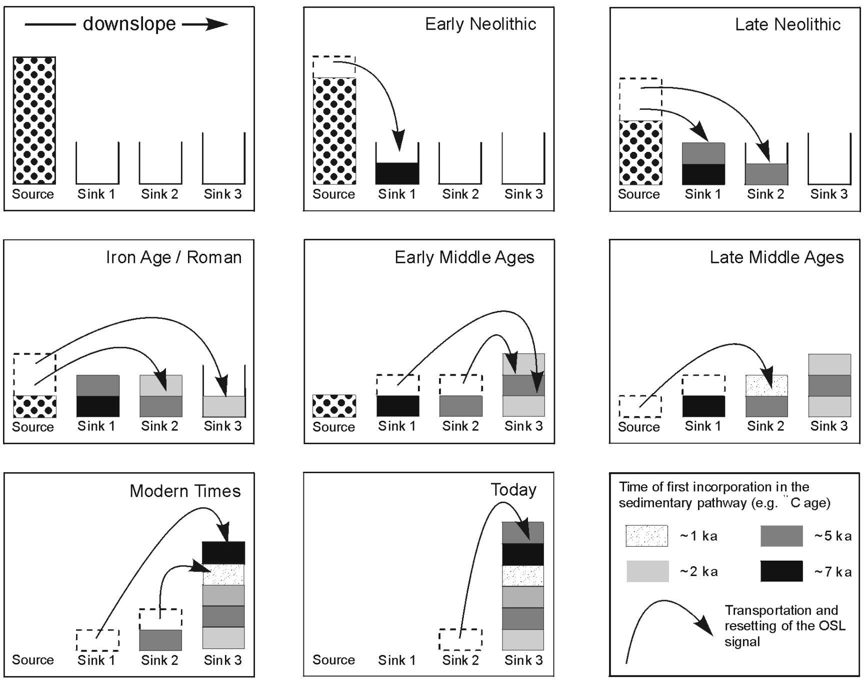


Figure 2.11: A qualitative model for the movement of sediment through a series of interim storage units (LANG & HÖNSCHEIDT 1999).

2.6 *Summary: Geomorphic Theory and this Study*

What are the implications of the various topics discussed in this chapter for the way in which geomorphic response to environmental change in the Pleiser Hügelland should be analysed? This summarising section of this chapter addresses this question, and in doing so specifically introduces the conceptual underpinning of this study. Clearly, one issue that has perhaps not yet been resolved despite considerable research relates to the relative significance in influencing erosional behaviour of, on the one hand climatic events – or meteorological, to be more accurate – and, on the other, human land use change and subsequent activity. Indeed, while there has been a great deal of research, it has not focussed systematically on the geomorphic behaviour of the landscape. From a systematic perspective, there are at least two principal geomorphic processes active in the post-environmental change landscape, i.e. rainfall-runoff induced water erosion and tillage translocation. These two processes have fundamentally different frequency/magnitude spectra. Thus the landscape system cannot be defined in terms of potential equilibrium between a single process and a characteristic form. More realistic from an analytic perspective is perhaps an attempt to establish transient form ratios. These may say something about the sensitivity of the landscape to the two different processes. But, recognising the significance which is being given to spatial or configurational aspects of landscape systems, the importance of these might also be investigated. For a process-response system defined by the flux of material and energy through space, configuration of the system is clearly an important issue. While the mechanics of processes can be described by physical laws, the geomorphological consequences of process activity must obey a further – more subtle and diverse – set of laws and principals. Many of these have been summarised in the preceding sections. While recognising and indeed incorporating these, the emphasis in this work is placed on addressing the spatial and configurational aspects of the landscape in attempting to elucidate geomorphic response to environmental change.

How can qualitative, or conceptual, models such as those of CROZIER & PRESTON (1999, Fig. 2.10) or LANG & HÖNSCHEIDT (1999, Fig. 2.11) be quantified? The geomorphic response to environmental change dealt with here can be broadly summarised as landform development through a sedimentary response. In a very simple sense, the response is a morphologic evolutionary system as defined by SLAYMAKER (1991). However, this is simply a description of two endpoints in landform development; it does not permit full elucidation of system behaviour. Alternatively, characterisation of the landscape as a process-response system as defined by CHORLEY & KENNEDY (1971) allows a more powerful analysis of the geomorphic response. Within this context, morphometric properties of the landscape define the morphological system/s component of the process-response system and function as decision regulators, while the sedimentary response – or sediment flux – is the cascading component. In the simplest sense, quantification of the sediment flux is, by definition, a sediment budget. Sediment budgets are an accounting of changes in sediment storage. Early examples of their application include the work of DIETRICH & DUNNE (1978) and SWANSON *et al*. (1982). For discrete spatial units this involves, at the simplest level, characterisation of inputs and outputs and an evaluation of change. Sediment budgets can be constructed for specific events such as single storms, e.g. PAGE *et al*. (1994), or for historical periods. REID (1982) refers to the use of flow charts and describes three-dimensional matrices which quantify amounts of sediment redistribution between various sources and sinks attributable to different processes.

Alternatively, temporal development of the sediment redistribution process and its behaviour can be represented graphically using system trajectories, enabling description of system condition with respect to chosen process indicators. For example, the behaviour of the sediment redistribution process may be represented by plotting erosion and/or sedimentation rates, or through a simple measure of colluvial volume or thickness in storage units. An illustrative example is given in Figure 2.12, in which it is assumed that a phase of sediment redistribution was initiated as a result of human interference with an otherwise stable system at "time zero". At that time the system could be characterised as having zero colluvium volume (or depth). Today, on the other hand, the system has quantifiable volumes and depths of colluvium. The temporal development of the colluviation system can thus be illustrated, in very simple terms, as the simple linear relationship plotted in Figure 2.12. Given sufficient data, more detailed changes in system state through time can be reconstructed, as represented by postulated curves on Figure 2.12.

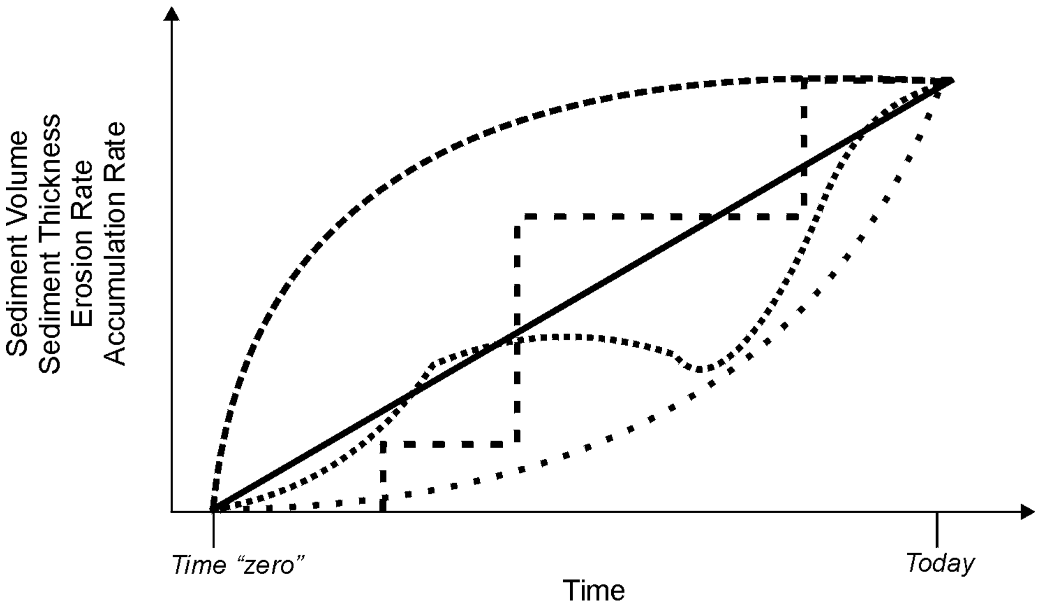


Figure 2.12: An hypothetical system trajectory representing the evolution of a sedimentary storage unit.

Generally, only one or two points that can be plotted in this way are available, i.e. the system condition is known only at isolated instances in time, and on the basis of such limited information, only cautious inferences regarding the system's evolution can be made. However, even this limited information provides an initial insight into system behaviour, and may serve as a tool in the development of further hypotheses. If such trajectories are developed for individual landforms and compared in a topological sense, i.e. recognising the spatial relationships in the landscape, they may provide a means of inferring the state of the landscape, and in particular enable some elucidation of the nature of geomorphic response to environmental change.

Chapter 3
Study Area – The Pleiser Hügelland

3.1 Introduction

The Pleiser Hügelland is a loess-covered predominantly agricultural area to the east of Bonn (Fig. 3.1). Although it is only ~3 km distant from and some 100 m above the contemporary Rhine channel, the general direction of drainage is to the northeast away from the Rhine. Small streams drain into the Pleisbach, then into the Sieg, and ultimately into the Rhine downstream from Bonn. The principal area of investigation was Gut Frankenforst – a research station operated by the University of Bonn's Institute for Veterinary Research. Additional investigations were carried out at the Gut Heiderhof farm. Specific descriptions of these sites are given in Chapter Five. This chapter provides firstly an overview of the general characteristics of the Pleiser Hügelland, in terms of its climate, geology and soils. Secondly, land use is discussed, with an emphasis on the historical development of human occupation and thus the timing of deforestation and the introduction of agriculture. Inevitably, less is known about the more distant pre-historical periods, while greater detail can be given for the more recent past. Parts of this discussion are therefore regional in some respects. Nevertheless, information pertinent to the specific sites is emphasised, including a brief review of previous soil erosion research carried out in the area.

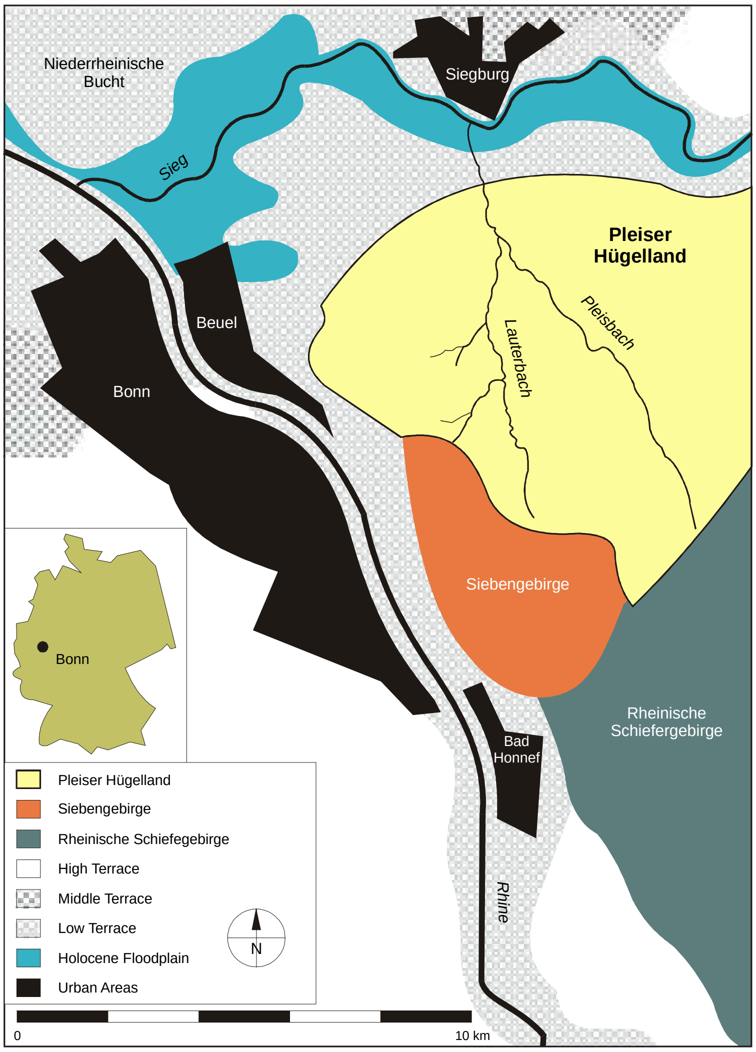


Figure 3.1: The Pleiser Hügelland within its regional setting.

3.2 Climate

During the Pleistocene the region experienced a cold and dry periglacial climate, with annual average temperature and average summer temperature lower than today by 8-13° C and 5-11° C respectively (SIEGBURG 1988). Throughout the Holocene, climate has been generally temperate, although with notable temporal variations. The Holocene is sub-divided into a series of periods representing climatic fluctuations. These are summarised in Table 3.1. In particular, the so-called Little Ice Age was a period of cooler temperatures, increased storminess and fluctuation in weather patterns. Although it is generally considered to have lasted from 1570 to 1850, with peaks between 1570-1620, 1680-1700, in 1755 and 1810-1850 (FLOHN 1993), the climatic deterioration began as early as 1300 (LAMB 1984). From this point on, climate became increasingly erratic with pronounced annual and decadal variation. The decade 1310-1320 was one of very wet summers, especially 1313-1317 (LAMB 1984); cool and wet summers also characterised 1340 and in the summer of 1342 much of central Europe experienced record flood levels associated with rainfall calculated to have a return period of well over 1,000 years (FLOHN 1949, 1958, 1967, PFISTER 1980, 1985).

Table 3.1. Holocene climatic periods. Climatic conditions are relative to the present.

years before present – ^{14}C	Period	Climate
	Würm Glacial	periglacial
12150 - 11350	Allerød	warmer
11350 - 10250	Younger Dryas	cooler
10250 - 9450	Pre-Boreal	warmer, drier
9450 - 7450	Boreal	warmer, drier
7450 - 4450	Atlantic	cooler, wetter
4450 - 2450	Sub-Boreal	warmer, drier
2450 -	Sub-Atlantic	cooler, wetter
1600 - 1200	Völkerwanderungszeit	cooler, wetter
500 - ~200	Little Ice Age	cooler, wetter

The Bonn region has a moderate maritime climate, with long warm summers and mild winters. The Niederrheinische Bucht has an annual average temperature of ~9° C, but with considerable variation throughout the year (January average: 1.8° C; July average >18° C). Annual rainfall varies within the range 600-750 mm. Highest rainfall intensities generally occur in the early summer months, which is the time when agricultural parts of the landscape are least protected by a crop cover (LAUX & ZEPP 1997). The Pleiser Hügelland itself is slightly cooler with an annual average temperature of 8.5° C and a slightly greater range of rainfall (550-800 mm) and an annual average of 700 mm. The region lies in the rain- and wind-shadow of the Rheinische Schiefegebirge and is thus sheltered from westerly, southerly and easterly weather patterns. Low wind speeds and relatively high sunshine hours (~1,500 per annum) combined with early springs provide conditions for plant growth. The region is thus climatically favoured for agricultural land use.

3.3 Geological Development and Contemporary Landforms

The Pleiser Hügelland is formed on a complex geology, comprising a Palaeozoic sedimentary basement, marine sediments and volcanic material of Tertiary age, and Quaternary sediments (Fig. 3.1). The Pleiser Hügelland lies in a transitional zone between the Palaeozoic Rheinische Schiefegebirge to the south and the Niederrheinische Bucht to the north. Tectonic uplift of the former, and the corresponding subsidence of the latter, have had a profound influence on the development of the Pleiser Hügelland. The rocks forming the Rheinische Schiefergebirge are primarily Silurian-Devonian slates with bands of resistant sandstones and quartzite (DEMEK & EMBLETON 1984), although in the vicinity of the Pleiser Hügelland Devonian schists and sandstones predominate (HENNINGSEN & KATZUNG 1992). A first episode of uplift of the Rheinische Schiefergebirge, and related subsidence of the Niederrheinische Bucht, occurred in the Carboniferous, although by the beginning of the Mesozoic the mountains had been largely eroded back to base level (GRUNERT 1988, HENNINGSEN & KATZUNG 1992). A second phase of uplift and subsidence commenced at the beginning of the Tertiary, resulting in the development of the modern Niederrheinische Bucht between the uplands of the Rheinische Schiefergebirge and Bergischen Land (HENNINGSEN & KATZUNG 1992, GRUNERT 1988). At various stages of the Tertiary the area of the modern Niederrheinische Bucht was either dry land (Eocene) or a shallow sea (Oligocene), due to both independent variation in sea level and fluctuations in uplift/subsidence rates. Marine and estuarine sediments deposited during the Oligocene form a significant part of the substrate and are exposed at the surface in various locations. Subsidence has been continuous since the lower Miocene, but the Niederrheinische Bucht has remained dry land due to high volumes of sediment delivery by the Rhine and its tributaries. Two further developments in the Tertiary have significance for the contemporary landscape of the Pleiser Hügelland. Beginning at approximately the transition between the Oligocene and Miocene was the development of a northwest/southeast oriented horst/graben system associated with ongoing tectonic activity (GRUNERT 1988). At the same time volcanic activity in the Siebengebirge complex began, producing deep deposits of trachytic tephras and a series of alkaline basalt and andesite intrusions (VIETEN 1983, VIETEN *et al*. 1988).

At the beginning of the Pleistocene, this region was characterised by a wide, shallow Rhine valley filled with coarse alluvial sediment (GRUNERT 1988). Relief was considerably lower than that of today’s lower Rhine gorge, which is the product of high rates of uplift throughout the Quaternary. BRUNNACKER & BOENIGK (1983) give an average Quaternary uplift rate of 0.082 mm/a for the Rheinische Schiefergebirge. Pleistocene climatic fluctuations against a background of continuing uplift resulted in both the generation and deposition of sediments during colder periods and valley incision during warmer periods. The result was the formation of a series of terraces of decreasing age and elevation in the main Rhine valley (SEMMEL 1972, BRUNNACKER & BOENIGK 1983). Throughout this time, the development of the horst/graben system continued. Most significant for the Pleiser Hügelland was the development of the Hardthorst, which separates the region from the Rhine valley. The Pleiser Hügelland lies within the corresponding Siebengebirgsgraben, with a general direction of dip to the north, and drainage is therefore towards the Sieg. The Pleiser Hügelland was thus isolated from the Rhine valley and did not experience the same degree of terrace development, although there were similar flights of terraces formed – on a smaller scale – by the Sieg. Most of these alluvial sediments have been eroded; today there are very few remnants – generally restricted to plateau areas – of the oldest and highest of the Pleistocene terraces in the Pleiser Hügelland, and virtually none of younger terraces.

During the Pleistocene glaciations, the region was covered with loess blown from the west (GRUNERT 1988). Earlier loesses and the interglacial soils they supported were for the most part eroded during subsequent cold periods. Late Pleistocene Würmian and/or Weichselian loesses are the most significant in the Pleiser Hügelland today, and those in which contemporary soils are formed are derived from the Pommersche stadial (~18,000 ybp). Although uplift began in late Pliocene, the Rheinische Schiefergebirge were never high enough to sustain glaciation during the Pleistocene (HENNINGSEN & KATZUNG 1992). Nevertheless, because of its close proximity to the inland ice the region was very much a periglacial environment, and periglacial mass wasting processes have had an influence on the nature of landforms throughout the Bonn region (SIEGBURG 1987, 1988). Slopes of both the major valleys and the small headwater basins exhibit a marked degree of asymmetry that cannot be fully accounted for by either tectonic tilting or differences in lithology (SIEGBURG 1988). Rather, the origin of this asymmetry is attributed to the effects of Pleistocene solifluction – the rates of which have been influenced by variation in both snow and insolation receipt. Differences in rates of solifluction on the slopes themselves, and the effect that differential delivery of debris from opposing slopes has on stream behaviour, are invoked to explain the widespread valley asymmetry (SIEGBURG 1987, 1988).

In general, with the exception of isolated volcanic features, the modern topography is one of subdued relief, with widespread loess deposition having concealed any more rugged terrain that may have existed under periglacial conditions. Nevertheless, there is a relatively high drainage density, and the landscape is deeply dissected in places. This suggests that there was already a maturely dissected terrain existing under periglacial conditions, that was subsequently buried by loess, and that Holocene landform development involves the re-exposure of this terrain. These relatively deeply incised small headwater basins are a characteristic feature of the landscape. Although superimposed on inherited Pleistocene valleys incised into Tertiary material and alluvial terraces, NICKE (1989) characterises these as Holocene landforms (*Siefen*), formed under the natural forest cover, when runoff had lower sediment loads and greater erosive power.

Small scale mining of brown coal took place in the 19th century, and there are localised relicts of this visible in the landscape today. However, these are limited mainly to small topographic hollows and areas of subsidence and, given the relatively small scale of operation, it is considered that this played only a minor part in the overall development of the landscape.

3.4 Soils

The parent material of most soils is loess, with the nature of the soil varying principally as a function of topography and the degree of weathering and/or erosion. Where initial Holocene development of soil in loess occurred under relatively dry climatic conditions with grassland vegetation, Chernozem soils formed. The greater availability of moisture and the associated vegetation pattern to a large extent precluded the formation of this soil in the Niederrhein region, and the initial soils formed in loess were Brown Earths, characterised by decalcified B horizons. Moister conditions, possibly beginning already in the Late Glacial period but certainly within the Holocene resulted in decalcification, the development of iron oxides and iron hydroxides, eluviation/illuviation, and the transformation of primary silicates into secondary clay minerals. Simple loess soils were thus degraded to Luvisols, which are considered to have been the pre-Neolithic climax soil. A typical horizon sequence is as follows (HEIDE 1988):

A_h **h**umic horizon
A_l illuviated horizon (~10% clay) (**l** = *lessiviert*, i.e. illuviated)
B_t relatively dense clay (~25%) and silt enriched horizon (**t** = *Ton*, i.e. clay)
B_v less dense/more porous horizon, lower clay content (**v** = *verwittert*, i.e. weathered)
C loess

A soil fully developed to this degree is termed a Parabrown Earth, while the intermediate stage prior to the development of the leached horizons is termed a Brown Earth, and is characterised by a simple A-B_v-C horizonation. On the gentle terrain of the Niederrheinische Bucht this soil has developed to depths of between 2.0 and 3.0 m (PAAS 1968), while depths ranging from 1.5m (GRUNERT 1994) to 2.0-4.0m (ERDMANN 1998) are given for the Pleiser Hügelland. Their high silt content renders these soils highly erodible. Indeed, VAN VLIET-LANOE *et al*. (1992) argue that the typical interglacial soil succession would be towards degraded and eroded soils as climate deteriorates, i.e. leaching, acidification, reduction in organic matter and increasing erodibility (BORK *et al*. 1998). The Parabrown Earths were therefore a climax soil only in the sense that they were the typical naturally developed soil at the time immediately preceding anthropogenic environmental change. As a result of agricultural land uses, what VAN VLIET-LANOE *et al*. (1992) term the natural interglacial soil succession has continued at an enhanced rate, such that most Parabrown Earths in the study area have experienced varying degrees of erosion. In places erosion has been so severe that the contemporary soil is once again a Pararendzina (calcaric Regosol), i.e. characterised only by a calcareous loess C horizon and an organic horizon of 20-30cm. While loess soils are the most widespread, volcanic material and alluvial sediments also constitute a small part of pedogenic regolith. A similar pattern of pedogenesis is characteristic also of these substrates, although development has generally not advanced sufficiently for the appearance of A_l/B_t horizons, and these substrates typically form Brown Earths rather than the eluviated/illuviated Parabrown Earth. The simple preliminary developmental (or eroded) A-C form is termed a Ranker rather than a Pararendzina due to the absence of carbonates.

On sites where there is only a shallow soil cover over a relatively impermeable substrate, or where drainage is impeded for any other reason (e.g. the development of a B_t horizon), or in topographic convergences, Pseudogley variants of the Luvisols have developed. These soils experience saturation during high rainfall events, but can become very dry without rainfall. They exhibit characteristic marbled and striped features, reflecting solution and redistribution of iron and manganese in wet phases and leaching and concretion development during dry phases. Gleysols occupy sites with more-or-less permanent groundwater influence. The oxidation of iron and manganese gives them a rust-red G_o horizon, overlying a thin, wet, pale grey, grey green or blue black reduction horizon (G_r).

The remainder of the contemporary soil mosaic comprises allochthonous sediments resulting from Holocene colluvial and alluvial processes. Colluvium by definition must be at least 40cm in depth. Characteristic features include a greater representation of fine grains (fine sand, silt, clay), humus to greater depths, and at the surface a slight elevation of carbonates and skeletal content.

3.5 Land Use History – Human Occupation, Deforestation and Agriculture

A Palaeolithic presence in the Niederrhein region is inferred based on archaeological finds, not least with respect to the Neanderthals, but with increasing frequency from the Younger Dryas period (REICHMANN 1988). Palaeolithic populations were present in both the lower Sieg valley and the Siebengebirge (VON PETRIKOVITS 1978).

The Neolithic agricultural revolution expanded into central and northwestern Europe at some time in the middle of the 6th millennium BC, associated with diffusion of the Linear Pottery culture westward from the Carpathians (WHITTLE 1994). This culture, and thus agriculture, had reached the Niederrhein region by the middle of the 5th millennium BC (VON PETRIKOVITS 1978,

RECH 1983, REICHMANN 1988). REICHMANN (1988) suggests that these were possibly not the first farmers in the Niederrhein region; as there is evidence of earlier inhabitants with cultural affinities to more northern people who also practised agriculture. There is no evidence of local agricultural activity from these earlier inhabitants however. The pre-agricultural environment consisted essentially of closed forest. Early Neolithic societies were defined, however, both by their cultivation of cereals and animal husbandry and by their sedentary existence. The early farmers "... pioneered the temperate woodlands [and] established a distinctive network of hamlets and small villages ..." (WHITTLE 1994:137). Their favoured sites were the edges of river valleys and fertile loess soils. Although little is known of their actual farming practices, it is evident that they were responsible for small episodes of deforestation – both for field establishment and to provide the raw material for the construction of their wooden houses (WHITTLE 1994, REICHMANN 1988).

The pattern of mid-Neolithic settlement and the nature of the transition from the mid- and late-Neolithic periods to the Bronze and early Iron Ages is not clear. There is, however, considerable archaeological evidence of human presence in the Niederrhein region (VON PETRIKOVITS 1978, REICHMANN 1988). Over the period 5500-1300 BC Neolithic peoples in the Niederrhein evolved through a series of cultural influences: *Rössener*, *Michelsberger*, Corded Ware and Bell-Beaker (*Glockenbecher*) (SHERRATT 1994a,b, RECH 1983). Although not yet universally adopted, agriculture and the associated sedentary lifestyle were increasing. The slow environmental transformation through forest clearance continued, but remained almost exclusively restricted to the fertile loess soils. Given the simple and primitive agricultural techniques available, fertility would have been severely limited once erosion occurred, and thus a pattern of shifting deforestation can be inferred. Agricultural groups were widespread on the loess soils of the Niederrhein Bucht and present also in the lower reaches of the Sieg (VON PETRIKOVITS 1978, RECH 1983).

The period from 1300-600 BC saw further cultural development with the Urnfield and Bronze Age *Grabhügel* cultures (HARDING 1994, RECH 1983). An important development within the Urnfield period was the expansion of field sizes, although this was not as pronounced in this part of Europe and occurred later than in other parts of western Europe (HARDING 1994). The Niederrhein region was on the periphery of the Iron Age Halstatt culture (CUNLIFFE 1994a), and the population increased steadily from the end of the 8th century BC (RECH 1983). This cultural influence was supplanted by the Celtic *La Tène* culture ~450-400 BC (CUNLIFFE 1994a, RECH 1983). Europe was still largely forested, but agriculture and pastoralism were firmly established as the basis of subsistence economy (HARDING 1994). There is evidence of inhabitation dated to this period in the loess zone south of the lower Sieg (RECH 1983). In this period it appears that the Niederrhein region, including the Pleiser Hügelland, was a transition zone and experienced conflicts between populations of southern-oriented Celtic peoples and northern Germanic groups (CUNLIFFE 1994a). Nevertheless, populations were sufficiently established to defend their territories, and the construction of hilltop fortification was also characteristic of this period (HARDING 1994). There are remains of both Germanic and Celtic fortifications in the area – at Troisdorf-Sieglar and Petersberg respectively (RECH 1983, TACKENBERG 1954, VON PETRIKOVITS 1978).

It should be noted that the evidence so far cited for prehistoric population distribution relates to archaeological finds and does not therefore preclude the presence of human groups or of agricultural activity in other areas; indeed, maps presented by VON PETRIKOVITS (1978) indicate that all cultures occupied hill country sites, and it is not unreasonable to suppose that they may also have been present in the Pleiser Hügelland. TACKENBERG (1954) refers to evidence of both *Grabhügel* and *La Tène* cultures in Stieldorf and Birlinghoven.

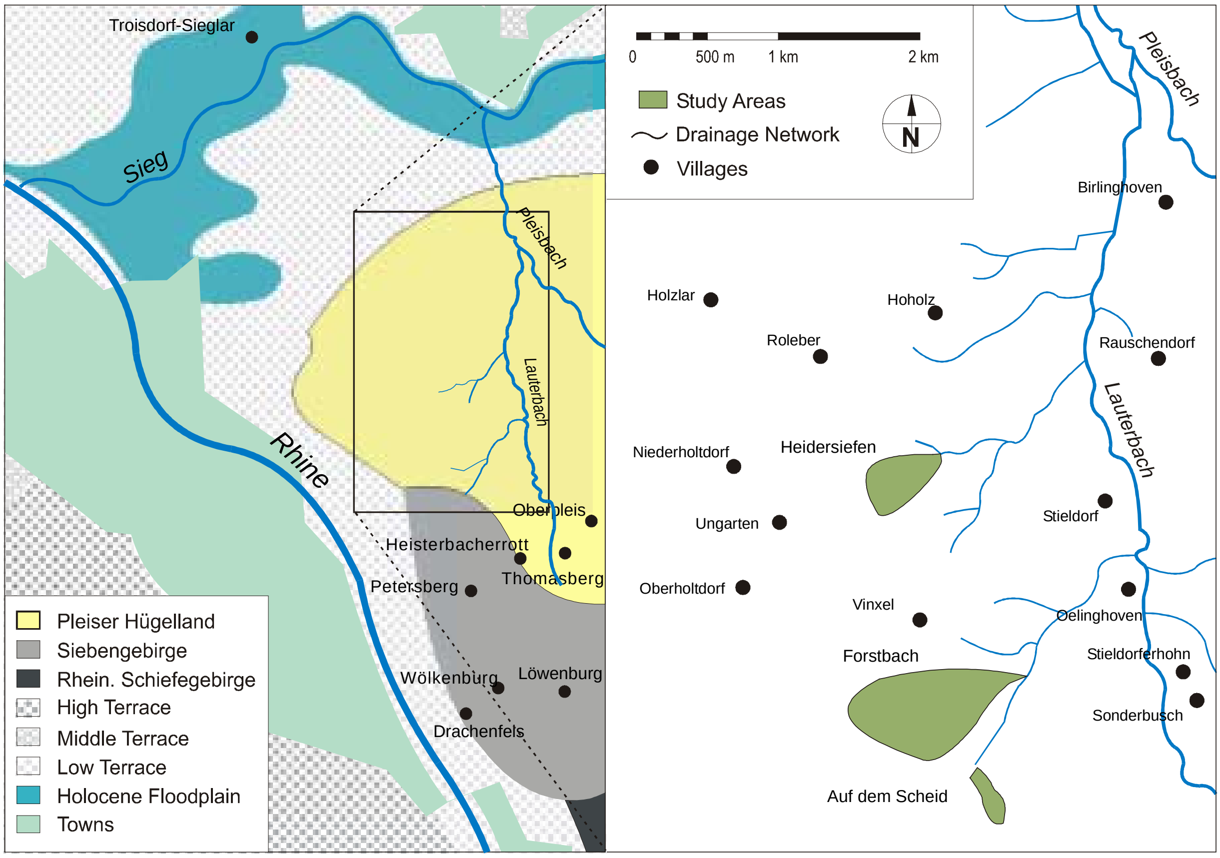


Figure 3.2: Location in relation to the three study areas of various towns and places mentioned in the text.

There are numerous small villages in the area (Fig. 3.2), and their history allows some conjecture about the timing of settlement and conversion to agriculture in the Pleiser Hügelland. Three phases of settlement can be recognised (HOMBITZER 1913): Celtic-Germanic-Roman (to 250 AD), Frankish (250-800), and Medieval (800-1300). On the basis of contemporary thoughts regarding climax vegetation patterns, HOMBITZER (1913) argued that both the Celts and the Germanic peoples who eventually superseded them found and occupied sites without forest, i.e. they did not themselves extend the area of cultivated land through deforestation. More recently, this idea has been demonstrated to be wrong, and that forest represented the climax vegetation for most of central Europe, i.e. other than for marginal ecotones (e.g. KÜSTER 1998). The presence of Celtic and Germanic peoples in the Pleiser Hügelland is inferred on the basis of archaeological finds in Stieldorf and Oberpleis. The site of the contemporary town of Vinxel is ascribed to a Germanic (or possibly Celtic) source, essentially because the name seems to have no meaning that can be attributed to subsequent residents (HOMBITZER 1913). An alternative explanation is that the name means "five fields" and derives from the Medieval period.

Romans arrived in the Niederrhein in ~55-53 BC and had conquered the left bank of the Rhine by 8 BC (REICHMANN 1988). Bonn itself was an administrative centre and garrison town, and there were attempts to expand east of the Rhine in the early decades of the first century AD. These were ultimately unsuccessful and the Rhine formed the eastern boundary of the Roman empire. Although the Germanic peoples occupying the area east of the Rhine traded extensively with the Roman-occupied Niederrhein (CUNLIFFE 1994b), it is likely that the immediate border area was probably not used for agriculture. The Romans had beachheads on the right bank of the Rhine and quarries in the Siebengebirge (BURGHARDT 1997), but it seems that the Pleiser Hügelland remained a fortified zone (HOMBITZER 1913, RECH 1983). Conflicts between the Romans and the expanding Germanic populations to the north and east saw the abandonment of the Rhine/Danube defensive system in 260 AD (TODD 1994). Following this, Frankish influence and population in the Niederrhein region began to increase from the middle of the 3rd century AD (TODD 1994, HOMBITZER 1913) and especially after the further demise of Roman influence following the sacking of Köln in 458 AD (RECH 1983, LAUX & ZEPP 1997). As with their Celtic and Germanic predecessors, the early Franks in the Pleiser Hügelland occupied formerly cleared sites (HOMBITZER 1913). On the basis of its *–lar* ending, HOMBITZER (1913) considers the town of Holzlar to be one such early-occupied site. Names ending with *–hoven* are attributed to a subsequent expansion into newer sites; Oelinghoven and Birlinghoven thus belong to this phase, and indicate that the valley of the Lauterbach, with its fertile loess slopes, was among the earliest areas settled by the Franks (HOMBITZER 1913). Heiderhof is also attributed to this first expansion phase (HOMBITZER 1913). Towns with names ending in *–dorf*, e.g. Stieldorf and Rauschendorf, are attributed to a second phase of Frankish expansion (HOMBITZER 1913).

The Frankish settlements developed into Medieval villages centred on the Carolingian Church (TODD 1994). The earliest archival references to many villages date back to the development of religious cloisters starting as early as 949 AD. One of the larger of these was the Cistercian cloister at Heisterbach, which was already in existence by 1197 AD (HOMBITZER 1913). Castles on the peaks of the Siebengebirge date from this period also: the Drachenfels castle was built some time between 1137-51, Wölkenburg in 1118, and Löwenburg prior to 1247. This was also the period in which sustained and extensive deforestation took place, principally on the terrace plateaux. Towns with origins in this Medieval period typically have names indicating their earlier forested nature, e.g. Stieldorferhohn, Hoholz, Sonderbusch, Heisterbacherrott. The phase of Medieval settlement was essentially over by 1300, and little has changed since then in terms of the addition of new settlements. The history of towns in the vicinity of the study area is briefly summarised in Table 3.2.

Table 3.2. Historical origins of selected towns in the Pleiser Hügelland (adapted from HOMBITZER 1913).

Settlement Phase		**Contemporary Town Name**	**First Historical Reference**
Celtic/German/Roman		Vinxel	1173
Frankish	*initial occupation*	Holzlar	
	First expansion	Birlinghoven	1117
		Oelinghoven	
		Heiderhof	
	Further expansion	Niederholtdorf	
		Oberholtdorf	1271
		Rauschendorf	1117
		Stieldorf	
Medieval (800-1300 AD)		Frankenforst	
		Heisterbacherrott	
		Hoholz	
		Roleber	
		Stieldorferhohn	
		Ungarten	
		Thomasberg	

Detailed information concerning the specific location and nature of agricultural activity is difficult to find, but it is assumed that agricultural land use in the vicinity of the study areas has been continuous since at least the 6th century AD, but may have been initiated as early as the Iron

Age – if not the Neolithic. Five farms existed in the area of Vinxel in the 12th century AD (LESSMANN-SCHOCH *et al*. 1991), while Frankenforst itself – the location of two of the study areas – dates back to at least 1475 (KELLERMANN AND HAVERMANN 1973). Similarly, it is difficult to reconstruct the timing and location of deforestation. Prior to human landscape changes, the natural vegetation in this region was mixed deciduous lowland forest (LÜNING *et al*. 1997). Cereals first appear in the regional pollen record ~3000 BC, i.e. in the Neolithic (REHAGEN 1963). Evidence of settlement increases from the late Bronze Age, as indicated by an increase of crop pollen and the simultaneous decline of alder. The latter, which is a typical riparian species, and thus one of the prime deforestation targets, declines steadily from this period (REHAGEN 1963). An increase in ash is also seen as possible evidence of deforestation, because it establishes more quickly than other species in disturbed forests. LESSMANN-SCHOCH *et al*. (1991) present pollen curves which indicate that in the 14th century the study area was experiencing a transformation from an already open woodland with significant areas of agriculture to a more-or-less completely deforested landscape. This confirms that the final phase of deforestation occurred at this time. It does not, however, give a fixed date for first deforestation – and lends at least circumstantial evidence to the suggestion that limited deforestation had occurred considerably earlier. Reversion to forest has also occurred at various times. Frankish settlers failed to occupy all previously deforested sites. Periods of less intensive agriculture and reversion to forest also occurred during a period of migrations following the demise of the Romans (the so-called *Völkerwanderungen*), and again following population decreases as a consequence of various Medieval catastrophes. Agricultural land use has intensified once again since the 18th century. Maps from the 19th century show widespread agricultural land use. Today, agriculture is restricted to the gentler slopes, and typically involves a three year rotation of corn, winter wheat/oats and barley/feed crops. Steeper slopes are in pasture. Only isolated stands of selectively logged mixed age deciduous forest remain, typically in gullies and in less favourable areas for agriculture.

3.6 Historical Soil Erosion

Considerable research into soil erosion has been carried out in the Pleiser Hügelland, and especially at Gut Frankenforst, by representatives of the University of Bonn's Soil Science and Geography Departments (BOTSCHEK *et al*. 1991; SKOWRONEK *et al*. 1994). Much of this has focussed either on characterising the extent of susceptibility to soil erosion and discussion of management or remediation aspects (e.g. BOTSCHEK *et al*. 1994, EVERDING *et al*. 1996, ERDMANN & ROSCHER 1991) or on parameterisation of empirical soil erosion models, e.g. the erodibility of soils (e.g. BOTSCHEK 1991), the erosivity of rainfall (e.g. ERDMANN & SAUERBORN 1991) and the influence of topography (e.g. ODINIUS & ERDMANN 1991). An important conclusion that can be drawn from this work is that runoff and sediment entrainment are not linearly related to larger scale morphometry (i.e. at the scale that is readily available from digital terrain data); microtopography is an important factor (SKOWRONEK *et al*. 1994, ODINIUS & ERDMANN 1991, ERDMANN & ROSCHER 1991). ERDMANN (1998) summarises a wealth of empirical soil profile data collected for the Bonn region, and relates the distribution of eroded soils to topographic factors.

GRUNERT (1994) gives a general overview of the history of soil erosion in the vicinity of Bonn. Truncated soil profiles at forest edges (WANDEL & MÜCKENHAUSEN 1950) are cited as evidence of prehistoric and historic soil erosion occurring since the Neolithic, although it appears that this is based on an assumption that deforestation at these particular sites dates back to this period. It is difficult to believe that the landscape has changed so little that a contemporary forest boundary – and associated erosion features – can provide evidence of Neolithic deforestation. Nevertheless, on the basis of average truncation of soil profiles, GRUNERT (1994) estimates an hypothetical average denudation of 0.1-1.0 mm/a since Neolithic deforestation. GRUNERT (1994) characterises the mid-Holocene (i.e. Sub-boreal, Sub-Atlantic, Bronze and Iron Ages) as a period with relatively dense farm settlement, soil erosion and the first evidence of floodplain sedimentation. Reference is made to extensive agriculture under Roman occupation, but no indication is given of whether there was erosion associated with this. Despite deforestation and constant expansion of agriculture (and associated soil erosion) since the mid-Neolithic, soil erosion is considered to have been of limited significance – with local exceptions – until the end of the 5th century AD. Further deforestation occurred between the 6th and 8th centuries, accompanied by soil erosion and floodplain development. The height of Medieval deforestation was between the 10th and 13th centuries, also accompanied by widespread erosion and floodplain development. Widespread erosion with colluviation and floodplain development is presumed to have been associated with both the catastrophic 1342 rainfall event and with climatic events at the height of the Little Ice Age. Erosional responses are also supposed for additional rainfall events that caused flooding of the Rhine. This pattern is essentially the same as that for most of central Europe (e.g. BORK *et al*. 1998), and GRUNERT (1994) does point out that little genuine knowledge is available for the study area.

One of the few studies of historical soil erosion in the study area was that of LESSMANN-SCHOCH *et al*. (1991), who suggest, on the basis of pollen analysis and radiocarbon ages from peat deposits, that anthropogenic colluviation in the study area commenced after the 14th century AD. Chronological information was obtained from a depositional site at Gut Frankenforst, where colluvial material of ~80-132 cm has buried organic-rich moor deposits. Pollen profiles from the underlying organic material indicate that it accumulated *in situ* (i.e. continuous development of the pollen curve, rather than a chaotic mixture), while its pedological development indicates accumulation under conditions of periodic overbank inundation and a more-or-less constant groundwater influence. The organic material has interfingering of mineral-rich material that is attributed to slope sources. Development of the moor was finally interrupted by a pulse of colluvium. Chronological information has been derived from the underlying organic material to obtain a maximum age estimate of the time at which this colluviation occurred. The presence of walnut (*Juglans regia*) pollen indicates that the formation of the organic horizons cannot have occurred prior to Roman presence in the region, while buckwheat (*Fagopyrum esculentum*) pollen further constrains the age of these deposits to post-15th century AD. ^{14}C ages from organic material underlying the colluvium are consistent at 470 ± 50 ^{14}C years BP (two samples; this corresponds to a calendar age of 1402-1611 AD[2]) and 500 ± 50 ^{14}C years BP (1326-1474 AD), and a branch that was incorporated within the upper extent of the moor material returns a ^{14}C age of 610 ± 60 ^{14}C years BP (1285–1434 AD). It was considered likely that the moist conditions will have led to groundwater contamination of the organic material, and that therefore the age from the wood, although stratigraphically inconsistent, was more reliable. Thus, the most recent moor accumulation cannot have occurred prior to 1285-1434 AD, which is therefore also the earliest time at which the colluviation event that terminated moor development could have occurred.

[2] The uncalibrated ages reported by LESSMANN-SCHOCH *et al*. (1991) – expressed here as, e.g. 470 ± 50 ^{14}C years BP – have been calibrated using a program developed by STUIVER & REIMER (1993). The calibrated calendar age range (2σ error) is quoted in parentheses. Where calendar ages alone are given, these are calibrated ages.

Pollen diagrams from the moor material (LESSMANN-SCHOCH *et al*. 1991) indicate that during its formation the regional vegetation was undergoing a transformation from an open woodland with significant areas of agriculture to a more-or-less completely deforested landscape. In other words, agriculture was already occurring in this area prior to the colluviation event that interrupted the formation of this moor deposit. If this colluviation event was indeed linked to a deforestation episode, the latter represented part of the final phase of the transformation to a deforested pasture/cropland, which commenced prior to 1285-1434 AD. It might further be speculated that in fact the colluviation event was not directly linked to a deforestation event; rather, it represents a case of enhanced erosion occurring some time after the landscape had been made more sensitive as a result of deforestation. This supports an hypothesis for the occurrence of erosional events in association with extreme climatic events in the early 14^{th} century, and provides circumstantial evidence in support of rapid deforestation occurring shortly prior to this.

WELP *et al*. (1999) investigated an adjacent colluvial profile and found approximately 1.5 m of colluvium overlying moor material. Samples of organic material from the colluvium were dated with ^{14}C, giving ages comparable to those of LESSMANN-SCHOCH *et al*. (1991). A sample from within the moor returns an age of 1300-1430 AD, while four samples from within the colluvium (at depths of 50-54 cm, 87-95 cm, 130-138 cm and 142-148 cm) returned ages of 1500-1955 AD, 1450-1650 AD, 1440-1640 AD and 1440-1640 AD respectively. On the basis of these ages, WELP *et al*. (1999) calculate accumulation rates for three periods: 12.2 mm/a for the first Medieval colluviation, 4.1 mm/a for the later Medieval period, and 1.8 mm/a for the modern period.

BRÄUER *et al*. (1996) investigated the development of Gut Frankenforst slopes as a function of soil erosion. Luvisols on middle and upper slopes have been truncated by between 120 and 170 cm and, in cases where fluvial transport of sediments has not been possible, there has been correlate colluvial accumulation on the footslopes. Where competent streams are present, some proportion of eroded material has been exported beyond the boundaries of these simple slope systems. Within one 50 m reach of a small ephemeral stream, fluvial transport has removed ~3,200 m^3 of material, leaving a terraced colluvial body of ~1,280 m^3 (BRÄUER *et al*. 1996). This represents a long term sediment delivery ratio from this reach of ~71%. Soil erosion has thus contributed to landform development: in the absence of streams, local relief has been reduced – loss of elevation of upper and middle slopes and gain in the topographic low points; where streams are present, the change in relief is more complex, and terrace features have formed.

Chapter 4

Methodology

4.1 Introduction

The objective of this chapter is to provide an overview of methods used in this study and to describe their conceptual bases. Specific and detailed descriptions of aspects of the methodology are given where necessary. There are three sections in this chapter that specifically deal with methods used in this work. Firstly, the identification and mapping of colluvial sediments is fundamental to this work, and the assumptions and definitions adopted in the analysis of field and laboratory samples are outlined here. Secondly, the use of caesium-137 (^{137}Cs) as a geomorphological tool is described, including a summary of the models that have been used to determine erosion and deposition rates on the basis of ^{137}Cs data. And thirdly, an overview of the optically stimulated luminescence dating technique is given. In the final section of this chapter, the use of these various techniques is summarised in a description of the methodological approach adopted by this study.

4.2 The Spatial Distribution of Soils and Accumulated Sediments

An objective of this study is the development of historical sediment budgets for discrete spatial units, and the development of trajectories of sediment redistribution and accumulation through time. This requires that the distribution of erosional and depositional areas be identified, and that volumes of both eroded soil and accumulated sediment be quantified. Various approaches are available for the quantification of sediment volumes in storage units. The more direct method involves three dimensional reconstruction of sediment bodies using stratigraphic information. Cross sectional profiles are established using a series of boreholes and exposures. Sampled locations of stratigraphic contacts can be treated as co-ordinates in three-dimensional space and used to reconstruct former surfaces. The accuracy of this approach is, of course, very much dependent on the density of sample points. Information for three dimensional extrapolation may also be acquired using geophysical techniques (seismic, geoelectric and ground penetrating radar), with borepoint data used for calibration purposes (e.g. LÖWNER 2000). However, this approach has not been fully established and will not be applied here. Another technique involves the use of soil type distributions where this is mapped with sufficiently detailed resolution (e.g. 1:5,000). Representative depths for respective soil units can be determined through field sampling, and multiplication of these by the area covered by each soil unit produces volumes of soil or sediment. In particular, volumes of sediment in storage can be estimated with reference to mapped distribution of colluvial and alluvial soils. Volumes of material eroded can be determined on the basis of soil profile truncation. This represents a simple and relatively quick means of obtaining information about sediment volumes. Such an approach for reconstructing prehistoric sediment redistribution has been taken by, for example, EVANS (1990) in Britain, by CLEMENS & STAHR (1994) in the Kraichgau hills of Baden-Würtemburg and by FEISE (1999) in the Heidersiefen study area.

The collection of data in the field involved a series of soil surveys using an auger and drilling using a percussion borer (5 cm diameter core). On the basis of the information so revealed the distribution of soil types as mapped was verified and representative depths determined. This information is used to construct a series of soil profiles and transects.

A crucial issue is the identification of colluvial/alluvial sediments, and the distinction between these and *in situ* soils. It is difficult to clearly identify material as colluvium in many cases. Colluvial *bodies* can often be easily identified on the basis of landscape morphology, or alternatively when major excavations and the exposure of stratigraphy are possible. Micromorphological analysis of sediments that have not been disturbed in the process of sampling can often give a good indication of colluvial accumulation, as distinct from *in situ* soil development. In some cases, outcrops are available, but usually identification must be done using minimal information from soil augers and drilling cores. The identification of colluvial – or allochthonous – sediments in a narrow soil auger or recovered core is not always easy, especially when the deposited material does not differ markedly from its source soil. This is particularly the case in arable areas, where tillage over long periods has destroyed not only pedogenetic horizons, but also event-based colluvial strata *if* these were in fact present. The most straightforward indicator of colluvium is of course the presence of "foreign" objects such as charcoal, organic inclusions and archaeological artefacts. The presence of stones within a sediment column can be somewhat ambiguous. Where these are clearly not related to the local substrate, they may reasonably be taken as an indication of sediment accumulation. Alternatively, if they are of the same lithology as the substrate, they may simply be an especially resistant and unweathered remnant of this. Consideration should also be given to location of stones within the sediment column, and the possibility that they may have been incorporated not only during colluvial accumulation of sediments, but also by tillage or as a result of solifluction.

As a simple diagnostic criterion, a humus content of >0.9% by weight is indicative of colluvium for the silty soils characteristic of the study area (AG BODEN 1994). Naturally, this needs to be seen in a stratigraphic context; surface soils with high organic contents are not necessarily colluvia. More significant is the variation in humus content throughout a soil column. Higher organic contents should not occur within the mineral horizons of a mature undisturbed soil, and may be an indicator of a colluvium derived from surface soil, or of organic material incorporated during transport. Not all soils that erode are humus-bearing, however, and higher organic contents are not a requisite defining characteristic of accumulated sediment. A good indication of accumulated sediment is given by variation in humus content throughout the sediment column, which can be seen as an indication of fluctuation between erosion and stability. Strata/horizons with higher organic contents may represent initial phases of soil formation, while those with low organic content correspond to deposition of non-organic soils. Alternatively, such a sequence may represent fluctuation in the energy conditions under which deposition occurs.

Within loess areas, the presence or absence of carbonate ($CaCO_3$) in soils and sediments has considerable diagnostic significance. Loess itself in the study area has a characteristic $CaCO_3$ content of ~20%. This, along with texture and colour, is a clear indicator of loess. Loess soils, by definition, are decalcified, so the presence of $CaCO_3$ is not expected in the various horizons of loess-derived soils. Where it is found in material that is clearly not loess, it is assumed to be diagnostic of a loess-derived colluvium. Its absence, however, does not have as clear an interpretation; such material may be an *in situ* soil, or it may be colluvium derived from non-$CaCO_3$-bearing soil.

As with organic content and the presence of $CaCO_3$, soil texture can serve as a diagnostic tool for identification of colluvium. Loess has a very characteristic silty texture, while its derivate soils can have elevated clay contents. Again, stratigraphic relationships are important, especially regarding the difference between lower clay contents in the eluviated A_l horizon and higher values in the illuvial B_t horizon. Less energetic erosional processes are size selective of the material that is entrained, and at the same time, the energy of transport media is a control on the location and texture of deposited material. Silt-sized particles generally have the lowest entrainment threshold, and are preferentially eroded in low energy rainfall-runoff. Similarly, silts are the first to settle out of transport as energy of flow decreases at the footslope. Silty textures can thus be expected to be characteristic of loess-derived colluvia. This is problematic, as this is also diagnostic of loess. Hence the need for recourse to other criteria. Higher clay contents, where these cannot be attributed to a B_t horizon may also be indicative of colluvia. At the same time, elevated contents of sandy textures – particularly when concentrated in narrow bands – are also indicative of alluvial deposition.

4.3 The Caesium 137 Technique

Caesium-137 (^{137}Cs) is a product of nuclear fission, such as occurs in nuclear reactors or in atomic weapons. It is not, therefore, a naturally occurring substance, and was not present in the natural environment prior to the middle of the 20th century. It is present in the environment today globally as a result of atmospheric testing of nuclear weapons, and on a geographically restricted basis due to accidental emissions from nuclear reactors. Early occurrences of anthropogenic nuclear fission were relatively small, and radioactive products were only locally distributed as fallout. However, the larger atmospheric weapons tests, which began in the early 1950s, released radioactive products into the stratosphere, where they entered the global circulation system. They are then returned to the surface of the Earth as fallout associated with precipitation. Although there are differences between the northern and southern hemispheres in the amounts of ^{137}Cs precipitated as fallout, due to the greater number of tests conducted in the north and limited inter-hemispheric mixing, ^{137}Cs has become to all intents and purposes globally ubiquitous. Due to its relatively long halflife of 30.07 years (FIRESTONE *et al.* 1996), considerable amounts remain in the environment, and it is easy to detect – even at low levels – with sophisticated modern gamma spectrometers.

In 1986, the Chernobyl nuclear reactor in the then USSR failed, releasing radioactive products into the atmosphere, including ^{137}Cs. This ^{137}Cs also contributes to concentrations found in the soil today. However, this was a leak rather than an explosion. Radioactive products therefore were not injected into the stratosphere, but were distributed with regional weather systems. As such, the pattern of Chernobyl derived fallout is quite distinctly different from that of the uniformly distributed weapons derived fallout. This is important when employing the ^{137}Cs technique for high resolution dating. However, in terms of relative ^{137}Cs concentrations at local scales, it is not a significant issue.

4.3.1 Caesium 137 as a Geomorphological Tool

At the Earth's surface ^{137}Cs is rapidly and strongly adsorbed onto soil particles, particularly those in the fine earth fraction (<2 mm). Adsorption occurs within the surface soils, i.e. the upper 5 cm, and once bound onto soil particles in this zone, ^{137}Cs is very resistant to subsequent detachment by water. Some movement of ^{137}Cs does occur within the soil profile through bioturbation, but for the most part redistribution of ^{137}Cs occurs in association with soil redistribution (ROGOWSKI & TAMURA 1965, 1970). As a well constrained temporal indicator, and because its redistribution is associated with the redistribution of soil and sediment particles, ^{137}Cs has considerable potential for use within geomorphology. Use of ^{137}Cs as a geomorphologic tool is briefly reviewed here, although first it is important to clearly define the sources of ^{137}Cs in the soil (Fig. 4.1). As described above, ^{137}Cs in the soil is derived directly as atmospheric fallout through precipitation. Clearly, this is to an extent subject to spatial variation in precipitation receipt, due to climatic patterns or local topography. However, on a local scale (GOVERS *et al.* (1996) give a figure of ~10 ha.) these factors can be discounted, and ^{137}Cs inputs assumed to be uniform. Alternatively, because of its strong adsorption onto fine grained sediments, ^{137}Cs may also be derived from sedimentary inputs. It is this last point that makes ^{137}Cs especially valuable in geomorphologic studies, but which also places a limit on possible interpretations.

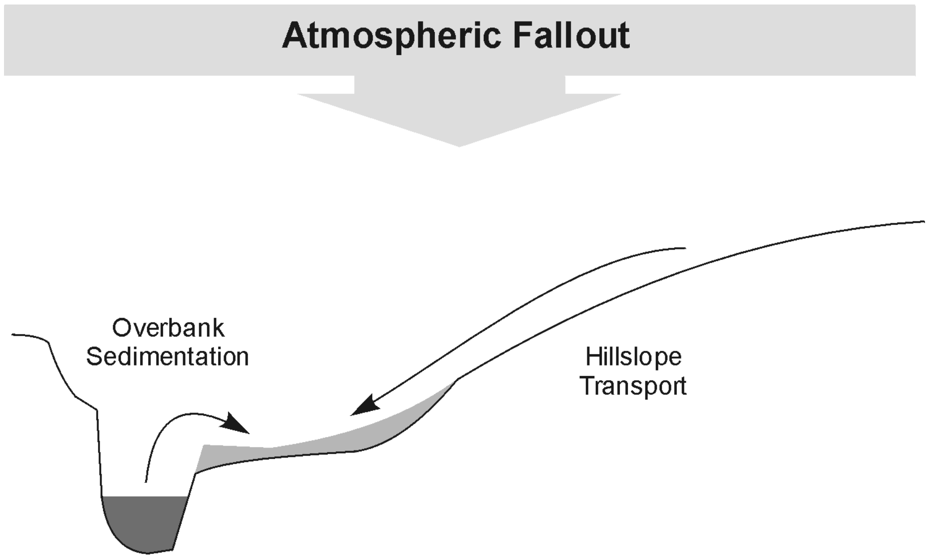


Figure 4.1: Pathways through which ^{137}Cs can enter sediments. It may be derived directly from atmospheric fallout, or it may be deposited in association with recent colluvial and/or alluvial sediments.

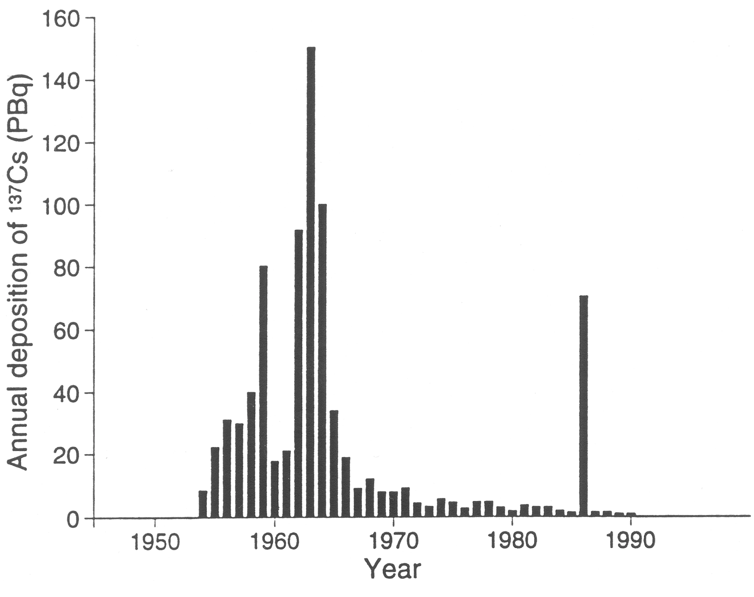


Figure 4.2: Historical pattern of ^{137}Cs fallout rates (from OWENS *et al.* 1996).

The temporal distribution of ^{137}Cs fallout is known, at least at global scales (Fig. 4.2) and, in some cases, at regional or local scales. This enables, in certain circumstances, dating of sediment deposition. In the simplest case, depth profiles of ^{137}Cs concentration within sedimentary soils can be correlated with the temporal distribution of ^{137}Cs fallout. The depth at which peak ^{137}Cs

concentration in the soil occurs is assumed to represent sediments deposited in 1963 – the year in which peak fallout occurred, synonymous with the height of atmospheric weapons testing (Fig. 4.2). This is a simple and powerful approach to dating of sediments, and to establishment of sedimentation rates. However, there are a number of restrictions to its application. Such a correlation can only be made in depositional environments. In stable soils, all the fallout ^{137}Cs is concentrated in the upper few centimetres, and hence depth profiles will show little vertical resolution. Neither is this approach valid for eroding sites, where some or all of the ^{137}Cs derived from either fallout or previous depositional events will have been removed. It is important that sediment deposition should have been continuous since at least 1954 – assuming that this is the year in which ^{137}Cs fallout commenced. If deposition has been discontinuous then vertical resolution within the concentration profile will be lost for the period of non-deposition, and if deposition has been interrupted by episodes of erosion, the concentration profile will be truncated. Similarly, if deposition does not pre-date receipt of fallout ^{137}Cs, vertical resolution will also not be apparent. Further, for such a correlation to be valid, it is necessary that sedimentary inputs of ^{137}Cs are either constant and can thus be discounted, or are known and can be subtracted from the overall concentration. If this last condition is not satisfied, variation in the relative contributions of atmospheric and sedimentary inputs preclude direct correlation of high ^{137}Cs concentrations with periods of high fallout input.

Clearly, if rates of sedimentation are already known, there seems little point in using ^{137}Cs concentrations other than for calibration or corroboration. Nevertheless, the record of temporal distribution of fallout may serve the useful purpose of establishing rates of sedimentation where these are *not* known. When known atmospheric contributions are subtracted from observed concentrations; the balance represents sedimentary input (WALLING & HE 1992, HE *et al*. 1996). Similar conditions regarding the nature of deposition must be satisfied however, and in this case it is essential that deposition should have been constant. If deposition were not constant, it is possible that: (a) high fallout inputs may have been distributed over a considerable depth if they are coincident with a period of high sedimentation, or (b) low fallout inputs may have been concentrated into a narrow depth range due to low sedimentation. Given these restrictions on the application of this approach, it is likely that direct annual correlation can be made only in very limited circumstances – possibly only in limnic or marine environments.

The foregoing discussion is intended to highlight the care that must be taken in interpreting ^{137}Cs occurrence within the stratigraphic record. However, while there are severe limitations to its use for dating with annual resolution, this does not completely invalidate the use of ^{137}Cs as a dating technique. The use of ^{137}Cs has proved immensely valuable in studies of both soil loss (e.g. M^C^HENRY *et al*. 1973, RITCHIE *et al*. 1974a,b, BROWN *et al*. 1981, DE JONG *et al*. 1983, LANCE *et al*. 1986, LOUGHRAN *et al*. 1987, LOWRANCE *et al*. 1988, SUTHERLAND & DE JONG 1990) and sediment redistribution at basin scales (e.g. CAMPBELL *et al*. 1986, WALLING *et al*. 1986, WALLING & QUINE 1990a, 1991a, QUINE & WALLING 1992, QUINE *et al*. 1994, 1997). Its true value lies in the fact that it enables elucidation of sedimentary spatial dynamics. The presence of ^{137}Cs in a depositional environment provides a well constrained date in that such sediments cannot have been deposited prior to 1954. With this approach, the temporal distribution of fallout is less relevant, although in defining the period to which analyses apply, the date at which fallout commenced is important. The important element within this approach is not intra-profile comparison of ^{137}Cs concentrations; it is inter-profile differences that are of interest. It is the total amount of ^{137}Cs at a given site – the ^{137}Cs inventory – that is measured rather than amounts at different depths. Comparison of sampled inventories with the inventory of an undisturbed site enables a distinction to be drawn between sites that have experienced erosion or deposition (Fig. 4.3). Furthermore, the loss or gain of ^{137}Cs relative to the inventory of the undisturbed site allows establishment of a *maximum net* rate of sedimentation since 1954 (see section 4.3.3 below). The derived rate is a *maximum* because it cannot be assumed that the sediments are not younger than this, and it is *net* unless it is known that there have been no intervening episodes of erosion. More recently, ^{137}Cs has been used as tracer (e.g. WALLING & WOODWARD 1992, WALLBRINK *et al*. 1998, WALLING & HE 1999a, WALLING *et al*. 2000, OWENS *et al*. 2000). However, this approach is not taken in this study and will not be further discussed.

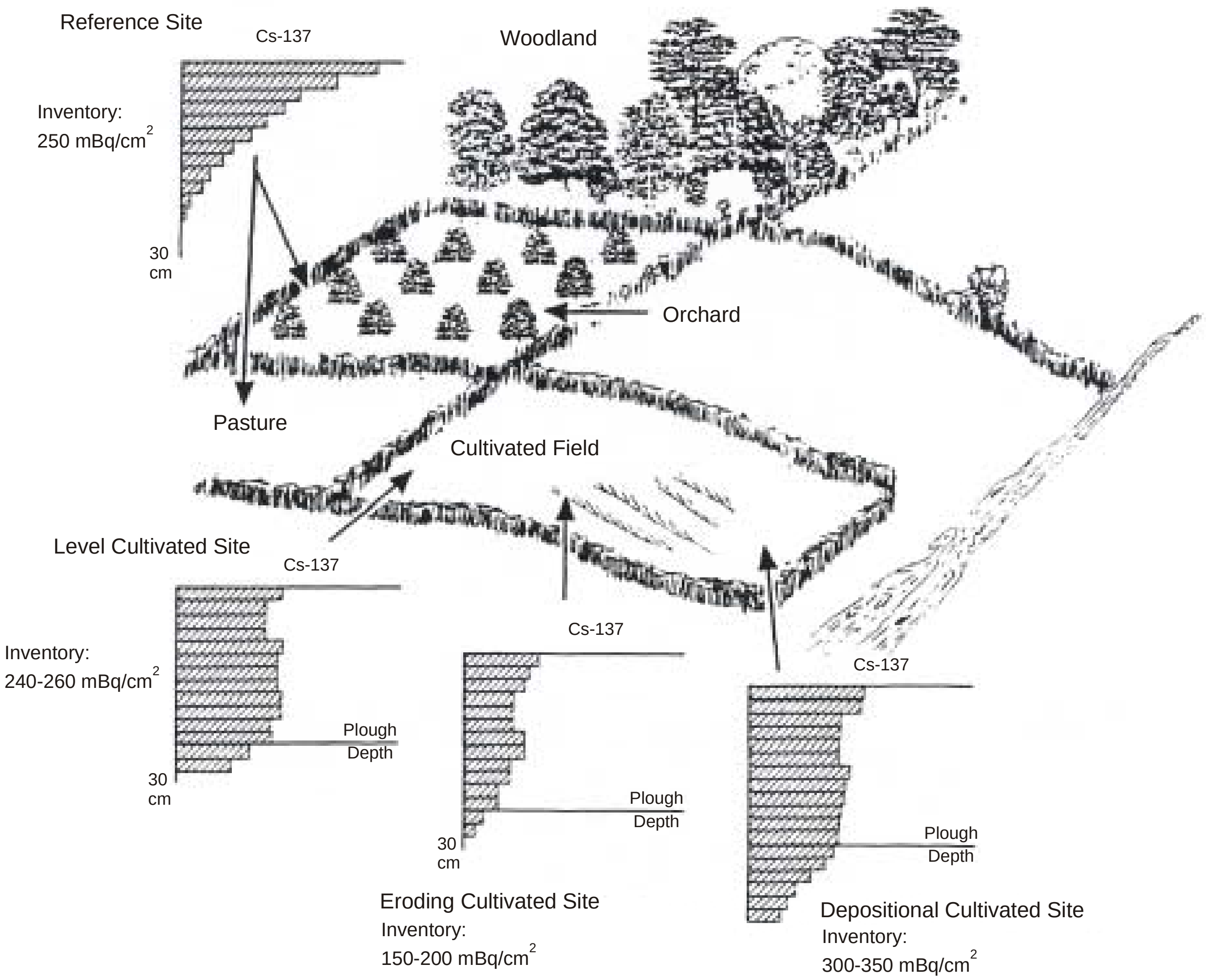


Figure 4.3: Distinguishing between undisturbed, eroded and depositional sites on the basis of ^{137}Cs inventories (WALLING & QUINE 1991b).

As with any technique or procedure, there are various assumptions underlying the use of ^{137}Cs as a tool within geomorphology. One must be aware of these if one is to reliably interpret ^{137}Cs data. Some are fundamental to the use of ^{137}Cs, while others are more specific to various modelling applications. While extensive discussion of these assumptions, and the validity of the technique, can be found in the literature (e.g. RITCHIE & M^{C}HENRY 1990, WALLING & QUINE 1991b, 1992, GOVERS *et al*. 1996), it is nevertheless appropriate that fundamental assumptions be reviewed here. These can be summarised as:

Uniform fallout distribution at local scale. This seems reasonable given the long period over which significant fallout occurred. The likely spatial variability within individual events is probably cancelled out over the long term. Chernobyl fallout is possibly an exception, because it was not stratospheric and occurred over a short period. Nevertheless, at very small scales this is considered unlikely to be significant.

Rapid adsorption onto soil particles. There is ample field and laboratory evidence supporting this assumption, e.g. BACHHUBER *et al*. 1982, LIVENS & LOVELAND 1988, WALLING & QUINE 1992.

Redistribution of ^{137}Cs is in association with sediment. This assumption underlies the first applications of ^{137}Cs to erosional studies, which were based on the experimental evidence of ROGOWSKI & TAMURA (1965, 1970). DALGLEISH & FOSTER (1996) argue that a proportion of incoming ^{137}Cs may be bound directly to sediments already in transit during large rainfall-runoff events, i.e. in overland flow. Where this has occurred – and they acknowledge that it is impractical to try and reconstruct this empirically – sediment deposition may be overestimated. This may also have implications for the determination of appropriate reference values where these are derived from the fallout record. More important is the preferential adsorption of ^{137}Cs to the silt and clay fractions. This is important where size selective redistributive processes are involved, e.g. where only finer fractions are removed, ^{137}Cs loss is greater for a given soil loss. Alternatively, where only finer sediments are involved, it should be assumed that deposited material will be relatively depleted in ^{137}Cs.

Erosion-deposition rates can be estimated from ^{137}Cs inventories. This assumption has the greatest uncertainty, but is also least important with respect to comparison of patterns. Error associated with modelling is systematic rather than point specific. Variation in estimates occurs as a result of different calibration procedures, although such variation is of limited magnitude. Nevertheless, there is increasing evidence of the validity of this assumption, e.g. KACHANOSKI 1987, QUINE & WALLING 1993, QUINE *et al*. 1994).

4.3.2 Sampling and Measurement

Collection of ^{137}Cs samples for measurement is relatively simple. Samples are taken in cores – vertically sectioned where high resolution (annual) dating is required, or bulked where this resolution of information is either not needed or cannot be derived due to site conditions or practical considerations. The volume of sample required varies with the type of measurement apparatus, ranging from tens of grams to 1-2 kg. Samples are air dried and, in many cases, sieved. Where necessary, organic matter may be removed first. As ^{137}Cs is preferentially bound to silts and clays, it is necessary only to separate the fine earth fraction (<2 mm). Dry weight of sample material is recorded.

In this study measurement of ^{137}Cs activity takes place by means of high resolution gamma (γ) spectrometry. The core of the γ-spectrometer is an extremely high purity germanium crystal flanked by positive and negative electrodes delivering a very high voltage. The sample is placed in a container (Marinelli beaker) surrounding this crystal. During radioactive decay quants of γ energy are emitted. Some of these will interact with the detector, inducing electron displacement within the germanium crystal. Displaced electrons are “immediately” attracted to the cathode of the detector, and replaced within the crystal by an electron delivered from the anode. In other words, the interaction of the γ-quant with the germanium crystal induces an electrical flux. Each such occurrence is amplified and recorded as a *count*. Each radioactive decay sequence emits γ quants of a specific energy, measured in electrovolts (eV), which determines the strength of the electrical field. Plotting the counts against γ energy enables identification of peaks indicating presence of a given radioactive isotope within a sample. The characteristic γ energy of the ^{137}Cs

→ ^{137}Ba decay is 662 keV. Thus a count peak (above background noise, and recognising that other radioactive decay series may also be occurring within the sample) at this energy level indicates the presence of ^{137}Cs, while the number of counts is an indication of its concentration. The precision of the measurement is dependent on counting statistics, with the 1σ error in the number of counts (δn) defined as $\sqrt{n}$, where n is the number of counts. For example, a count of 1,000 would be associated with an error of ± 31.62 (i.e. ± ~3%). It is necessary, therefore, to run each sample measurement for sufficient time such that enough counts are recorded to reduce the error term to an acceptable level. Measurement time is thus dependent on both the efficiency of the detector and the desired accuracy, and of course sample size and the concentration of ^{137}Cs within the sample. Typical counting times are on the order of 43,200 s to 172,800 s (i.e. from 12 to 48 hours). Count measurements are calibrated by reference to a standard material, i.e. a sample with a known ^{137}Cs activity. The unit of activity is the Bequerel (Bq), defined as 1 count per second. ^{137}Cs concentrations within a sample of given dry weight are expressed in units of Bq/kg.

In an initial survey for this study, ^{137}Cs was found to a depth of 30 cm at a nearby depositional site, confirming similar measurements made in the area by WELP *et al*. (1999). It was considered therefore that sampling to a depth of 50 cm enabled recovery of all ^{137}Cs present. Bulk samples were taken in an open cylinder with a diameter of 6.8 cm, which ensured that sufficient volume of soil was recovered for measurement using a Marinelli beaker with a 1 litre capacity. The dry weight of sample material (<2 mm) was recorded. The content of ^{137}Cs in each sample was determined by γ-spectrometry at the Max-Planck-Institut für Kernphysik in Heidelberg, and expressed as concentrations of ^{137}Cs per unit weight. Concentrations per unit weight (Bq/kg) have been converted to areal activity (Bq/m^2) using the following equation based on SUTHERLAND & DE JONG (1990):

$$Cs_{area} = Cs_{mass} \times BD \times D \times 1000 \qquad (4.1)$$

Cs_{area}	total areal activity	(Bq/m^2)
Cs_{mass}	concentration per unit mass	(Bq/kg)
BD	bulk dry density	(kg/m^3)
D	depth of sampling	(m)

Multiplication by a factor of 1,000 converts the measured value from a 1 litre Marinelli beaker to a value appropriate to a cubic metre of soil/sediment. Data are listed in Appendix B.

4.3.3 Modelling Sediment Redistribution Rates using ^{137}Cs

Determination of sediment redistribution rates, i.e. quantification of erosion and deposition, is based on establishing a relationship between the loss/gain of ^{137}Cs and soil/sediment. This may be done empirically or, as is discussed in this section, using numerical models based on the behaviour of ^{137}Cs and the physical processes of sediment redistribution. Quantification of absolute ^{137}Cs loss and gain is achieved by comparison with a reference inventory of ^{137}Cs activity at a stable, undisturbed site which is assumed to represent the total fallout received at the study site over the entire period of fallout. Alternatively, the input of ^{137}Cs fallout to the soil system can be derived through reference to local fallout records where these exist.

Considerable progress has been made in recent years in the development of numerical models for determining soil loss and gain on the basis of ^{137}Cs measurements (e.g. QUINE 1989, 1995, WALLING & QUINE 1990b, QUINE *et al.* 1996, 1997, WALLING & HE 1997, 1998, 1999b). Increasingly, these are based on a recognition of process behaviour. The movement of ^{137}Cs through the landscape occurs with all soil/sediment redistributive processes, and represents therefore an integral signal of all processes that have been active over a period of decades. This will include virtually all geomorphic processes, but for the landscape considered here these include principally water erosion (overland flow, rilling, gullying) and tillage translocation. There are important differences between these two processes that have considerable significance for the redistribution of soil/sediment and thus also of ^{137}Cs. These relate to distance of transport and size selectivity of both particle entrainment and deposition. Tillage is not size selective; it entrains and transports all particles within the depth of the plough horizon. This occurs only over a short distance with each tillage operation. However, over a longer period the distance of transport of each individual particle may be considerable – dependent on the pattern of tillage. Topography – principally slope angle – also influences transport distance. In representing the tillage process within a numerical model, relevant variables that should be considered therefore include: topography slope angle, tillage depth, direction, frequency and variations in these. By contrast, low magnitude water erosion processes generally affect only the surface soils, and thus a more limited range of particle sizes. Furthermore, dependent on the energy of the event, a selective range of particles will be entrained – not simply all that are present. More extreme water erosion events, i.e. gullies may, however, erode and transport all material to considerable depths. Transport distance for each particle size class is also dependent on energy, which is a function of event magnitude and intensity and of topographic controls on flow. Ideally, event magnitude and intensity would be included in truly physically based model; this is difficult to achieve, however, and energy is typically represented within models by topographic factors.

It should also be kept in mind that the effectiveness of water in both entraining and transporting particles will be influenced by land use, e.g. similar magnitudes of runoff will have different impacts on agricultural land and pasture. Thus land use, insofar as it determines the range of processes by which ^{137}Cs in the soil may potentially be eroded and transported, is an important factor in determining the choice of model used to relate ^{137}Cs loss/gain to soil loss/gain. WALLING & HE (1997, 1999b) present a range of models appropriate to cultivated or uncultivated surfaces and with varying parameterisation requirements. Two of these will be applied to the Auf dem Scheid catchment. A full description of the equations employed within these models is given in Appendix C, and the details of their parameterisation are described here.

Mass Balance Model

The mass balance approach recognises that soil loss/gain is not simply proportional to loss/gain of ^{137}Cs. Rather, the response of ^{137}Cs in the soil relative to both soil properties and the relevant aspects of process behaviour must be taken into account. The particular mass balance model used here incorporates both water erosion (sheet) and tillage translocation processes. As input the model requires:

- The temporal distribution of ^{137}Cs fallout. This has been derived from a dataset, based on published fallout records (CAMBRAY *et al.* 1989), supplied with the software used to run the model. It describes the temporal pattern of ^{137}Cs fallout for the northern hemisphere for the period 1954-1988. Subsequent weapons-derived fallout was negligible (Fig. 4.2). However, Chernobyl fallout in 1986 is not included in the supplied dataset, and has been added to this. A value of 700 Bq/m^2 was assumed to be appropriate to represent Chernobyl ^{137}Cs fallout in the soils near to Bonn, based on values reported by DÖRR & MÜNNICH (1987).

- A proportional factor (γ), representing the proportion of ^{137}Cs receipts that are removed in runoff before incorporation in the plough layer. The value of γ is dependent on the timing of tillage relative to the occurrence of erosive rainfall. It is the proportion of material that is *not* incorporated into the plough layer, and thus has a maximum value of 1.0 in the hypothetical case of all erosive rainfall occurring immediately prior to tillage. In practice, it can be estimated as the proportion of annual rainfall that is considered to be erosive because of its timing relative to land condition, and which causes surface runoff – and is thus somewhat subjective and imprecise. Given the relatively low rainfall of the study area, it is considered that this factor is not likely to be of great significance. Nevertheless, when intense rainfall does occur, it is typically at the time when arable surfaces are at their most exposed, so a low proportionality factor has been used – arbitrarily set at 0.05 – to reflect the possibility that loss of ^{137}Cs in runoff may occasionally occur before tillage incorporation.
- A relaxation mass depth (H), representing the depth to which ^{137}Cs initially infiltrates. The factor H represents the depth of initial infiltration of ^{137}Cs when first delivered to the soil's surface. It is expressed as a mass depth (kg/m^2), i.e. the mass of soil in 1 m^2 above the depth to which ^{137}Cs initially infiltrates. HE & WALLING (1997) have published empirical values of H: 3.8 kg/m^2 for cultivated soil and 5.2 kg/m^2 for undisturbed surfaces. The former has been adopted for use within the Mass Balance model for the arable zone.
- The mass depth of the plough layer. The mass depth is estimated similarly as the mass of soil above the depth of the plough layer. For Auf dem Scheid, the tillage depth is 20 cm and the average density of soils in the plough layer is 1,499 kg/m^3 (n = 25; PARKNER 2000). The mass depth of the plough layer is thus estimated as 299.8 kg/m^2, approximated to 300 kg/m^2.
- A tillage constant. The tillage constant varies with type of tillage machinery and direction, timing and pattern of tillage. There is thus considerable variation in tillage "constants"; according to VAN OOST *et al*. (2000), a range of 500-1000 kg/m/a is representative for the technology and land use practices of western Europe. The tillage-induced sediment flux is generally higher for contour tillage – as is practised at Auf dem Scheid. LINDSTROM *et al*. (1992) report a value of 363 kg/m for each contour tillage operation. With two tillage operations per year in Auf dem Scheid, an approximate value of 720 kg/m/a has been adopted for the tillage constant.
- A reference inventory representing the amount of ^{137}Cs remaining in undisturbed soils. The derivation of a reference inventory value is discussed below.
- An input data file with measured ^{137}Cs inventories for sample points. This mass balance model specifically applies to slope transects, and requires that input data be arranged sequentially in a downslope direction. The input file contains, for each point: the measured ^{137}Cs inventory (Bq/m^2); the length of slope segment incorporating the point; the input and output angles to and from that slope segment; a particle size correction factor (P). See Appendix C for an illustration of the slope length and input/output angles. The particle size correction factor recognises preferential entrainment and/or deposition of particles dependent on their size, and is thus a function of the textures of undisturbed soil, eroded sediment and deposited sediment. Given the restricted range of soil textures in the Auf dem Scheid catchment, and the empirical observation that *in situ* soils and colluvium have essentially the same textures, this factor is not considered relevant, and has been set to unity.

<u>Migration and Diffusion Model</u>

The vertical distribution of ^{137}Cs within uncultivated soils is significantly different from that of tilled soils in which ^{137}Cs is mixed throughout the plough layer. In many cases, the vertical distribution of ^{137}Cs in the soil exhibits an exponential decline with depth. This does not remain constant, however, as ^{137}Cs slowly migrates through the soil profile. The Diffusion and Migration model allows for this. Obviously, it does not model tillage translocation and thus does not require a tillage constant or parameterisation of the plough depth. It does require, however, information concerning the vertical distribution of ^{137}Cs within the soil profile. As input the model requires:

- The temporal distribution of ^{137}Cs fallout. The same input data as for the Mass Balance model was used.
- A relaxation mass depth (*H*), representing the depth to which ^{137}Cs initially infiltrates. The relaxation mass depth (*H*), as with the Mass Balance model, is taken from the published value of HE & WALLING (1997), i.e. 5.2 kg/m^2 for undisturbed surfaces.
- A diffusion coefficient (*D*) and a migration rate coefficient (*V*). Values of *D* and *V* are based on the depth of maximum concentration of ^{137}Cs and the depth at which concentration decreases to 1/*e* of the maximum. Because the emphasis in sampling in this study was on the spatial distribution of ^{137}Cs and the collection of bulk cores, detailed information on the vertical distribution of ^{137}Cs in Auf dem Scheid soils is not available. WALLING & QUINE (1992) present a representative profile for silty soils, indicating that these depths can, respectively, be taken to be 5 and 11 cm. The average density of surface soils in the pasture area of Auf dem Scheid is 1,353 kg/m^3 (n = 21; PARKNER 2000). Thus the mass depth at 3 cm is 40.6 kg/m^2, and 148.8 kg/m^2 at 11 cm, and the mass depth of the increment between these two depths is 108.2 kg/m^2. Solving Equations C16 and C17 (Appendix C), with a sampling year of 1999, *D* is estimated to be 63.5 kg^2/m^4/a and *V* to be 1.13 kg/m^2/a.
- A reference inventory representing the amount of ^{137}Cs remaining in undisturbed soils. The derivation of a reference inventory is discussed below.
- An input data file with measured ^{137}Cs inventories for sample points. The input data file for this model is simpler than that of the Mass Balance model, as it requires no morphometric information. It consists simply of the point inventories and a particle size correction factor, which once again has been set to unity.

Reference Inventory

Common to both models, and indeed to most techniques involving ^{137}Cs, is the requirement for a reference inventory value. Ideally, a reference inventory should be estimated from an undisturbed site within the study area, thus providing a good estimate of fallout receipts for the immediate locality. SUTHERLAND (1998) suggests that because of spatial variability a minimum of 12 sites is required to achieve statistical validity of reference inventory estimation. Unfortunately, such undisturbed sites are rare within the extensively agriculturally used Frankenforst study area. Therefore, a number of alternative approaches were considered for estimation of a reference inventory value.

A reference value of total ^{137}Cs input can be estimated from records of fallout. These are not available for the Auf dem Scheid area. However, a value can be estimated based on various values in the literature. Various authors report values of ^{137}Cs present in soils at various times and places (Table 4.1). SCHIMMACK *et al*. (2001) quote values from loess cropland in Bayern. The mean and median of a sample of 12 sites were identical at 2,790 Bq/m^2, while these were 2,720 and 2,640 Bq/m^2, respectively, from a sample of 275 sites over a wider area. They maintain that the latter is a better estimate of reference inventory, if it is assumed that most of eroded soil has remained within the catchment. BUNZL *et al*. (1995) report values from soils sampled under pine forest (elevation: 400 m; 710 mm annual precipitation). The mean value (5 sites) in the upper 30 cm was 1,830 Bq/m^2. At an agricultural site some 60 km northwest of Bonn, BACHHUBER *et al*. (1987) found an average (100 sites) ^{137}Cs content of 3,300 Bq/m^2. No date of sampling is given, but it is assumed that their work pre-dates the Chernobyl incident. DÖRR & MÜNNICH (1987) present data for various locations throughout the western part of Germany. For the two sites closest to Bonn, total ^{137}Cs concentrations immediately after Chernobyl in 1986 were approximately 1,200 and 1,100 Bq/m^2, of which ca. 800 and 600 Bq/m^2 respectively is attributed to Chernobyl fallout. There is no indication, however, of whether these values relate to undisturbed sites. Furthermore, they are only for the upper 2-5 cm of soil and cannot be taken as indication of total receipts of weapons derived fallout. However, the values of Chernobyl fallout are considered reliable because they were sampled immediately after the event, i.e. negligible (if any) diffusion through the soil profile will have occurred. In the Belgian loam belt, VANDEN BERGHE & GULINCK (1987) found an average (16 sites) post-Chernobyl ^{137}Cs activity of 3,533 Bq/m^2 for samples taken from the entire plough layer (30 cm). Because these values were recorded at different times, they are not *prima facie* directly comparable, and the effect of radioactive decay must be accounted for. The loss of ^{137}Cs due to radioactive decay can be determined with the following equation (STOLZ 1996):

$$Cs_t = Cs_{t_0} e^{-\lambda(t-t_0)} \tag{4.2}$$

Cs_t — ^{137}Cs activity at time t
Cs_{t_0} — initial ^{137}Cs activity at time t_0
λ — decay constant for ^{137}Cs

The interval t-t_0 is expressed in years, and the decay constant for ^{137}Cs (λ) is defined as:

$$\frac{0.6931}{30.07a} \tag{4.3}$$

where 30.07 a is the halflife of ^{137}Cs.

Table 4.1: Selected ^{137}Cs inventory values for Germany and western Europe, and their corresponding values in 1999 allowing for interim radioactive decay. (Sources: 1. SCHIMMACK *et al*. (2001). 2. BUNZL *et al*. (1995). 3. VANDEN BERGHE & GULINCK (1987). 4. BACHHUBER *et al*. (1987). 5. DÖRR & MÜNNICH (1987). 6. Based on UNSCEAR (1982).)

Source	Site and Sample Details			Reported Values		Corrected to 1999
	Location and Type	Depth	*n*	Date	(Bq/m^2)	(Bq/m^2)
1	Loess cropland in Bayern	1.2 m	12 sites	1st January 1994	2,790	2,486
				(mean/median)	2,790	
1	"	"	275 sites	1st January 1994	2,720	2,423
				(mean/median)	2,640	2,352
2	Pine forest in Bayern	30 cm	5 sites	Sampled in 1991	1,830	1,522
3	Belgian loam belt	30 cm	16 sites	post-Chernobyl	3,533	2,620
4	Eschweiler-Lohn	"	100 sites	[?1985?]	3,300	2,390
5	Wilmsdorf (Total)	2 cm		post-Chernobyl	1,200	890
5	Wilmsdorf (Chernobyl)	"		post-Chernobyl	800	593
5	Breitscheid (Total)	5 cm		post-Chernobyl	1,100	815
5	Breitscheid (Chernobyl)	"		post-Chernobyl	600	445
6	North temperate zone			1980	4,770	3,080

Of the values given in Table 4.1, the most likely to be geographically comparable to Auf dem Scheid is that from Eschweiler-Lohn (BACHHUBER *et al*. 1987). Unfortunately, there is uncertainty associated with their values because no date of ^{137}Cs measurement is given. The sites in Bayern are either under forest or likely to have been considerably more influenced by Chernobyl fallout than the Auf dem Scheid catchment. The Belgian values (VANDEN BERGHE & GULINCK 1987) are likely to be more appropriate.

Alternatively, rather than relying on published values, a further method is available for estimating fallout of ^{137}Cs. The production of ^{90}Sr relative to ^{137}Cs, and hence the relative amounts in fallout, follows a more-or-less constant ratio of 1.65:1 (HIROSE *et al*. 1987), enabling estimation of ^{137}Cs fallout rates from ^{90}Sr data. Fallout of ^{90}Sr to 1980 for the north temperate zone (50°-60° latitude) amounted to 2,890 Bq/m^2 (UNSCEAR 1982). This equates to a ^{137}Cs fallout to 1980 of ~4,770 Bq/m^2. Decayed to 1999, a remaining input from global weapons testing of ~3,080 Bq/m^2 is estimated. This does not, however, include inputs from Chernobyl that are expected to be present in the soils of Auf dem Scheid. A median of the two values quoted by DÖRR & MÜNNICH (1987) for the sites nearest to Bonn has therefore been included in attempting to estimate a total inventory for the Auf dem Scheid site. Taking a median Chernobyl input of 700 Bq/m^2, a 1999 value of ~520 Bq/m^2 for Chernobyl input is obtained. Combining this with the value based on ^{90}Sr fallout (see Table 4.1), a reference inventory of 3,600 Bq/m^2 has been estimated using this approach. As the ^{137}Cs data for Auf dem Scheid (Appendix B) indicate, however, only 7 of the 120 samples return inventories lower than 3,600 Bq/m^2, and it appears that this value may represent a considerable underestimate.

At the time of sampling, two sites were thought to be potentially representative of total fallout receipt on topographic grounds. Point 35 (Fig. 5.8) is at the upper part of the catchment on an essentially level surface. Although subject to tillage, it was thought that tillage losses and gains at this point would balance each other, with no net effect on the total ^{137}Cs inventory. Point 68 is within the pasture zone at a topographic high point. It thus receives no ^{137}Cs other than from fallout and water erosion losses were not thought to be likely. These points both have ^{137}Cs inventories of 4,660 Bq/m^2, which appears to confirm original thoughts. However, nearby sites within the arable zone, which should have similar inventories to Point 35 if the above assumption is valid, in fact have very different values. It may be purely coincidental that Points 35 and 68 have such similar values.

If 4,660 Bq/m^2 is a valid estimate of the reference inventory, then it must also be recognised that spatial variability of fallout is rather high. As mentioned above, SCHIMMACK *et al*. (2001) have suggested that a mean value from sampled points can give a good approximation of the total ^{137}Cs fallout receipt, if it is assumed that all ^{137}Cs remains within the study area. Given the closed nature of the Auf dem Scheid catchment over the period of ^{137}Cs deposition, this assumption is likely to be satisfied. However, sample size is important, and the 120 samples taken in this study is considerably less than the 275 taken by SCHIMMACK *et al*. (2001). Furthermore, sampling was not random in this study, with greater emphasis given to potential depositional zones. Accordingly, the mean inventory value from Auf dem Scheid (5,530 Bq/m^2) may well be an overestimate. The data contain three extremely high values and one that is very low. The dataset is thus somewhat skewed and the median (5,299 Bq/m^2) is lower than the mean, but still rather high. A mean value calculated without theses outliers (5,410 Bq/m^2) is also considered rather high.

The decision on which value to use for a reference inventory was finally decided by plotting the distribution of measured sample inventories, and comparing the topographic location of points with surpluses and deficits relative to the two potential reference inventories (i.e. 4,660 Bq/m^2

and 5,530 Bq/m^2). This indicated that the sample mean certainly provided a more sensible pattern. Therefore, use of the sample mean is considered to give as good a statistical estimate, if not better. This value (5,530 Bq/m^2) has been adopted for use as a reference inventory value.

The values used to parameterise the sediment redistribution models are summarised in Table 4.2.

Table 4.2: Values used in parameterisation of sediment redistribution models.

Factor	Mass Balance Model	Diffusion and Migration Model
Proportionality Factor (γ)	0.05	n/a
Relaxation Mass Depth (H)	3.8 kg/m^2	5.2 kg/m^2
Mass Depth of the plough layer	300 kg/m^2	n/a
Tillage Constant	720 kg/m/a	n/a
Diffusion Coefficient (D)	n/a	63.5 kg^2/m^4/a
Migration Rate Coefficient (V)	n/a	1.13 kg/m^2/a
Reference Inventory	5,530 Bq/m^2	5,530 Bq/m^2

4.4 Optically Stimulated Luminescence

It goes almost without saying that reconstruction of historical erosion rates requires a chronology of sedimentation. Various techniques are available for dating sedimentary bodies, with dating of human artefacts and organic inclusions among the most commonly applied. Both these latter approaches suffer, however, in that they do not in fact date the event of interest, i.e. sediment deposition. Rather, they date with greater or lesser precision respectively the time of manufacture of an artefact and the cessation of respiration of an organism. An alternative dating approach is that of luminescence dating. In recent years considerable advances have been made in the development of these techniques that specifically date the time of sediment deposition. A brief review of this technique is given in this section. The physical basis of the luminescence technique is described by AITKEN (1998), while summaries of its application in geomorphology are provided by STOKES (1999) and DULLER (2000) among others, and to the dating of colluvial/alluvial sediments by LANG *et al*. (1998).

All matter is subject to continuous low levels of ionising radiation from the decay of radioactive elements – principally those of the uranium and thorium decay series and potassium. This radiation causes damage to minerals within soils and sediments. Electrons are displaced and trapped in storage sites within the mineral’s crystal lattice. It is this build up trapped electrons that produces latent luminescence, and the longer the exposure to radiation continues, the greater will be the accumulation of a latent luminescence signal. Because natural radioactive decay can be considered to be constant over the period of interest, the magnitude of the luminescence signal is proportional to the amount of time to which a mineral has been exposed to ionising radiation. Crucially for dating purposes, the luminescence signal is dissipated by exposure to heat or light (thermoluminescence (TL) and optically stimulated luminescence (OSL) respectively). The amount of ionising radiation (SI unit: Gy, i.e. Gray) to which a mineral grain has been exposed is known as the *palaeodose*, while the rate at which this occurs – a function of ambient radioactivity – is called the effective *dose rate* (Gy/s). Thus, if one measures the amount of luminescence accumulated within a mineral grain, i.e. the palaeodose, and compares this to the dose rate delivered to the mineral grain by natural radioactivity from the surrounding environment, one has a measure of the period since the mineral was last heated or exposed to light, i.e. its age, which is thus the quotient of the palaeodose and the effective dose rate:

$$A = \frac{P}{D_E} \tag{4.4}$$

A	Age	(years)
P	Palaeodose	(Gy)
D_E	Effective dose rate	(Gy/s)

Early applications of the luminescence technique were within the field of archaeology, where TL was used to date the time of production of ceramic artefacts and the age of hearth materials. Of greater significance for geomorphology is the highly light sensitive OSL signal, that allows determination of the time of last exposure to light, and thus the time at which deposition or, more specifically, burial occurred.

There are various assumptions and requirements that must be satisfied if this technique is to be successfully applied. Perhaps the most critical issue is the measured palaeodose, and the assumption that this is in fact the luminescence signal accumulated *since the geomorphic event of interest*. The paramount requirement in this respect is that the luminescence signal be fully reset during sediment transport and prior to deposition. In many cases, this crucial assumption may not be satisfied, i.e. when sediments are transported and deposited either at night or during low light conditions (which are typical of large rainfall-runoff events), or when transport and deposition is so rapid that insufficient time is available for bleaching. In such cases, an overestimate of the age of deposition will be returned, because the measured luminescence signal includes a component that was accumulated during an earlier period of exposure to ionising radiation. Earlier applications within geomorphology were for studies of aeolian and glacially transported sediments, where transport was either slow or over long distances and it could be reasonably assumed that the luminescence signal had been sufficiently reduced. The technique has subsequently been extended to colluvial and alluvial sediments. Independent age controls confirm that sufficient signal reduction can also be achieved for colluvially and alluvially deposited sediments (LANG 1994, 1996, LANG & NOLTE 1999). LANG & WAGNER (1996) demonstrated that sufficient bleaching occurred with 30 minutes daylight exposure under low light conditions, and STOKES (1999) cites empirical evidence indicating that the OSL signal can be reset with exposure to daylight of one minute, and after 3-4 hours under 12 m of water. A second source of uncertainty relating to the palaeodose relates to a phenomenon known as anomalous fading. Certain feldspars are less capable of retaining a luminescence signal than others. Rather than accumulating continuously, the luminescence signal fades over time. In such cases, the reported age will be an underestimate.

Determination of the effective dose rate assumes that the exposure of minerals to ionising radiation has been constant. In many instances this will not be the case, and the determination of effective dose can be complicated by temporal variability in radiation attenuating phenomena. Most dramatic is the effect of water within sediment. Water absorbs part of the radiation emitted by a radioactive source, thus reducing the dose received by a given mineral grain. If water content within the sediment changes through time – i.e. because of throughflow or fluctuation in ground water – the dose rate to the mineral grain will also vary. The extent of this cannot be known; rather, it must be modelled on the basis of assumptions, and the degree of uncertainty associated with age determination increases. Secondly, radioactive disequilibria may occur, i.e. chemical processes may selectively alter the concentrations of mother and daughter nuclides within the uranium and thorium decay chains. This will also result in altered dose rates to mineral grains. Radioactive disequilibrium can be detected using high resolution γ-spectrometry.

However, uncertainty in age determination will increase because the time at which radioactive disequilibrium commenced cannot be known and must also be modelled. Uncertainties arising from these phenomena are usually (in the case of reliable laboratories) accounted for within error ranges quoted for reported ages.

In contrast to conventional or traditional techniques used in the establishment of sedimentation chronologies, luminescence is capable of dating accurately the event of geomorphic interest, i.e. the last time a sediment was exposed to light prior to its deposition. An illustrative example was provided by LANG & HÖNSCHEIDT (1999). Ages derived from artefacts and organic material revealed a chaotic and stratigraphically nonsensical chronology – because they didn't actually date the deposition of material; rather the period of artefact construction and the death of an organism respectively were dated. These give only maximum ages for sediment deposition as they place a constraint on the earliest time when these objects can have entered the sediment flux. Luminescence dating, by contrast, dates the time at which sediments were deposited. The range of ages that can be detected is governed, at least in part, by the strength of the luminescence signal. At the upper extreme, signal saturation becomes an issue. Nevertheless, for fine-grained sediments the last inter/glacial cycle can be dated (STOKES 1999). For younger sediments with minimal accumulated luminescence, both the sensitivity of the mineral grains and the sensitivity of the detector will be important. Ages as low as several tens of years have been reported (MURRAY 1996).

4.5 The Methodological Approach of this Study

The use of ^{137}Cs allows identification of points that are eroding and accumulating. Dependent on the number of points that are sampled, a reasonably good spatial distribution of eroding and accumulating areas can be derived. There is thus a spatial element to the information provided by ^{137}Cs, and it allows some elucidation of sediment redistribution dynamics for a tightly constrained period of 45 years. In contrast, the chronological information provided by OSL dating of colluvial sediments represents an integral signal for the whole catchment for periods of 10^2-10^3 years. This information is therefore not only applicable to different time scales, it is also not *prima facie* directly comparable. To achieve the objectives of this study, however, information for different periods that is comparable within a single chronology is needed. This requires that (a) the integral information derived from the borepoints be extrapolated to the whole catchment, and (b) that an integral signal be derived from the spatially distributed ^{137}Cs data. Both of these approaches will be attempted.

4.5.1 Long-term Sediment Budget

The volume of soil eroded from each soil type unit can be calculated on the basis of assumptions regarding initial soil depth and the degree of soil profile truncation. Similarly, the volume of sediment contained in depositional zones is calculated on the basis of an average accumulation depth within depositional zones. Chronological information is to be derived chiefly through the use of optically stimulated luminescence, supplemented where possible by ^{14}C dating of organic material. Rates of accumulation can be determined for a range of periods, dependent on the sampling resolution, i.e. the number of OSL ages determined. The deficit side of the budget, i.e. erosion, can only be calculated for the entire period. A source of uncertainty relates to the unknown internal sediment delivery ratio and trap efficiency. In other words, there will no doubt have been interim storage within the catchment rather than direct transport of material to a final accumulation site (see reference to LANG & HÖNSCHEIDT (1999) in Chapter 2). The shorter term information derived from ^{137}Cs should enable some elucidation of the significance of internal storage within Auf dem Scheid. Further, some of the material may have been delivered beyond the bounds of the Auf dem Scheid system. The significance of this should become apparent through comparison of amounts eroded and deposited respectively.

4.5.2 ^{137}Cs Sediment Budget

WALLING *et al*. (1986) presented an early attempt at using ^{137}Cs for construction of a sediment budget. Their approach was based on the calculation of a total ^{137}Cs input by multiplying the reference value by the number of cores sampled, producing a ^{137}Cs INPUT. Points were classified as erosional or depositional based on whether they had lower or higher inventories than the reference inventory. The average amount by which eroded inventories were less than the reference value was multiplied by the number of such cores and subtracted from INPUT to derive a total ^{137}Cs LOSS. Similarly, the average amount by which depositional inventories exceeded the reference value was used to calculate a ^{137}Cs GAIN. At that time, the modelling of sediment loss and gain on the basis of ^{137}Cs loss/gain was not well advanced, and their approach involved the construction of a ^{137}Cs budget, which was then extrapolated to a whole catchment sediment budget on the basis of measured sediment yields. An improvement on this spatial averaging approach can be attempted for Auf dem Scheid using modelled soil/sediment redistribution rates, and by subdividing the basin into two zones based on land use.

Thus, a coarse sediment budget can be derived for each part of the Auf dem Scheid catchment, if it is assumed that sufficient points are sampled to characterise each part of the catchment and to give a good indication of relative areas of erosion-deposition. This makes no allowance for redeposition and sequential movement within each zone, thus sacrificing much of the value inherent in the ^{137}Cs data. Nevertheless, it allows comparison with integral catchment information provided by the longer term sediment budget.

4.5.3 Summary

The volumes of material eroded and in storage will be estimated by spatial extrapolation of soil profile truncation and sediment accumulation depths respectively. An historical sediment budget will thus be constructed. While precise methods are available for performing these functions within GIS software, these have not been used. It is felt that this approach would provide a degree of precision that does not match the coarse approximation possible from the data available.

OSL ages will be used to generate chronologies of sediment redistribution. These chronologies enable construction of trajectories of erosion and accumulation through time as described in Chapter 2. In turn these enable inferences regarding aspects of geomorphic behaviour to be made. In particular, the information from the historical sediment budget will be contrasted with that revealed by the ^{137}Cs budget. This approach is to be applied in the Auf dem Scheid catchment. Comparison is made with two other study sites (Forstbach and Heidersiefen) in the Pleiser Hügelland. Sediment delivery ratios were calculated for both Heidersiefen (FEISE 1999) and a section of the Forstbach catchment (LÖWNER 2000), and will be compared with those derived for Auf dem Scheid.

For the three study areas – Auf dem Scheid, Forstbach and Heidersiefen – the contemporary morphological evidence will be used to make inferences regarding the sensitivity of the landscape to different processes, i.e. linear processes generated by large magnitude rainfall-runoff events and diffusive processes induced by more common low magnitude events. This will involve the use of the concept of a transient form ratio (BRUNSDEN & THORNES 1979; see Chapter 2).

Chapter 5

Results and Discussion of Field Evidence

5.1 Introduction

Three landscape elements within the Pleiser Hügelland, representing systems of varying complexity, were selected for investigation. The small headwater basin Auf dem Scheid is part of the Versuchsgut Frankenforst veterinary research facility, with both agricultural and pastoral land uses. A small lake at the foot of this catchment means that it is essentially a closed system with respect to sediment redistribution through terrestrial processes (i.e. other than aeolian). Although both the catchment area and the topography of this basin suggest that it should be able to sustain at least an ephemeral channel, none is present. The Forstbach study site is also part of the Versuchsgut Frankenforst, and comprises a single slope, low relief zero-order catchment, tributary to the second order Forstbach channel. The Heidersiefen study area comprises a second order system, with channels in both of its first order tributaries. The results of field investigation, ordered geographically – Auf dem Scheid, Forstbach and Heidersiefen – are presented in this chapter. For Auf dem Scheid, this includes the results of both a drilling programme and the ^{137}Cs analysis, and for Forstbach and Heidersiefen the results of drilling. Following the presentation of results for each study site is an interpretation of them. Interpretation of their significance for the purposes of this study follows in Chapter Six.

5.2 Auf dem Scheid

Auf dem Scheid is a small headwater basin with no contemporary channel. Despite its small size (~5.4 ha), the catchment has a complex geology (Fig. 5.1(a)). Remnants of early Pleistocene alluvial terrace material are found at the surface of its uppermost extent. These are underlain by Tertiary tuff, while the eastern boundary of the basin is formed by a Tertiary basalt pluton. The whole area has been blanketed by loess, and soils are formed in this or in periglacial cover layers that have also incorporated underlying substrate material (Fig. 5.1(b)). The lower part of the catchment is under pasture, while the upper part is still ploughed with a three-way crop rotation. The boundary between these two land uses is marked by an abrupt break in slope, representing the accumulation of ~1 m of material at its greatest. In the past, the Auf dem Scheid catchment was tributary to the Eichenbach channel, which flowed from west to east, approximately through the position of the two lakes marked on Figure 5.1. Today, this channel is no longer open, and terminates in the western of these lakes. This lake is indicated on the oldest available topographic map of the area from 1845. The lower (eastern) lake was first mapped in 1960, and represents part of an artificial change to the drainage line of the Eichenbach that was undertaken in the 1950s (ERDMANN 1998). The modern lower boundary of the catchment is defined by a farm road that first appears on a topographic map published in 1940. Coupling between the Auf dem Scheid basin and the higher order drainage system is thus complicated, and under normal conditions Auf dem Scheid is a closed sediment redistribution system.

The Auf dem Scheid catchment was selected for various reasons. It is a small basin with a relatively uncomplicated morphology. There is no contemporary evidence of erosional processes other than water erosion and tillage translocation. Perhaps most importantly, the road at the bottom of the catchment (Fig. 5.1), which closes the system, has been present throughout the period of ^{137}Cs deposition.

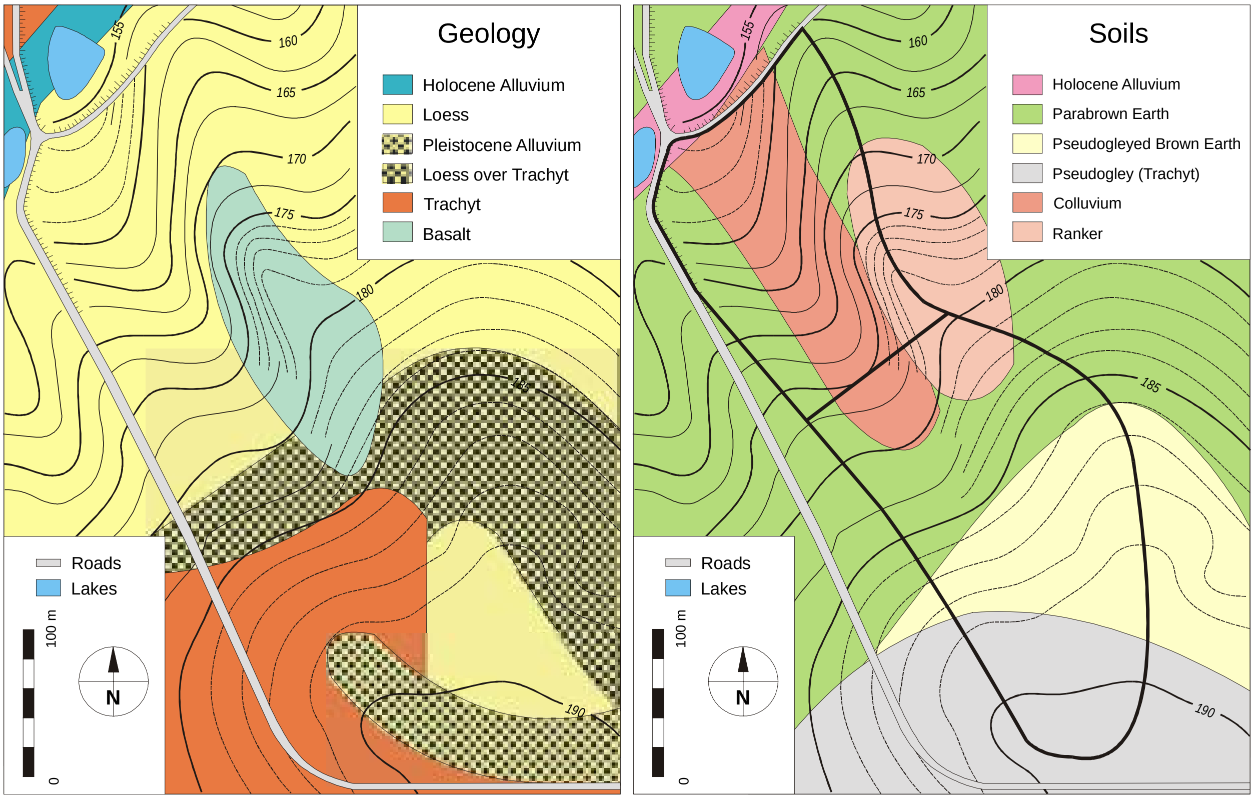


Figure 5.1: Geology and soils of Auf dem Scheid. The catchment boundary and the line separating arable and pasture zones is marked on the soil map. (Based on (geology) Geologisches Karte von Nordrhein-Westfalen, 1:25,000 sheet 5209 Siegburg and (soils) Bodenkarte von Nordrhein-Westfalen, 1:50,000, sheet L5308 Bonn).

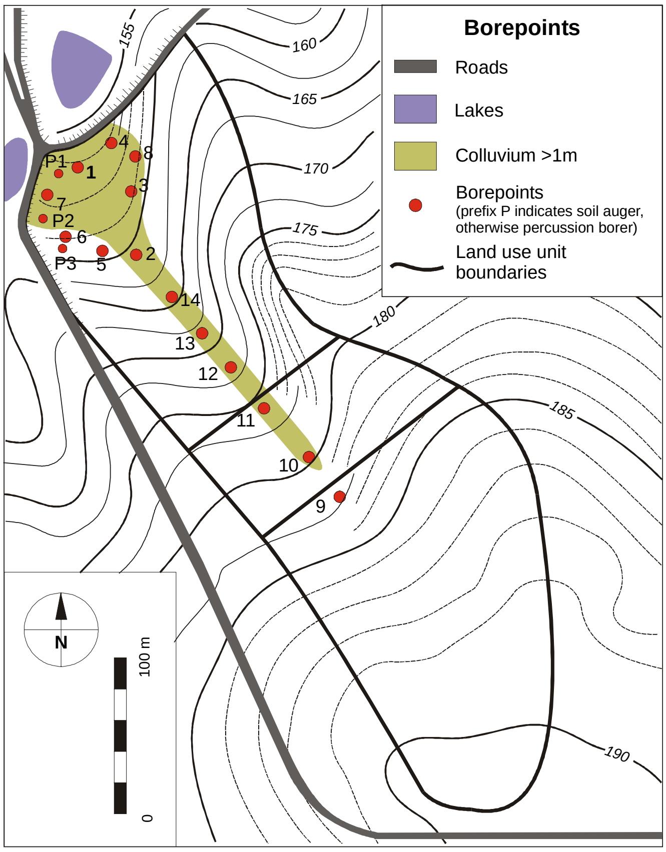


Figure 5.2: Location of sample sites within the Auf dem Scheid catchment. Sites where cores were taken with a percussion borer (AdSx in the text) are labelled simply with their numbers, and soil auger sites with the prefix P. The approximate distribution of the principal colluvial body is indicated.

5.2.1 Sedimentary Stratigraphy – Results from the Drilling Programme

A series of cores were taken using a percussion borer and 5 cm diameter closed tubes from various points within the Auf dem Scheid sedimentary body (Fig. 5.2). In addition, a number of points were sampled using a 2 cm diameter soil auger. The nature of soils and sediments was inferred partly on the basis of stratigraphic relationships and partly on the basis of material properties (Appendix A). In general, the identification of colluvial material was difficult, with very little differentiation in the textures of *in situ* soils and colluvia. Most of the samples were silty with only minimal variation in clay contents. The presence of $CaCO_3$ has been taken as an indication of colluvium in some cases, and in others anomalously high humus content has been used diagnostically. Above all, the presence of stones and allochthonous material has been used as an indicator of colluvially derived sediment. These cores are described in the following section, grouped according to location.

<u>The foot of the accumulation zone: AdS1 and AdSP1</u>

A core taken from the deepest part of the basin (AdS1, Fig. 5.3) was considered to represent an integral signal for the whole of Auf dem Scheid. This core contains 6 m of accumulated sediments, while an adjacent probe with a soil auger (AdSP1) revealed a contact with an underlying clayey trachyt weathering horizon at ~6.5 m. Within these 6 m of accumulated sediment, there is considerable variation in humus content and bands of high stone frequency, suggesting distinct colluvial units. At various points within the column, clear strata and laminations are evident, and there is a particularly clear sequence of fine laminations in the lower section of the second metre. However, above ~1.6 m and below ~3.85 m lamination is less evident, and colluvia appear more homogeneous. Six samples were taken from this core for OSL dating (Fig. 5.3, Table 5.1). The deepest dated sediment (5.73-5.78 m) returns an age of 3,370 ± 280 a. Sediment from 4.58-4.62 m exhibits signs of radioactive disequilibrium, so two ages are given (980 ± 90 a, 1,040 ± 90 a), based on possible extremes. Sediment from 3.56-3.61 m also exhibits radioactive disequilibrium and an age range of 1,460 ± 140 a to 1,580 ± 140 a is given. Further, there is evidence that the latent OSL signal of these sediments was only partially bleached, and the quoted age must be interpreted as a maximum. Sediment from 2.62-2.67 m returns an age of 1,620 ± 180 a, from 1.53-1.62 m an age of 420 ± 60 a, and from 1.10-1.22 m an age of >600 a, although this last must be regarded as a minimum because of anomalous signal fading.

Table 5.1: OSL ages from Auf dem Scheid.

Sample Location	Depth below surface (cm)	Age ± 1σ error (years)	Comment	
Auf dem Scheid 1	110-122	>600	Fading	Minimum Age
	153-162	420 ± 60		
	262-267	1,620 ± 180		
	356-361	1,460 ± 140 – 1,580 ± 140	Rad. Diseq.; Partial Bleaching	Maximum Age
	458-462	980 ± 90 – 1,040 ± 90	Rad. Diseq.	
	573-578	3,370 ± 280		
Auf dem Scheid 8	66-73	>3,600	Fading	Minimum Age
Auf dem Scheid 11	116-123	>2,000	Fading	Minimum Age
	172-180	1,920 ± 350		
	218-225	4,590 ± 1,000		
	254-262	3,740 ± 760		
	326-333	5,700 ± 1,170		
	412-419	4,630 ± 1,330		
Auf dem Scheid 12	119-133	>700	Fading	Minimum Age
	220-229	>2,000	Fading	Minimum Age
Auf dem Scheid 13	123-133	4,400 ± 900		
Auf dem Scheid 14	127-137	900 ± 100		
	263-273	>2,400	Fading	Minimum Age

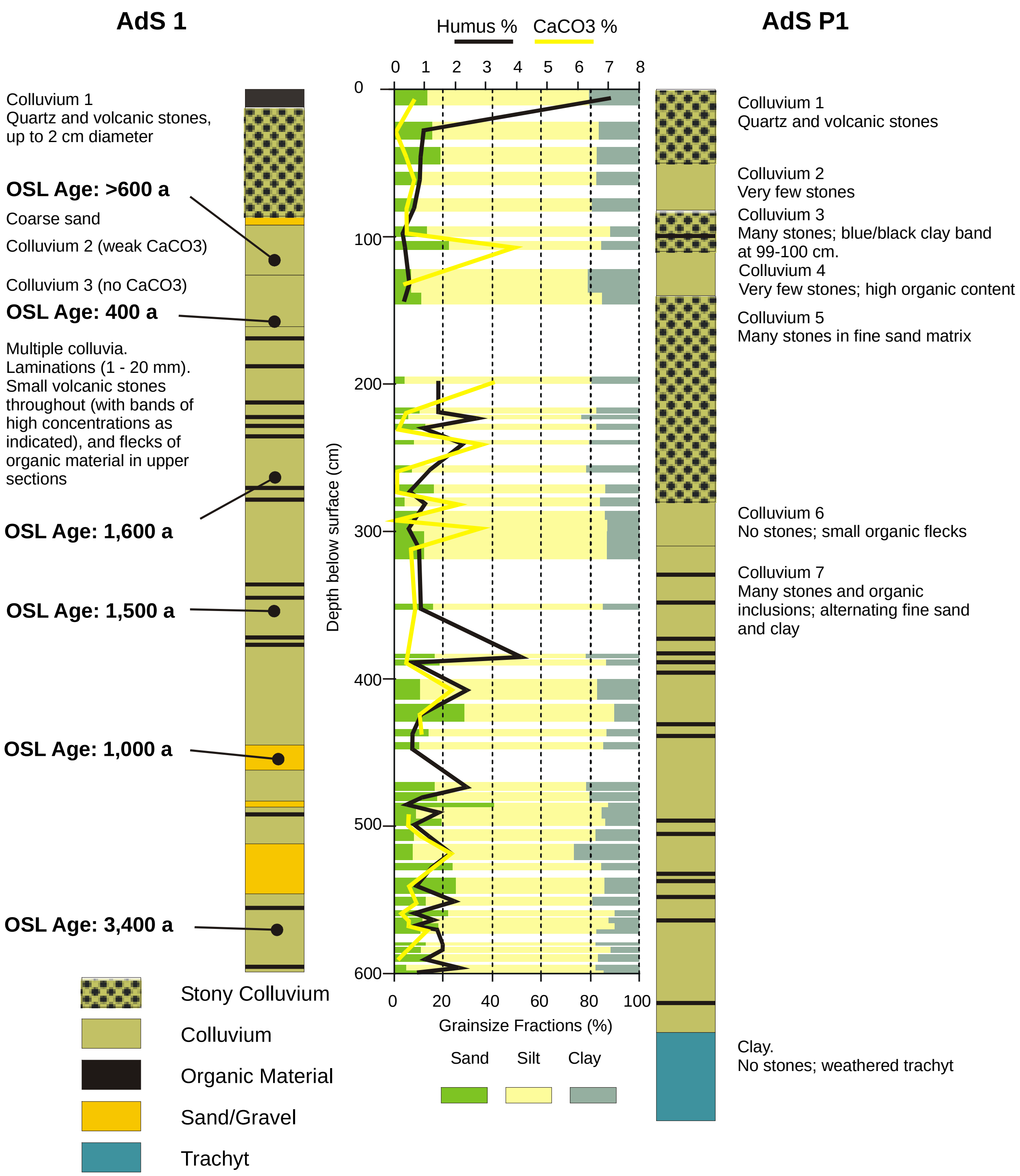


Figure 5.3: Core AdS1 with grainsize fractions and percentages of humus and $CaCO_3$ (mass). OSL ages are rounded to the nearest 100 years. The nearby soil augering AdSP1 is also plotted for comparison. See Figure 5.2 for location of borepoints.

The eastern flank of the accumulation zone: AdS2, AdS3, AdS4 and AdS8

Core AdS2 (Fig. 5.4) was taken in the thalweg of the catchment's lower section, at the base of the basalt hill. It reveals ~2 m of colluvial sediments directly overlying the weathered basalt substrate. Organic material found at this boundary returns a calibrated ^{14}C age range of AD 1660-1950 (1σ). Two colluvia are inferred, based on differences in stone frequency and $CaCO_3$

content. The upper colluvium has weak carbonate throughout, while this is absent from the lower colluvium.

Cores AdS3, AdS4 and AdS8 (Fig. 5.4) were taken from the foot of the slope below the basalt hill, i.e. on the eastern side of the depositional zone at the base of the catchment. Core AdS3 also contains two distinguishable colluvia. As with AdS2 they differ in stone frequency, but in contrast to AdS2, these are not distinguished on the basis of $CaCO_3$, which is present in both. These overlie an eroded loess soil of ~40 cm thickness. Clay contents suggest that this comprises some 20 cm each of B_t and B_v horizons. Some 1.5 m of loess overlie a dense layer of reddish, angular stones at the bottom of the core. There are also two colluvia in Core AdS4, distinguished by stone frequency, but containing $CaCO_3$ throughout to a depth of 5.4 m. Large organic objects are present in the 4th and 5th metres. Colluvia lies directly over loess. Core AdS8 reveals ~3 m of colluvial material directly overlying loess. Two colluvia are inferred on the basis of the difference in stone frequency. The upper of these colluvia (1.13 m thickness) contains weak to moderate $CaCO_3$, while the lower colluvia shows no carbonate reaction. Humus contents, other than in the upper 30 cm, are low. A basalt stone (>1 cm b-axis) was found at the boundary between the lower colluvium and the underlying loess. One sample for OSL dating (0.66-0.73 m) was recovered from this colluvium. It exhibits anomalous fading, and the age of >3,600 a must be interpreted as an underestimate. The eastern side of the depositional zone is thus characterised by two generations of colluvia. The more recent of these has a high frequency of stones and contains $CaCO_3$, while the lower has fewer stones and shows inconsistency with respect to the presence of $CaCO_3$. A truncated loess soil was found in only one core; otherwise, colluvia directly overlie loess or, in the case of AdS2, weathered basalt.

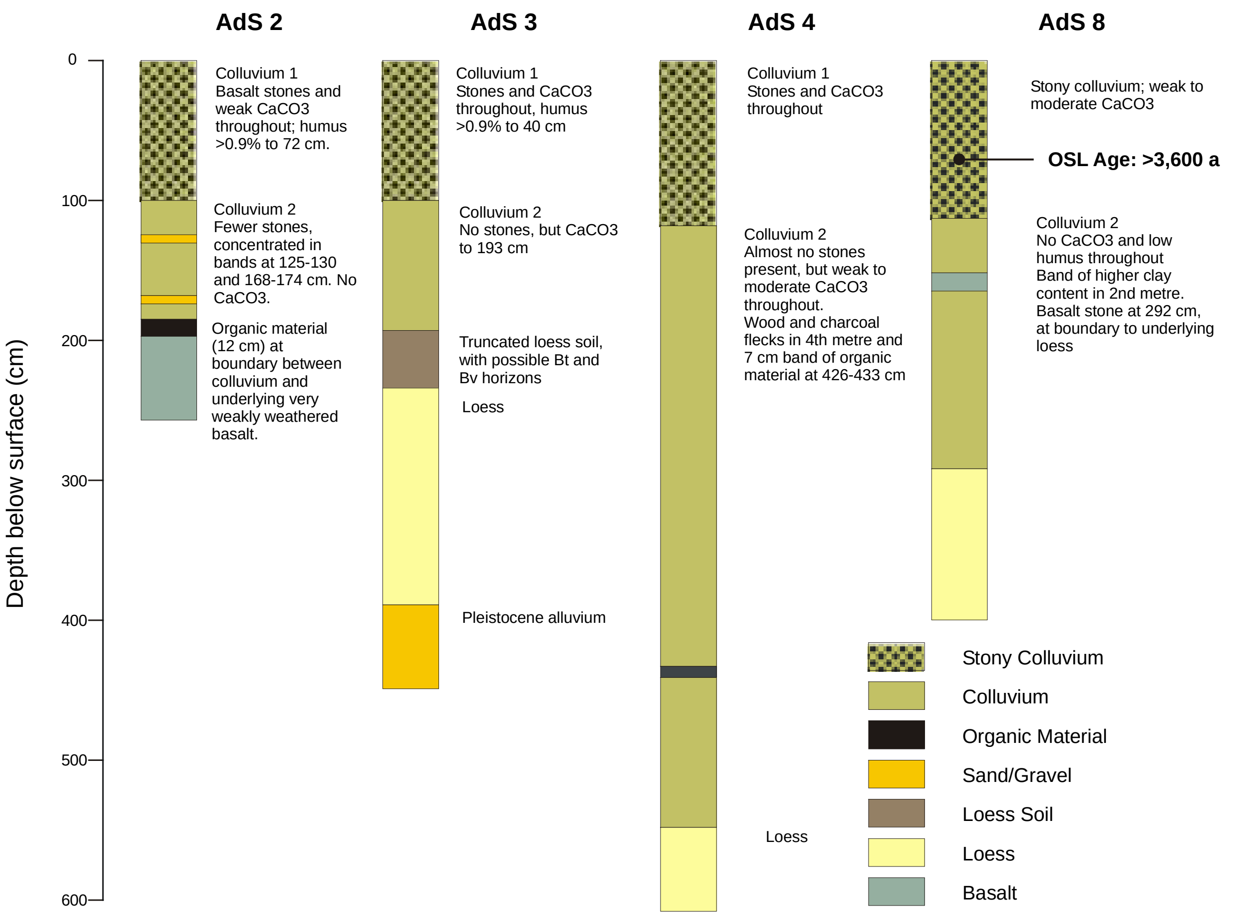


Figure 5.4: Cores from the eastern flank of the Auf dem Scheid accumulation zone (AdS2, AdS3, AdS4 and AdS8). The OSL age (AdS8) is rounded to the nearest 100 years. See Figure 5.2 for location of borepoints.

The western flank of the accumulation zone: AdS5, AdS6, AdSP2 and AdSP3

The cores AdS5 and AdS6, along with results from soil augers AdSP2 and AdSP3 are illustrated in Figure 5.5. These points are located on the western side of the depositional zone. Core AdS5 contains ~0.5 m of colluvial material overlying a loess soil. Drilling was not deep enough to determine the thickness of this soil. However, the absence of an A horizon indicates truncation, and the adjacent soil auger probe (AdSP3) indicates quite strong truncation. These points – and AdS6 – are very close to each other, and there is thus a considerable difference in the thickness of remaining loess soil within a short distance. Core AdS6 contains an almost undisturbed – although strongly gleyed – loess soil, covered by some 60 cm of colluvium. The nearby auger point (AdSP2) reveals a partly truncated loess soil and 1.10 m of colluvium. A further point was sampled (Core AdS7), but the ground was too wet, and no more than a metre of material could be recovered. This was all colluvium. In contrast to the eastern side of the depositional zone, the western side can be characterised by the presence of one colluvium overlying variably truncated loess soils. This colluvium ranges in depth between 0.5 and 1.1 m; it has a moderate frequency of stones and consistently contains $CaCO_3$. Loess underlies three of the four points sampled, and probably also the remaining point.

Seen in the context of the whole depositional zone, it appears that considerable depth of sediment accumulation is restricted to the eastern side and the very foot of the basin. The existence of loess soils and the shallower accumulation of colluvium suggest that the western side of the basin has been geomorphically less active. It is inferred that erosion has been much greater on the eastern side, and that the steep slopes of the basalt hill represent the source of much of the colluvium. Two generations are inferred. The first was derived from a loess cover on these slopes; the second, more stony, colluvium is derived from soils formed in the basalt.

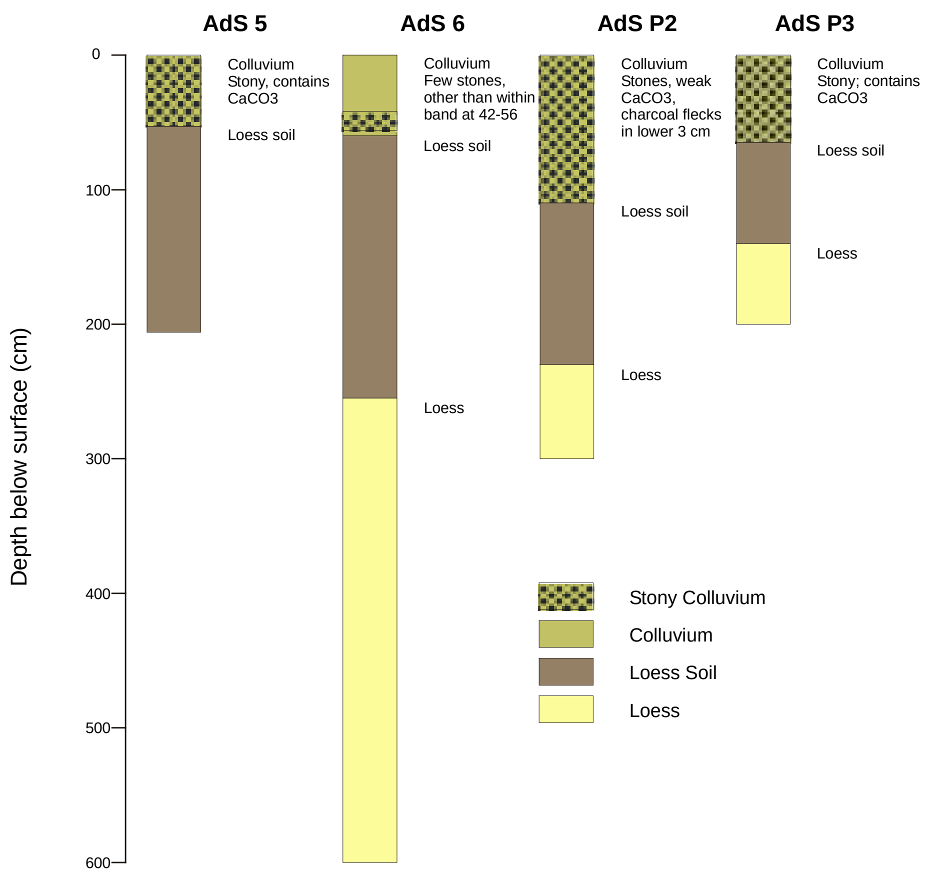


Figure 5.5: Cores from the western flank of the Auf dem Scheid accumulation zone (AdS5 and AdS6, and soil auger points AdSP2 and AdSP3). See Figure 5.2 for location of borepoints.

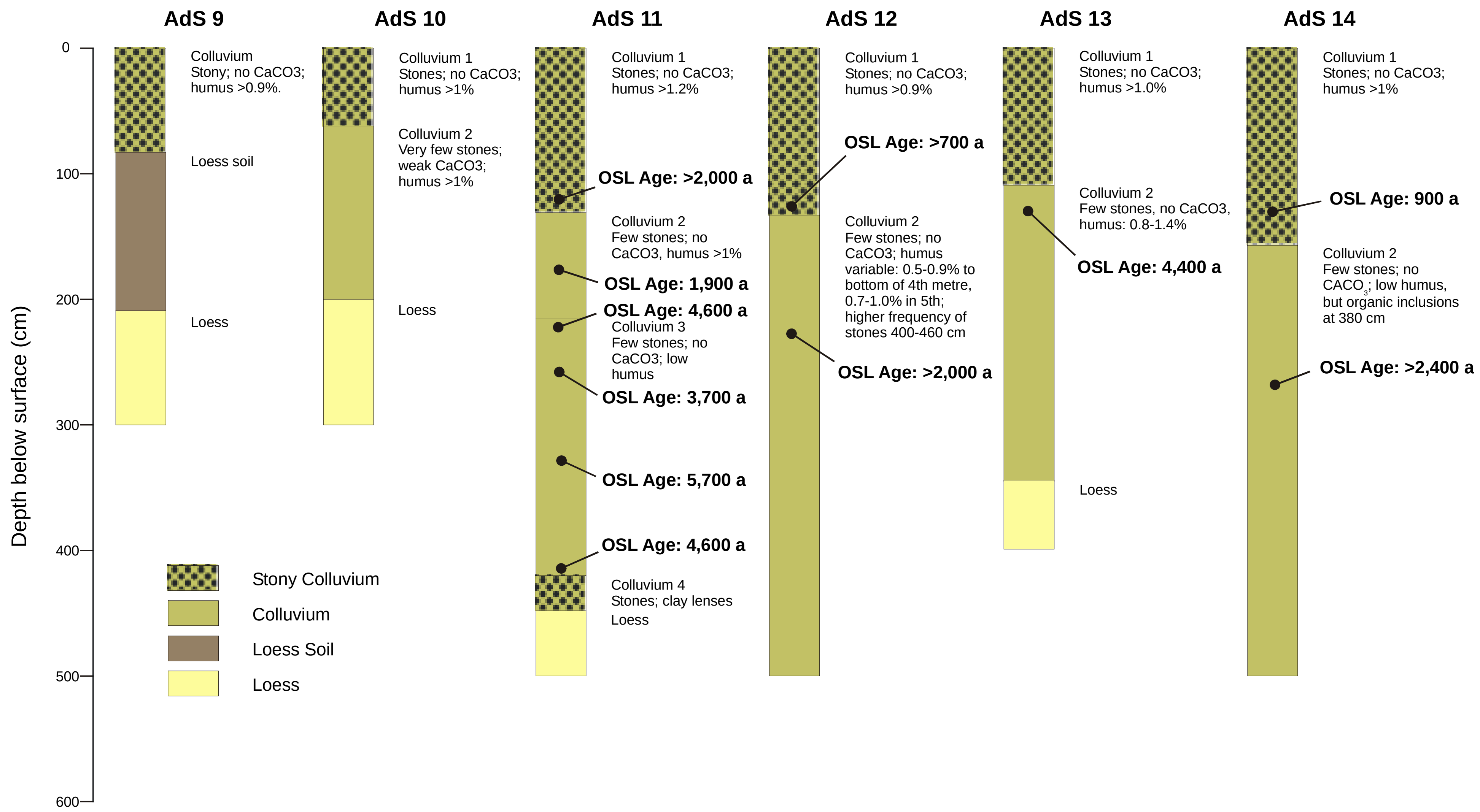
The thalweg: AdS9 – AdS14

The cores AdS9 – AdS14 (Fig. 5.6) represent a longitudinal profile through the thalweg of the catchment. Cores AdS9 –AdS11 were taken from the cropland in the upper part of the catchment, while AdS12 – AdS14 are from the pasture zone. Core AdS9 has 0.83 m of stony colluvium overlying a partly truncated loess soil. This colluvium shows no $CaCO_3$ reaction, but has high humus contents. Loess parent material was found ~2 m below the surface in this core and in AdS10. The latter, however, contains no soil, with colluvium directly over loess. Two colluvia are inferred, distinguished on the basis of stone frequency although both have humus contents greater than 0.9%. Core AdS11 presents a considerable contrast to these two, with some 4.5 m of colluvium again directly in contact with the underlying loess. Four colluvia are inferred – designated 1 to 4, from top to bottom. Colluvia 1 and 4 contain a high frequency of stones, while these are rare in Colluvia 2 and 3. The upper two colluvia (1 and 2) are relatively humus rich (>1.2% and >1% respectively), while the lower two have a relatively constant low humus content (~0.5%). Six samples were recovered from this core for OSL dating (Table 5.1). One sample was taken from the base of Colluvium 1 (1.16-1.23 m), which unfortunately shows significant signal fading and thus the age of >2,000 a must be taken as a minimum estimate. A sample from the middle of Colluvium 2 (1.72-1.80 m) returns an age of 1,920 ± 350 a. The four samples taken from Colluvium 3 yield considerably older ages than the overlying colluvia. Respectively, these are 4,630 ± 1,330 a (4.12-4.19 m), 5,700 ± 1,170 a (3.26-3.33 m), 3,740 ± 760 a (2.54-2.62 m) and 4,590 ± 1,000 a (2.18-2.25 m). Given their error margins, these ages cannot be differentiated at the 2σ level, and only the middle two of the four differ significantly at 1σ – and then only by 30 a.

As with AdS11, there are significant depths of colluvium in cores AdS12-14. Core AdS12 has at least 5 m of colluvium. At a coarse scale, two colluvia are recognised, distinguished on the basis of stone frequency and, to a lesser extent, humus content. The upper colluvium has a relatively high frequency of stones and humus contents >0.9%. Below ~1.3 m there is both a considerably smaller number of stones and lower humus contents. The latter vary between 0.5% and 0.9% for much of the column, but are somewhat higher in the lower part of the core. Two OSL samples both exhibit anomalous fading, and the ages of >700 a from the base of the upper colluvium, and >2,000 a from the lower, are again minimum estimates. AdS13 contains “only” ~3.5 m of colluvium, although again, this is in direct contact with underlying loess. There are relatively high humus contents throughout, but a clear boundary between two colluvia – distinguished on the basis of stone frequency – is discernible at ~1.1 m. One OSL sample was taken, from the lower of these colluvia, returning an age of 4,400 ± 900 a. As with AdS12, AdS14 also has at least 5 m of colluvium and two generations can be distinguished, on the basis of stones and elevated humus content in the upper colluvium. The lower is characterised by occasional stones and although humus content is low, organic objects are present. Two OSL samples were taken. One, from near the base of the upper colluvium returns an age of 900 ± 100 a, while the second, from the lower colluvium, exhibits anomalous fading and its age of >2,400 a is thus a minimum.

Lateral transects indicate that significant depths of colluvial material (>1 m) are almost exclusively restricted to the area marked on Figure 5.2, which is considered to be the filling of a former gully or channel. This is the conduit transporting material from the upper part of the catchment to the lower.

Figure 5.6: (following page) Cores from the Auf dem Scheid thalweg (AdS9 – AdS14) OSL ages are rounded to the nearest 100 years. See Figure 5.2 for location of borepoints.


AdS 9
AdS 10
AdS 11
AdS 12
AdS 13
AdS 14
Depth below surface (cm)
0
100
200
300
400
500
600
Colluvium
Stony; no CaCO3;
humus >0.9%.
Loess soil
Loess
Colluvium 1
Stones; no CaCO3;
humus >1%
Colluvium 2
Very few stones;
weak CaCO3;
humus >1%
Loess
Colluvium 1
Stones; no CaCO3;
humus >1.2%
OSL Age: >2,000 a
Colluvium 2
Few stones; no
CaCO3, humus >1%
OSL Age: 1,900 a
OSL Age: 4,600 a
Colluvium 3
Few stones; no
CaCO3; low
humus
OSL Age: 3,700 a
OSL Age: 5,700 a
OSL Age: 4,600 a
Colluvium 4
Stones; clay lenses
Loess
Colluvium 1
Stones; no CaCO3;
humus >0.9%
OSL Age: >700 a
Colluvium 2
Few stones; no
CaCO3; humus
variable: 0.5-0.9% to
bottom of 4th metre,
0.7-1.0% in 5th;
higher frequency of
stones 400-460 cm
OSL Age: >2,000 a
Colluvium 1
Stones; no CaCO3;
humus >1.0%
Colluvium 2
Few stones, no CaCO3,
humus: 0.8-1.4%
OSL Age: 4,400 a
Loess
Colluvium 1
Stones; no CaCO3;
humus >1%
OSL Age: 900 a
Colluvium 2
Few stones; no
CACO3; low humus,
but organic inclusions
at 380 cm
OSL Age: >2,400 a
Stony Colluvium
Colluvium
Loess Soil
Loess

5.2.2 *Evaluation of Dating Results and Identification of Colluvial Generations*

To an extent, the OSL results are inconclusive. Many samples exhibit evidence of signal loss due to anomalous fading, and of those that do not, it seems that the possibility of this cannot be entirely ruled out. The signal fading that is so prevalent in the samples from Auf dem Scheid is very probably due to the presence of plagioclase in the sediment. The presence of plagioclase in loess, and therefore in colluvia derived from loess and loess soils, cannot be discounted – especially if this was of local origin. However, the most significant source of plagioclase is the volcanic substrates (basalt and trachyt tuff) and the soils formed in them. Because of anomalous fading, many age estimates are described as minima. While it is difficult to place a maximum constraint on the age of a sample that exhibits signal loss, an attempt can be made. The loss of luminescence signal due to anomalous fading is an exponential phenomenon, i.e. it has its greatest influence on older sediments. LAMOTHE & AUCLAIRE (1999) propose a solution to the problem of anomalous fading and procedures are being developed to correct for this signal loss and the associated age underestimation. For young sediments such as those of Auf dem Scheid, it is likely that a correction factor would be ~20% at maximum. The analysis required to enable such a correction requires storage of sediment samples for long periods, and it has not yet been possible to undertake this. However, given the relatively low ages of the sediments investigated here, it is thought that adding a conservative value of 20% to the quoted minimum ages will provide a more realistic age estimate. In addition, for many of the samples there is evidence of radioactive disequilibrium, decreasing the precision of age estimates. In broad terms, therefore, development of a sedimentation chronology for Auf dem Scheid must rely on OSL ages that are imprecise and in some cases inaccurate. For the present they remain preliminary, and further analysis may enable some improvement in both precision and accuracy. Nevertheless, in comparison to many extensive studies of colluviation, there is chronological evidence to supplement the physical evidence from the cores, and some inferences can be drawn regarding different generations of colluvia.

Within the AdS1 colluvia, the deepest dated sediments return the most reliable ages, indicating that these can be attributed, respectively, to accumulation phases in the Bronze Age and early Medieval period. Overlying sediments must be younger, and the ages of sediments from the middle section of the core (~2.6 m and ~3.6 m) are attributed to partial bleaching during transport – due perhaps to either a short transport distance, rapid transport or transport under low light conditions. There is evidence of partial bleaching for the sediments from ~3.6 m and, although there is no evidence of partial bleaching indicated for the sample above this (~2.6 m), it is assumed on stratigraphic grounds that the age must also be an overestimate. The ages quoted for these sediments are thus considered to be overestimates, although it is difficult *prima facie* to know to what extent this is the case. An apparent age inversion such as this has also been found within Medieval colluvia in southern Germany (KADEREIT *et al.* in press). Within the upper part of the AdS1 colluvium, the sample from ~1.5 m gives what appears to be a reliable age, although the stratigraphically higher sample returns an older minimum age. It is thus difficult to establish an appropriate chronology for sediments above ~4.6 m solely on the basis of the OSL ages they return. Nevertheless, OSL ages from AdS1 do indicate the occurrence of prehistoric sediment accumulation, followed by extensive accumulation since the height of the Medieval period.

The second Auf dem Scheid site from which a significant number of OSL samples was taken is AdS11. There is a clear distinction between two colluvial units at a depth of 2.15 m. The four samples from below this depth range in age between ~3,700 and ~5,700 years old. No signal loss due to fading is indicated, and the apparent stratigraphic inconsistency can be disregarded when the error ranges of ages are taken into account. Within the 2σ error range, all four of these sample ages are statistically indistinguishable. Within the upper of these two units, however, there is stratigraphic inconsistency due to anomalous signal fading. This is a similar situation to that in AdS1. If the assumption referred to above regarding the magnitude of signal loss is accepted, the age of the uppermost sample in AdS11 (~1.2 m) lies within the range 2,000 – 2,400 a, which overlaps the 1σ error range of the sample at ~1.75 m. On both chronological and physically diagnostic grounds, it therefore seems that AdS11 contains a prehistoric colluvium and another that may correspond to either the Roman period or the late Iron Age. Although the prehistoric colluvium appears to be older than that of AdS1, it is difficult to be certain of this given the wide range of uncertainty associated with these ages.

With respect to other sites, samples taken from ~1.25 m at AdS12 (>700 a) and ~1.3 m at AdS14 (900 ± 100 a) are of a comparable age to the AdS1 Medieval colluvium. Sediments from the middle sections of these two borepoints show evidence of signal loss (>2,000 and >2,400 a respectively). Assuming maximum ages of these samples of ~2,400 and ~2,900 on the basis of a maximum 20% signal loss associated with fading, these sediments are thought to correspond to the younger colluvium of AdS11. However, the single sample taken from AdS13 (~1.3 m) returns an age of 4,400 ± 900 and thus belongs to an older colluvial generation. The sample from AdS8, returning a minimum age of 3,600 a, may also belong to this generation.

Thus, several generations of colluvia are inferred within the context of a broad reconstruction of the mid- to late Holocene development of Auf dem Scheid. Although largely eroded from the upper part of the catchment, loess soils remain on the western slope of the pasture zone, and indeed under the shallow colluvium of the western part of the accumulation zone. Their presence supports an inference of early to mid-Holocene geomorphic stability, and although only a single small remnant of such a soil within the AdS3 core remains on the eastern side of the accumulation zone, it seems reasonable to assume that mature soils were also present there. Regardless of the nature of pre-existing soils on the eastern side of the contemporary accumulation zone (i.e. whether formed in loess or in basalt or Pleistocene solifluction cover layers), they have now been almost completely eroded, and their truncated remains are overlaid with several metres of colluvium both within the thalweg (AdS9-14, AdS2) and to the east of it (AdS3, AdS4 and AdS8). The occurrence of an erosional event (or events) is thus inferred. This may have been either headward extension of a sufficiently large channel, or gullying. In any case, there was rejuvenation of the previous relief. An exact timing of this event, or events, is not possible. However, given the ages of the colluvia (e.g. AdS13, lower section AdS11) that initially filled this erosional feature, it must have occurred some time prior to (very approximately) ~4 ka.

The deepest sediments of AdS1, although also prehistoric, appear too young to have been associated with this event. It is therefore speculated that the deep colluvia on the eastern side of the accumulation zone and in the thalweg are the filling of a former gully that drained into the former Eichenbach channel to the east of the AdS1 site. In this scenario, the AdS1 site at that time may have been a narrow terrace at the foot of a slope formed in undisturbed loess and loess soils, or indeed a part of that slope. The loess soils underlying the western side of the accumulation zone were not affected in this early erosion-deposition event. However, the filling of this gully created a topography resembling that of today, i.e. causing the lower part of the thalweg to migrate some tens of metres to the west, directing subsequent thalweg erosion and sediment delivery toward the site of AdS1. Such a sequence accounts for the absence of the older colluvium in the AdS1 core. Alternatively, sediments corresponding to this earliest depositional phase may well have been present at the location of AdS1, but were eroded prior to the deposition of a later colluvial generation.

A second depositional phase, relating to the late Iron Age or possibly the Roman period is tentatively inferred from the ages of colluvia in the upper part of AdS11 and the middle sections of AdS12 and AdS14. As with the earlier phase of accumulation, no evidence of this is found within AdS1. Possibly sediments were not able to be transported that far. Alternatively, they may be present at AdS1 but were not dated (i.e. their thickness is less than the OSL sampling interval), or were present and have subsequently been eroded. The sediments of AdS2 – intermediate between AdS14 and AdS1 – should be able to offer some clarification of this issue, and samples for OSL dating were taken from this core, but unfortunately were damaged in the laboratory.

A third depositional phase occurred early in the Medieval period, as evidenced principally by the age of sediments at ~4.6 m in AdS1, and supported by ages from the upper parts of AdS12 and AdS14. Unfortunately, stratigraphic inconsistencies within AdS1 (due to the partial bleaching derived age inversion in the middle of this column and signal loss in its upper part) preclude any further temporal resolution on the basis of OSL ages. Certainly, fluctuation in humus content and specific zones of high skeletal and sand content indicate distinct colluvial units. However, between the dated sediments at ~5.7 m and ~4.6 m it is difficult to know which of these to attribute to either the prehistoric or Medieval periods – or indeed whether a remnant Iron Age/Roman colluvium remains here. Similarly, the partial bleaching of sediments in the middle section of the core represent circumstantial evidence of a large erosion-deposition event – or series of events. The concentration of organic material at ~3.85 m could mark the onset of such a period, and the more laminated nature of sediments between this point and ~1.6 m may represent a large pulse of sediment generated within a relatively brief period, i.e. one that is synonymous with those reported elsewhere for the 14th century. However, in the absence of direct chronological evidence, it is difficult to make firm inferences in this regard.

Lastly, a further depositional phase of late Medieval/early modern age is inferred from the upper section of AdS1 and from AdS2. The ^{14}C age of organic material at the base of the AdS2 colluvium (~200 a) suggests an accumulation of ~2 m since the late 18th or early 19th century. However, the 1σ range associated with this ^{14}C age is wide (1660-1950 AD), and the colluvium at the base of AdS2 can also be attributed to a late Medieval accumulation phase. Diagnostically the colluvia of AdS2 appear to represent at least two different generations. The upper colluvium clearly differs from deeper colluvia on the basis of its high stone content, and is qualitatively similar to the colluvia in the upper sections of all cores. In general, this most recent colluvium completes the horizonation inversion that is often characteristic of eroding soils and their correlate sediments. A broad pattern can be detected in Auf dem Scheid of silty, decalcified colluvia (an inferred former B horizon) overlaid by $CaCO_3$-bearing and increasingly stony colluvia as erosion advances into C horizons. However, this is a broad pattern only, because Auf dem Scheid has distinctly different sources of colluvial material – soils formed in both loess and Tertiary igneous substrates.

These different generations of colluvia are illustrated with a longitudinal sequence through the basin's long profile, where the deepest colluvial sediments are found (Fig. 5.7). It has been constructed from the cores AdS9-14, AdS2 and AdS1.

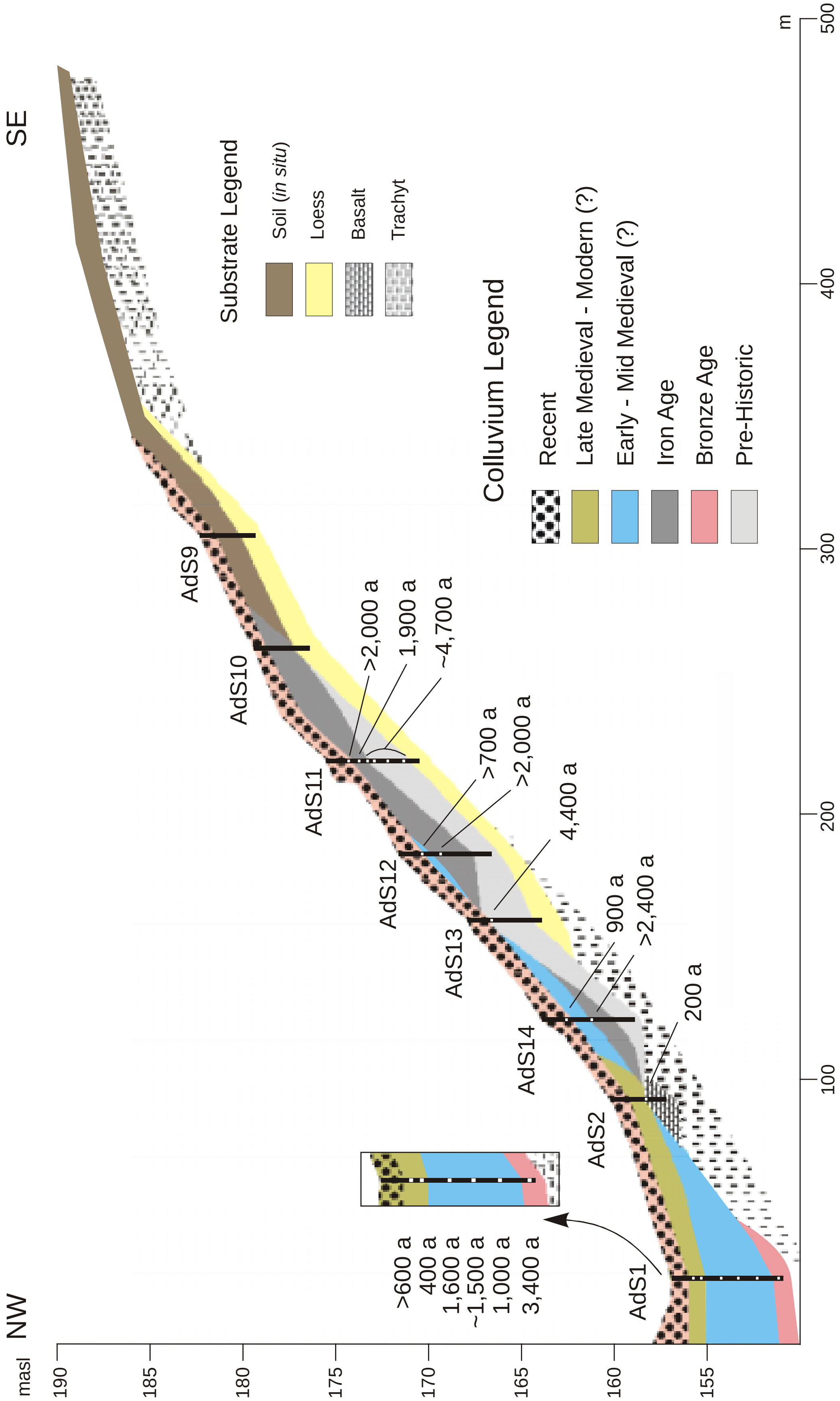


Figure 5.7: Long profile through Auf dem Scheid. As discussed in the text, various generations of colluvium are inferred on the basis of OSL ages and core interpretation. OSL ages (rounded to nearest 100 years) are indicated for each point; the age given for the base of AdS2 is a ^{14}C age. Unless verified by drilling, the lithological disposition is speculative, based on inference from the geological map and supplementary drillings not located on this profile. The slope profile has a 7x vertical exaggeration.

A simple long term sediment budget has been constructed for Auf dem Scheid (Table 5.2). The zone of substantial colluvial storage as marked on Figure 5.8 occupies an area of 5,775 m^2. Assuming a representative colluvial depth of 3 m, this represents 17,325 m^3 of colluvium. The density of this material remains essentially the same as the soil from which it was derived, i.e. 1,300 kg/m^3 (FEISE 1999), and this volume converts thus to ~22,500 tonnes of colluvium stored within Auf dem Scheid. The mass of soil eroded from Auf dem Scheid has been estimated using some broad simplifying assumptions regarding the original undisturbed condition of soils. Firstly, it is assumed that the whole of Auf dem Scheid was blanketed with a Parabrown Earth formed in loess. According to BRINKMANN & SKOWRONEK (1999), the maximum depth to which these Parabrown Earths developed in the study area is 2.5 m. Recognising that there will have been some degree of spatial variability, a representative depth of 2 m has been assumed here. The magnitude of erosion has been estimated on the basis of remaining soil depths within each of the soil type units indicated on Figure 5.8.

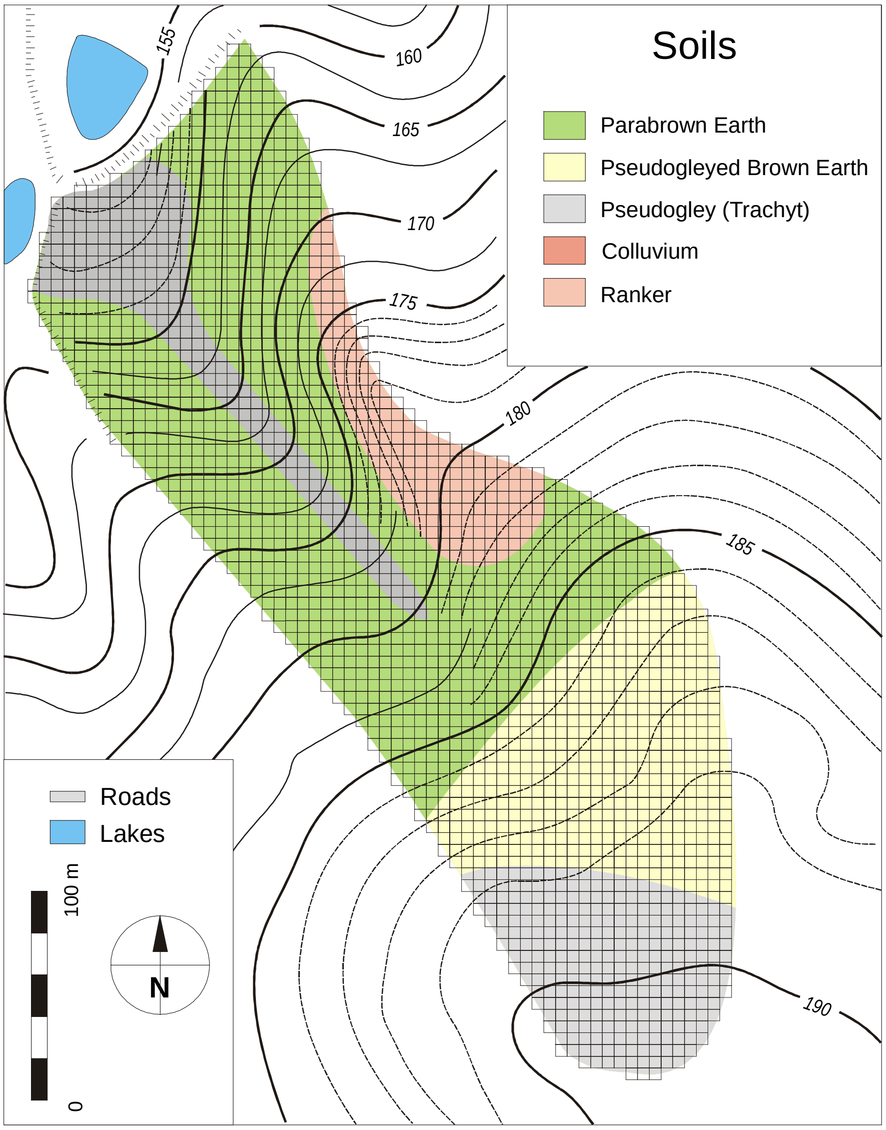


Figure 5.8: Distribution of soil type units used to estimate amounts of erosion and deposition for a Holocene sediment budget in Auf dem Scheid.

For the Parabrown Earth and pseudogleyed Brown Earth units ~1 m of soil truncation is assumed, while for the Pseudogley (Trachyt), Ranker and Colluvium soil units it is assumed that the entire 2 m loess soil has been eroded. In addition it is assumed that 0.5 m has been lost from the basalt soil that is now characterised as a Ranker. Volumes of erosion have been estimated on the basis of these depths and the areas of respective soil units, and converted to mass estimates using densities of 1,300 kg/m^3 for the Parabrown Earth and 1,500 kg/m^3 for the soil formed in basalt. On the basis of these assumptions a total Holocene erosional loss of ~95,000 tonnes is estimated (Table 5.2). The net sediment loss, i.e. the material that does not remain in colluvial storage, is thus ~70,500 tonnes. This has been exported beyond the boundaries of Auf dem Scheid and represents a Holocene sediment delivery ratio of 74.4%.

Table 5.2: Holocene erosion and deposition within Auf dem Scheid. The area of each soil type unit was estimated on the basis of numbers of 25 m^2 grid cells (see Fig. 5.8). The density used for volume/mass conversions is 1,300 kg/m^3, except for the basalt soil eroded from the Ranker unit which was assumed to have a density of 1,500 kg/m^3.

	Soil Unit	Area (m^2)	Depth (m)	Volume (m^3)	Loss/Gain (t)
Gain	Colluvium	5,775	3	17,325	+ 22,522.5
					+ 22,522.5
Loss	Parabrown Earth	25,525	1	25,525	– 33,182.5
	Pseudogleyed Brown Earth	11,275	1	11,275	– 14,657.5
	Pseudogley (Trachyt)	7,200	2	14,400	– 18,720.0
	Ranker (Parabrown Earth)	4,575	2	9,150	– 11,855.0
	Ranker (Basalt soil)	4,575	0.5	915	– 1,372.5
	Colluvium	5,775	2	11,550	– 15,015.0
					– 94,802.5

5.2.3 ^{137}Cs and Modelled Sediment Redistribution Rates

The distribution of ^{137}Cs within the soils of the Auf dem Scheid catchment has been mapped on the basis of 120 samples. Although all terrain types within the catchment were sampled, the sampling strategy placed an emphasis on areas where concentrations were expected to vary or where more useful information was anticipated, e.g. at breaks in slope and in depositional zones.

Point activities expressed in both Bq/kg and Bq/m^2 are listed in Appendix B, and the distribution of ^{137}Cs is illustrated in Figure 5.9. Intervals were chosen so as to indicate areas with values greater and smaller than the reference inventory of 5,530 Bq/m^2. The distribution of measured activity in samples is wide, with a 1σ range of 3,880 – 7,180 Bq/m^2, and an analytical error of ~295 Bq/m^2. Applying this value to the assumed reference inventory (i.e. 5,530 ± 295 Bq/m^2) gives a range of 5,235 – 5,825 Bq/m^2. Of the 120 samples, 20 have activities within this range, and may have influenced the location of boundaries between erosional and depositional areas to a small extent. The areas indicated on Figure 5.9 are based on a kriging interpolation between points with known values and are thus indicative only. Recognising analytical error, a fuzzy approach to interpolation may have been more appropriate. In addition to statistical considerations, it should also be recognised that some degree of variability in activity may be attributed to variability in fallout receipt. No attempt is made here to quantify this effect, and greater importance is attributed to the spatial distribution of ^{137}Cs activities and the erosion-deposition rates derived from them.

Within the pasture zone there are extremes of both low and high ^{137}Cs activities. However, with the exception of Point 106, there are few points with activities greatly lower than reference. More marked in this zone are the high concentrations at the base of slopes and especially within the thalweg. The arable zone on the other hand does not have as extreme a range of high activities, and is characterised more by the predominance of values lower than reference. Within the arable zone itself, another pattern can be detected, reflecting the division of the arable zone into two fields with different cropping histories, and with different topography. The upper part – which is essentially a plateau – shows values slightly higher than the reference inventory on its higher boundaries but lower concentrations in the gently sloping middle section. A further zone of higher concentrations is evident at the boundary between this field and the adjacent lower field. This pattern of higher concentrations continues into the central zone of the lower field, which has a pronounced thalweg. In contrast to the upper field, the pattern of ^{137}Cs distribution in the lower arable field appears to be broadly related to topography: highest values are in the thalweg and adjoining slopes have lower values – extremely low in the case of Points 72-74. Again, there is a concentration of higher values at the lowest point of the boundary separating this field from the downslope pasture zone.

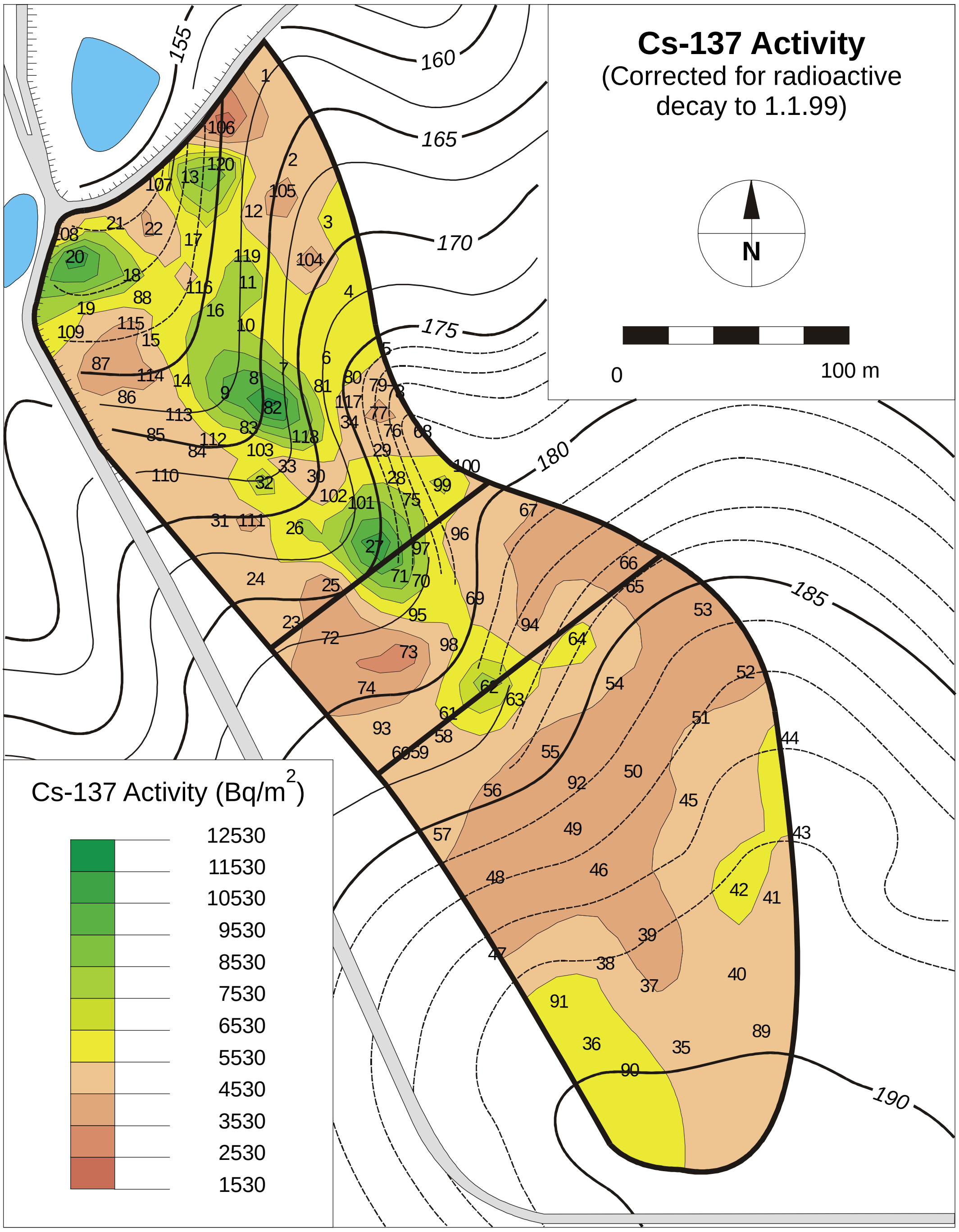


Figure 5.9: Distribution of ^{137}Cs activity in Auf dem Scheid. Sample points are numbered. For legend of base map, see Figure 5.2.

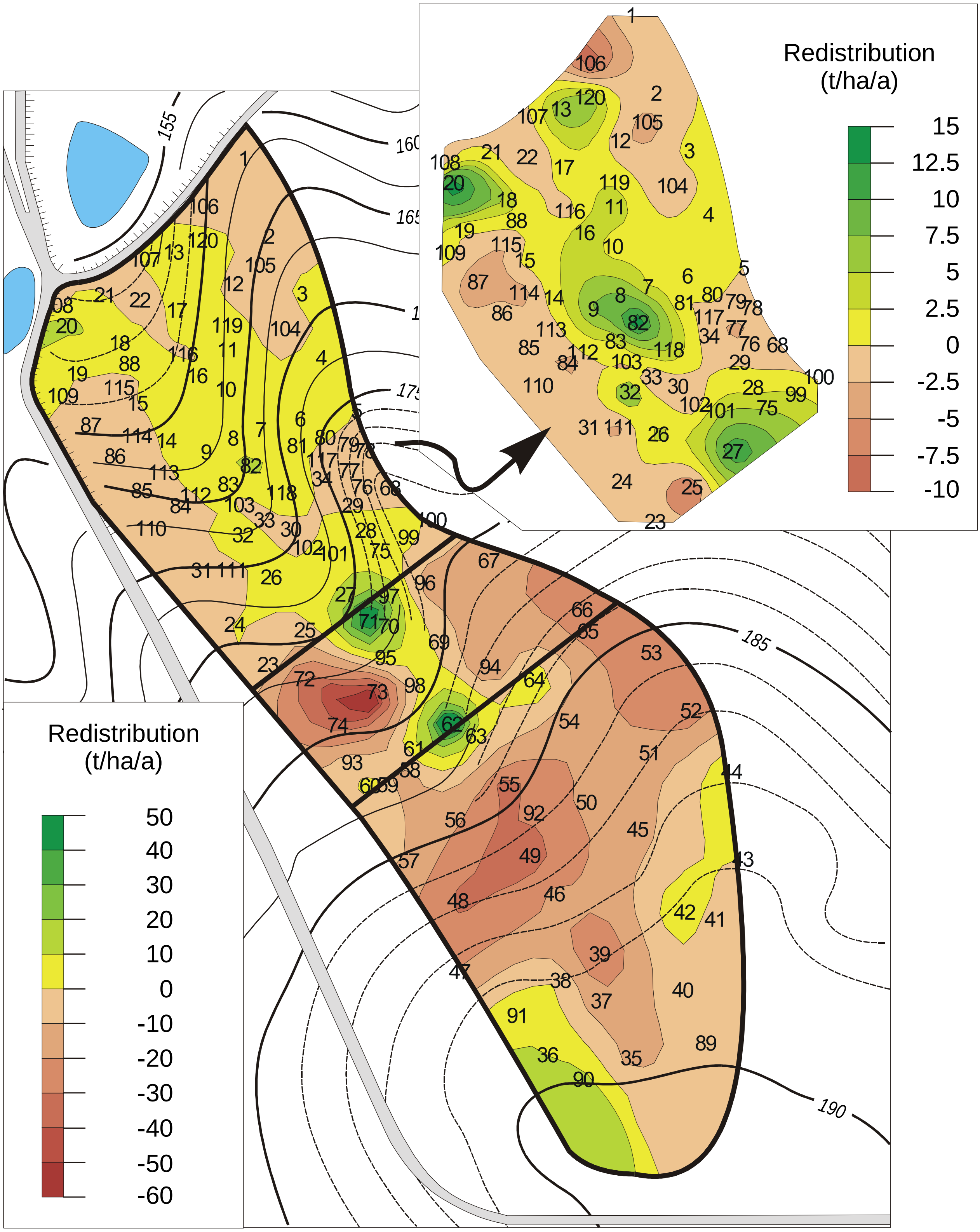
As with the lower arable field, in the pasture zone there is a broad relationship between topography and ^{137}Cs activity. However, this is by no means simple. This area has much steeper slopes, but these do not exhibit especially low ^{137}Cs activities, and indeed in some cases show values greater than reference. A preliminary inference that can be drawn for the pasture zone, and indeed for the whole of Auf dem Scheid, is that topography perhaps plays a small role in determining ^{137}Cs activity, but only within a configurational context, i.e. the spatial relationship between areas of greater and lesser slope. Second order morphometric properties such as curvature and contributing area may be more significant.

Recognising the high variability of activities, two related preliminary inferences can be drawn on the basis of the spatial distribution of ^{137}Cs activities. Firstly, there is a clear concentration of higher activities in the thalweg and at the base of the steeper slopes. Secondly, it appears that the predominance of high activities in the pasture zone is not associated with a comparable amount of low activities, which may imply that some of the excess ^{137}Cs in the pasture zone can be attributed to sources in the arable zone.

Because of the difference in land use, two different modelling approaches were applied for determination of erosion and deposition rates. These were selected from a range of software models produced by WALLING & HE (1997). For the upper arable part of the catchment, the Mass Balance 3 model was used, and the Diffusion and Migration model was applied to the pasture part of the catchment. A full description of the equations employed within these models is given in Appendix C and their parameterisation was discussed in Chapter 4. The results of their application are presented here.

Calculated rates of erosion and deposition for each sample point are listed in Appendix B, and the spatial distribution of net erosion and deposition rates is illustrated in Figure 5.10. The most striking observation from Figure 5.10 is the contrast in rates of sediment redistribution between the two land use zones. The arable zone shows greater extremes of both erosion and deposition, with the pasture zone, as expected, appearing rather geomorphically inactive by comparison. To some extent, this is due to the range of magnitudes of process activity within the arable zone. The inset of Figure 5.10 shows redistribution rates for the pasture zone only, plotted with a separate colour scale. Clearly, there has been redistribution of sediment associated with water erosion in the pasture zone, but this has not been extreme. For the most part, there appears to be a good coupling between erosional and depositional sites. This is not the case, however, for the high rates of accumulation around Point 27 – adding support to the inference mentioned above, that the material deposited within the pasture zone – and especially that lying within the thalweg – is derived from the arable part of the catchment.

Figure 5.10: (following page) Net rates of soil erosion and sediment deposition in Auf dem Scheid, modelled on the basis of ^{137}Cs activities. Sample points are numbered. Rates for the arable zone are derived from a mass balance model parameterised for both water erosion and tillage translocation, while those for the pasture zone are modelled with a diffusion/migration model incorporating water erosion only. The inset shows rates for the pasture zone plotted with a finer class interval. For legend of base map, see Figure 5.2.



Note that Figure 5.10 shows rates of *net* sediment redistribution. The mass balance model applied to the arable zone delivers rates of sediment redistribution due to both water erosion processes and tillage translocation. These are compared in Figure 5.11, clearly illustrating the different effects of these two processes. For the greatest part of the arable zone, tillage produces relatively low rates of erosion. These are slightly higher on the eastern flank where slope angle is greater. Deposition due to tillage, however, is restricted to a very limited area at the base of the arable zone, exemplifying the development of a colluviation terrace at the arable field boundary. While there is a slight topographic effect due to local slope angle, the principal influence on tillage translocation appears to be the pattern of tillage (cross-slope) and the interaction of this with the overall catchment gradient. The effect is more-or-less uniform, and a clear pattern emerges of erosion for the most part of the arable area, with high rates of deposition concentrated in the lowest parts of the zone. Water erosion, on the other hand, produces a more diverse pattern of sediment redistribution, and a greater range of values – especially for erosion. Different patterns can be discerned for the two land units with different topography and cropping histories. The lower, steeper unit is characterised by eroding slopes and an accumulating thalweg zone. The upper unit, on the other hand, shows erosion within the central depression as well, with some accumulation on the almost flat flanks, where presumably runoff has insufficient energy for transport. The boundary between these two units represents a clear barrier to sediment transport in runoff, as best indicated by the accumulation at Points 62 and 63. While the pattern of net sediment redistribution within the arable zone appears to be best approximated by water erosion, the interaction between the two processes of water erosion and tillage translocation has implications for the whole of Auf dem Scheid. Tillage accumulation at the lower edge of the arable zone is partly further reworked by water erosion, with a net effect of concentrating accumulation in the thalweg outlet to the pasture zone.

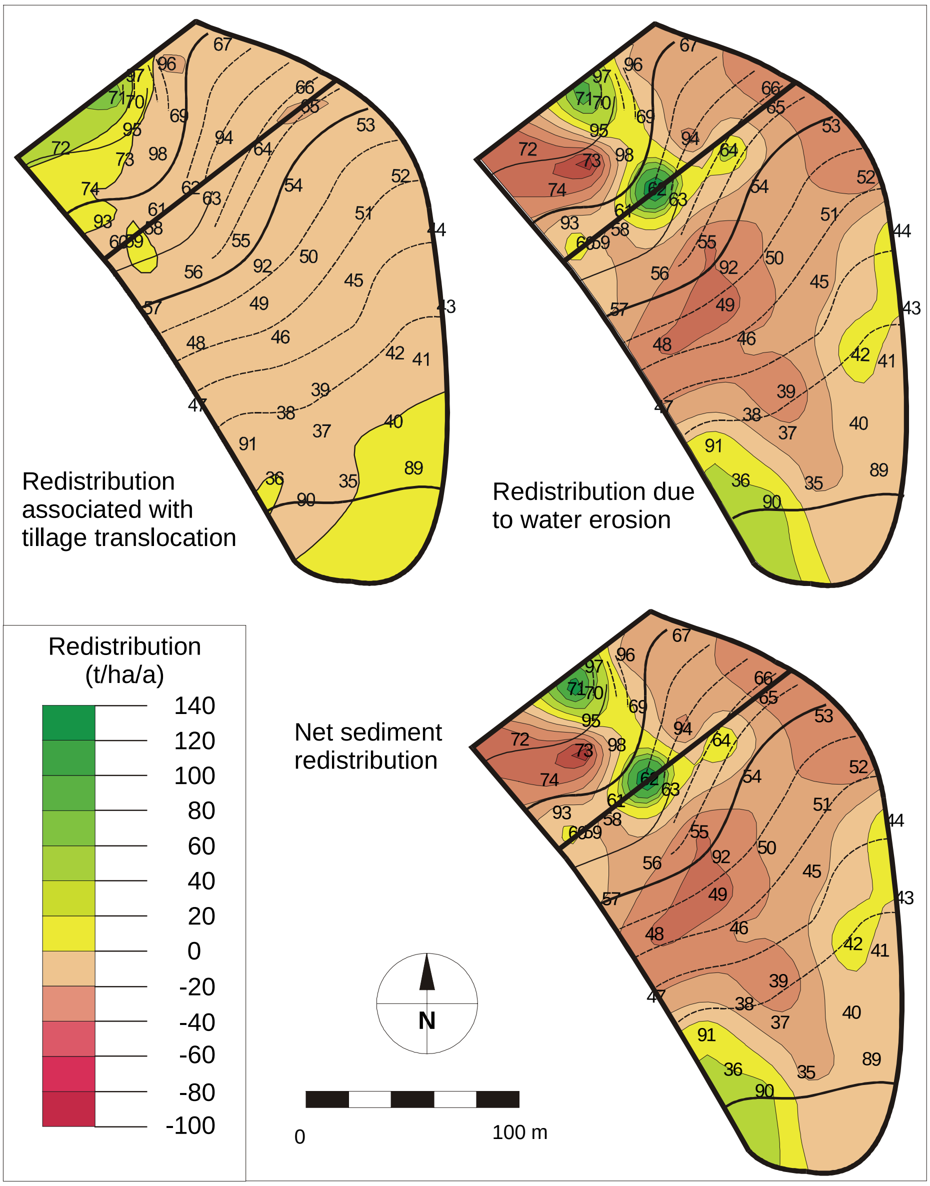


Figure 5.11: Rates of tillage translocation and water erosion in the arable zone of Auf dem Scheid. Sample points are numbered, and the boundary between the two arable fields is indicated.

This is also true for the whole of Auf dem Scheid with respect to the land use boundary dividing the catchment across its middle. Although an arable zone source is inferred for the thalweg deposition in the pasture zone, this deposition is of considerably lower magnitude than the accumulation upslope of the land use boundary, which is thus a reasonably effective barrier to transport between the two zones. The extent to which this is the case will be tested using a sediment budget approach.

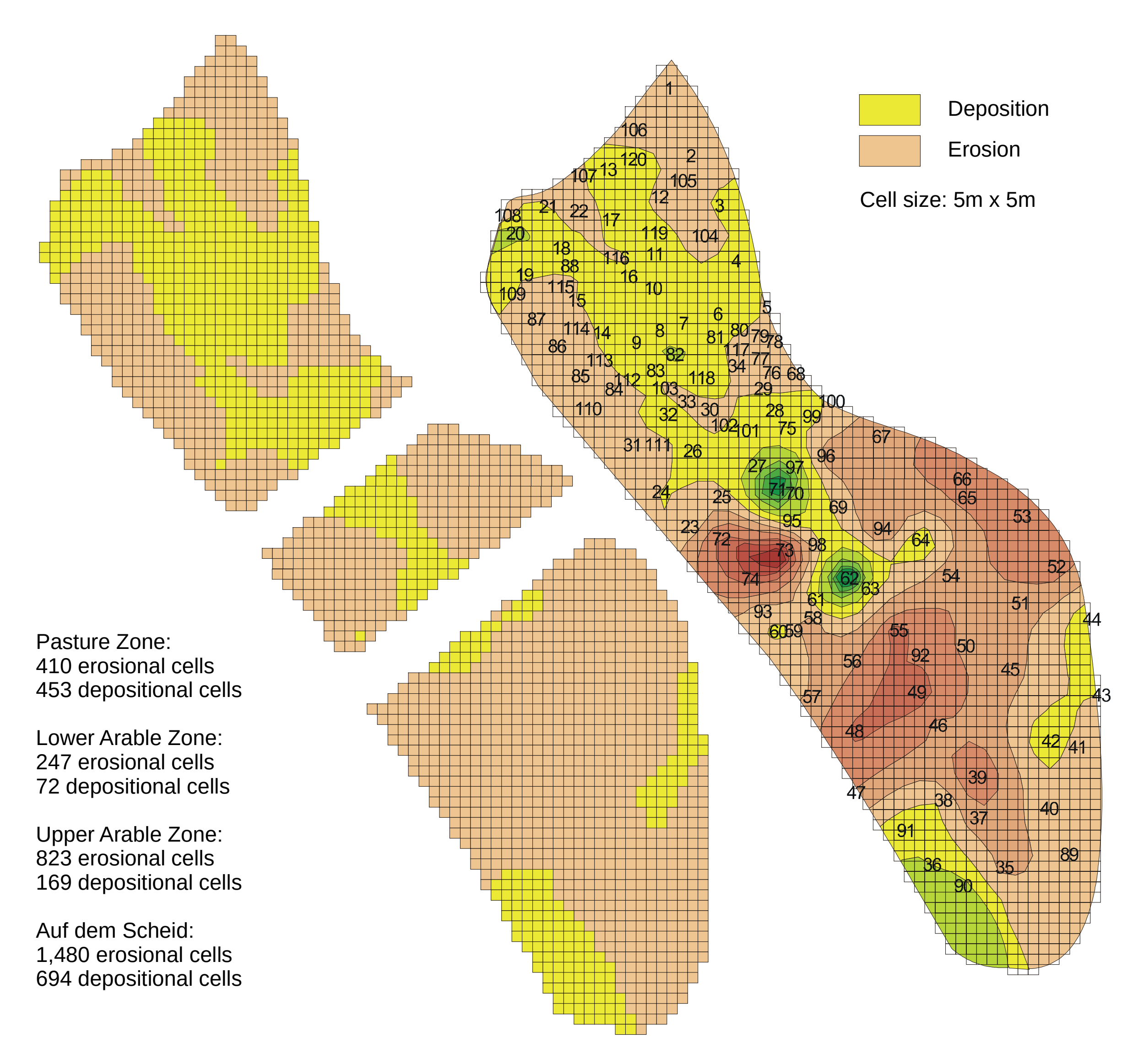


Figure 5.12: Subdivision of Auf dem Scheid's three land use zones into erosional and depositional areas.

For the development of a sediment budget based on this information, it is necessary to distinguish between erosional and depositional areas, and to quantify these in terms of their area. A grid of 25 m^2 cells has been overlaid on the net redistribution map illustrated in Figure 5.10, and each cell has been characterised as either erosional or depositional (Fig. 5.12). Erosional and depositional areas within each of the three zones of Auf dem Scheid are thus approximated by multiplying numbers of cells by 25 m^2. These values are summarised in Table 5.3. On the basis of this simple analysis it appears that, in terms of area, both arable zones are significant net erosional units and that the pasture zone is a net accumulating unit.

Table 5.3: Erosional and depositional areas determined from the proportion of eroding and depositional cells within each zone (see Figure 5.12).

	Total Cells	**Total Area (ha)**	Erosional Cells	**Depositional Cells**	**Erosional Area (ha)**	**Depositional Area (ha)**
Arable Zone (upper)	992	2.4800	823	169	2.0575	0.4225
Arable Zone (lower)	319	0.7975	247	72	0.6175	0.1800
Pasture Zone	863	2.1575	410	453	1.0250	1.1325
Totals	*2,174*	*5.4350*	*1,480*	*694*	*3.7*	*1.7350*

This analysis, however, does not allow for magnitudes of erosion and deposition. A more detailed budget has been constructed, using a similar cell-based approach to quantify volumes of material eroded and deposited within each of the three zones (Fig. 5.13). Volumes of material eroded and deposited within each land use unit have been estimated by multiplying the interpolated area within each redistribution class by its median sediment redistribution value (Table 5.4). Summing these provides an estimate of the volumes of material eroded from and accumulated within each zone.

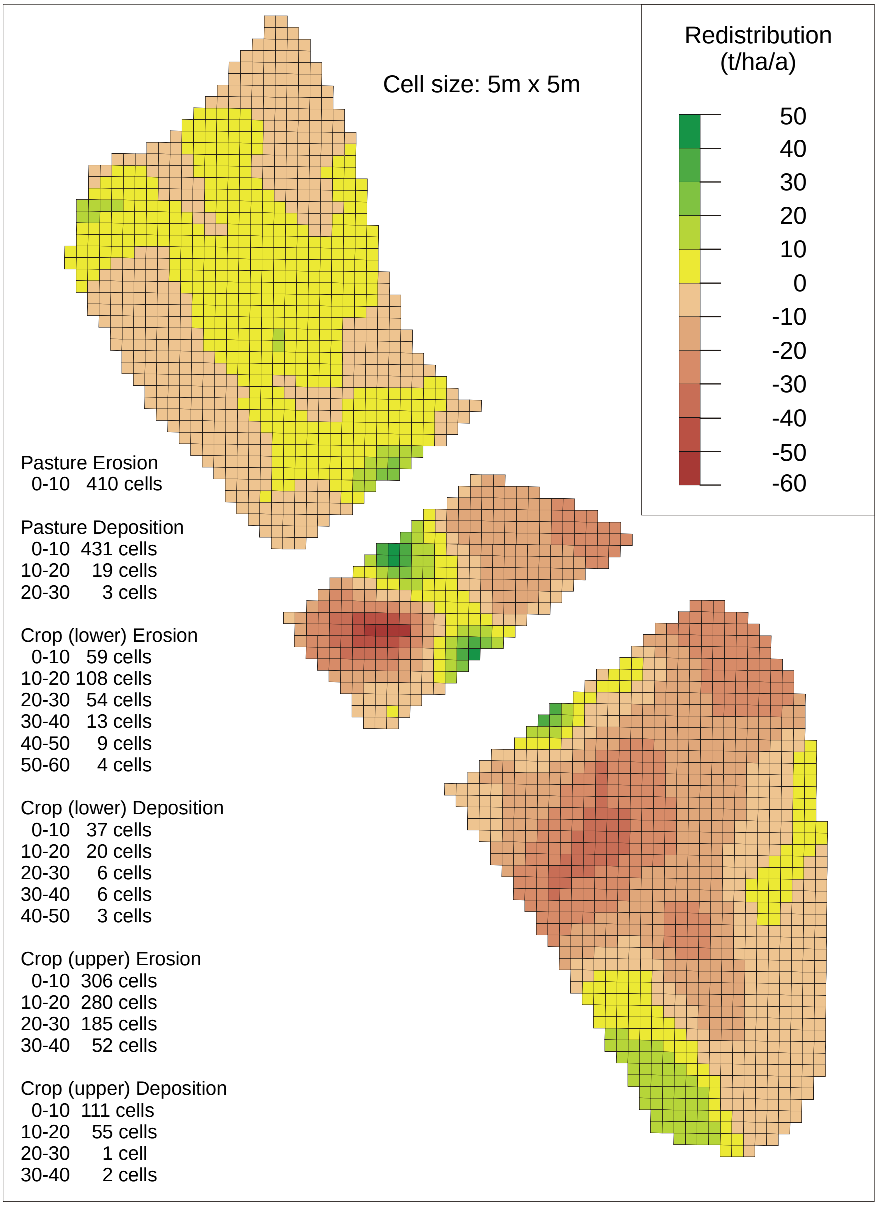


Figure 5.13: Cell-based determination of areas within erosional and depositional classes. The number of 5x5 m cells within each erosion-deposition class (interval 10 t/ha/a) is indicated. See Table 5.4 for further analysis.

Table 5.4: ^{137}Cs-derived sediment redistribution for the three land use units of Auf dem Scheid (see Figure 5.13).

	Class	Median	Area		Volume	Unit Flux	Cum. Flux
	(t/ha/a)	(t/ha/a)	(cells)	(ha)	(t/a)	(t/a)	(t/a)
Upper Arable Erosion	0-10	5	306	0.7650	-3.8250		
	10-20	15	280	0.7000	-10.5000		
	20-30	25	185	0.4625	-11.5625		
	30-40	35	52	0.1300	-4.5500		
			823	*2.0575*	*-30.4375*		
Upper Arable Deposition	0-10	5	111	0.2775	1.3875		
	10-20	15	55	0.1375	2.0625		
	20-30	25	1	0.0025	0.0625		
	30-40	35	2	0.0050	0.175		
			169	*0.4225*	*3.6875*	-26.75	-26.75
Lower Arable Erosion	0-10	5	59	0.1475	-0.7375		
	10-20	15	108	0.2700	-4.0500		
	20-30	25	54	0.1350	-3.3750		
	30-40	35	13	0.0325	-1.1375		
	40-50	45	9	0.0225	-1.0125		
	50-60	55	4	0.0100	-0.5500		
			247	*0.6175*	*-10.8625*		
Lower Arable Deposition	0-10	5	37	0.0925	0.4625		
	10-20	15	20	0.0500	0.7500		
	20-30	25	6	0.0150	0.3750		
	30-40	35	6	0.0150	0.5250		
	40-50	45	3	0.0075	0.3375		
			72	*0.1800*	*2.4500*	-8.41	-35.16
Pasture Erosion	0-10	5	*410*	*1.0250*	*-5.1250*		
Pasture Deposition	0-10	5	431	1.0775	5.3875		
	10-20	15	19	0.0475	0.7125		
	20-30	25	3	0.0075	0.1875		
			453	*1.1325*	*6.2875*	1.16	-34.00

The upper arable zone is estimated to have lost to erosion an average 30.4 tonnes of soil per year over the period 1954-1999. Only 3.7 t/a of this has been retained within this unit, which is clearly a net sediment exporting zone with a high sediment delivery ratio (87.9%). This efflux of sediment (26.75 t/a) from the upper arable zone represents an influx to the lower arable zone. This influx and the volume of sediment generated within the lower arable unit itself represent a total of ~37.6 t/a of mobilised sediment, of which only 2.45 t/a is stored locally. In terms of net sediment flux, the lower arable zone thus functions as a conduit, or transport zone. Considered as a single unit, the arable zone has a high sediment delivery ratio of ~85%. By contrast, the pasture zone considered in isolation appears to exhibit net sediment accumulation, with more material (6.3 t/a) accumulated within this zone than is eroded within its boundaries (5.1 t/a). However, in terms of net sediment flux, the pasture zone would appear to behave as a conduit in the same way as the lower arable zone. Although a greater volume of material is stored within the pasture zone than is generated therein, this volume of storage represents only a small fraction of the flux when the contribution from the arable zone is considered. Indeed, on the basis of this analysis it appears that Auf dem Scheid as a whole must be a net sediment exporting unit with a sediment delivery ratio of ~73.2%. This is in direct contradiction to the assumption that Auf dem Scheid has been a closed sediment redistribution system over the late 20th century. Whether there genuinely is a sediment delivery ratio of ~73% from Auf dem Scheid cannot be adequately answered for the present. Assuming that Auf dem Scheid is in fact a closed system with respect to sediment delivery other than through aeolian processes, the excess accumulation in the pasture zone should be equivalent to the volume of material lost from the arable zones. Clearly this is not the case, and there is a discrepancy between volumes of redistribution in absolute terms. The closed system assumption is considered to be justified, and this discrepancy is attributed to the fact that different models were used to estimate rates of sediment redistribution in each zone. On these grounds, comparison between the different land use types in terms of absolute values is perhaps spurious.

Further, this sediment budget is highly dependent on sampling density and especially on the nature of spatial interpolation between points with known values. Given the costs and measurement time required for ^{137}Cs, 120 samples from an area of <6 ha, with an error of mean estimation of ~5%, is considered reasonable. Inevitably, however, considerable resolution is missing, which influences the accuracy of interpolation. This is perhaps more the case in the arable zone with a lower sampling density than the pasture zone. It is to be emphasised therefore that the rates and volumes estimated here are indicative only, and no attempt is made to close the sediment budget for Auf dem Scheid. Nevertheless, the patterns and results within each land use unit, within which systematic modelling errors can be considered to be uniform, can be evaluated. These confirm that the arable units are indeed net sediment exporting units, and that the pasture zone has experienced deposition greater than can be accounted for by the sediments generated within its own boundaries.

5.2.4 Summary: Auf dem Scheid

Given the degree of truncation of soils – both in the upper catchment and under the contemporary colluvial body – there has clearly been extensive erosion within Auf dem Scheid. There is also a large volume of material in colluvial storage. Although the estimated long term sediment delivery ratio seems high, it is not inconsistent with drainage area/sediment delivery relationships reported in the literature (e.g. WALLING 1983, COOKE & DOORNKAMP 1997), and could in fact be interpreted as being rather low for such a small catchment. As always, with long term or large scale integral measures, use of a sediment delivery ratio obscures some of the detailed geomorphic information available. There is some evidence that colluvium derived from earlier erosion-deposition phases may have been removed and replaced by younger colluvia. This would mean that the volume of colluvial material currently stored in Auf dem Scheid should more correctly be related to a fraction of the eroded volume, rather than to the total. Greater resolution – both spatial and temporal – would enable sediment delivery ratios to be calculated for specific periods. An inference that can be drawn is that in the absence of large rainfall-runoff events, transport of material from the Auf dem Scheid accumulation zone to the next higher order system element is not likely. Certainly, the ^{137}Cs analysis indicates that for the latter part of the 20th century this has been the case. Thus, systematic configuration is important – specifically the topology of the coupling between different hierarchical levels of the landscape system.

The influence of configuration and spatial phenomena can also be seen within the Auf dem Scheid catchment. A comparison of the magnitudes of erosion and deposition between the different zones of Auf dem Scheid is perhaps not justified, given the different bases on which they were modelled. However, patterns within each unit can justifiably be assessed. These appear plausible and certainly indicate that the behaviour of erosional phenomena varies with land use and to an extent with topography. More importantly, the presence of boundaries between units influences sediment redistribution, and depositional behaviour in particular. Although sediments have been exported from both arable units, there are also clearly concentrations of deposition upslope of these boundaries. This suggests that although transport over these boundaries is possible, there may be an event magnitude threshold that must be exceeded before this is possible.

The different effects of water erosion and tillage translocation are clearly indicated within the arable zone. Tillage produces a very uniform effect of low magnitude erosion, while water erosion produces a more spatially diverse pattern. Model results suggest that greater rates of both erosion and deposition are produced by water erosion. The interaction between these two processes is interesting, and has important implications within the context of overall within-basin sediment redistribution. Tillage appears to have a net effect of transporting sediment to areas where it is susceptible to water erosion, which then concentrates sediment in areas where they are further susceptible to export into the downslope pasture zone. Importantly, tillage entrains material from areas where it would not be susceptible to water erosion, and delivers it to areas where it can be acted upon by the latter process. Tillage clearly has a relief levelling effect, as does water erosion, which removes material from higher elevations and deposits it in topographic low points.

Both the prevalent OSL signal fading and the predominance of volcanic stones within colluvia suggest that a significant source area is the trachytic and basalt soils and substrate of the upper and eastern parts of the catchment. Erosion of loess soils cannot, however, be discounted given the high silt content and the presence of $CaCO_3$ in more recent colluvia. Indeed, while water erosion may be the principal agent by which sediment is redistributed throughout the catchment, tillage must also be recognised as an important preparatory factor. Tillage of shallow soils and the incorporation of substrate within the plough horizon, which is then susceptible to water erosion processes clearly plays an important role in supplying material for reworking by water erosion. The increasing frequency of stones in more recent colluvia suggests – as does the evidence of shallow and truncated soils – that the soil storage is almost exhausted and that the erosion of Auf dem Scheid’s soil cover is well advanced.

5.3 Forstbach

The Forstbach catchment (Fig. 5.14) is underlain by southward dipping Tertiary clays, which are overlain on the northern slopes by weathered Tertiary tephras and remnants of early Pleistocene alluvium. South of the Forstbach channel, clay is overlain by loess deposits of up to ~10 m thickness. The channel has incised through these, possibly migrating southwards, and its current position represents their northern boundary. The study site is a low relief slope forming a zero order tributary to the main Forstbach channel, although elevated some 5 m above the channel and separated from it by forest. Contemporary land use is the growth of winter fodder.

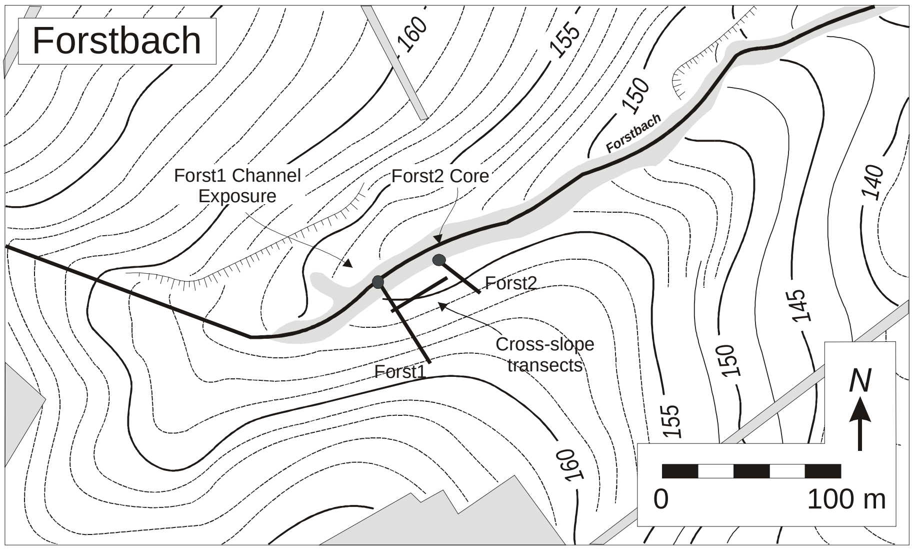


Figure 5.14: The Forstbach catchment. Locations of transects Forst1 and Forst2 are marked, along with the approximate position of cross slope transects given in Figure 5.16. The locations of the Forst1 channel exposure and Forst2 borepoint from which OSL samples were taken are also given.

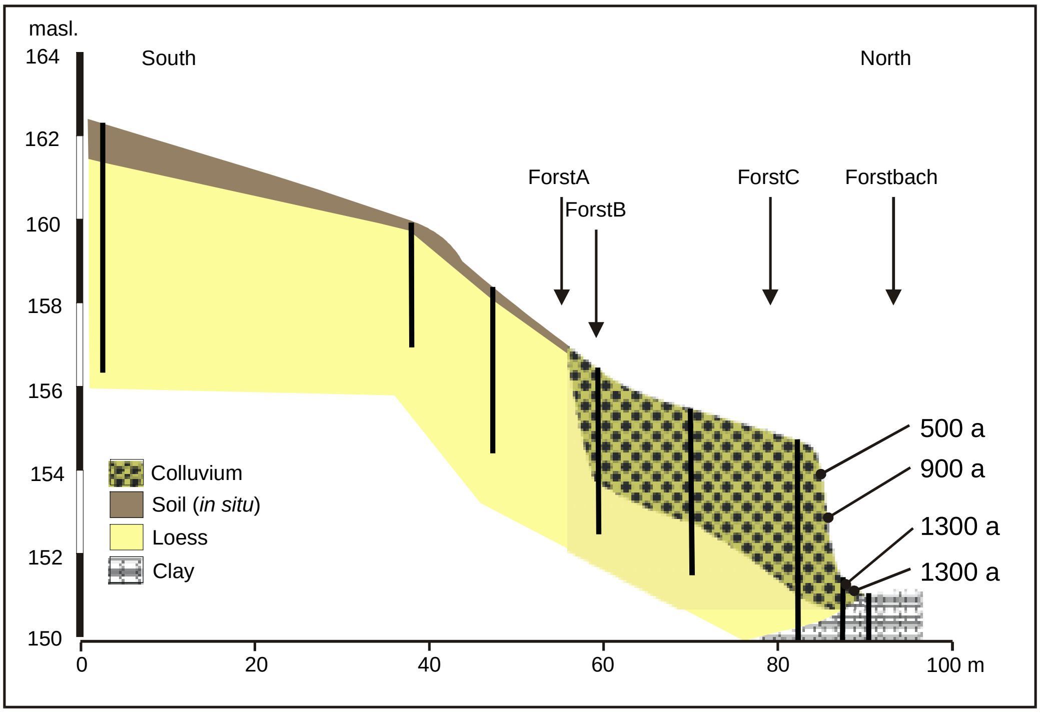


Figure 5.15: Transect Forst1, perpendicular to the channel. Soils formed in loess have been strongly eroded in the upper part of the slope, while loess substrate has also been eroded from the lower section. OSL ages from the channel exposure are rounded to the nearest 100 years. The locations of the cross-slope transects illustrated in Figure 5.16 are marked. Vertical exaggeration: x 5. See Figure 5.14 for location of transect.

A transect (Forst1)was made through the study site, perpendicular to the Forstbach channel, using a percussion borer. This reveals a sequence of eroded soils and a body of colluvial sediment (Fig. 5.15). The form of the depositional body as present in this transect suggests that colluvial material may be an eroded pediment occupying a former channel, and led to speculation that this stratigraphic situation may extend along the slope parallel to the Forstbach.

However, cross-slope transects (Fig. 5.16) reveal that this is not the case, and that this slope is made up of a network of fossil gullies (LÖWNER 2000). As indicated on Figure 5.16, two generations of colluvial gully fill are inferred on the basis of diagnostic properties. The older of these is characterised by small organic objects; these are absent from the overlying colluvium, which is characterised by the presence of $CaCO_3$.

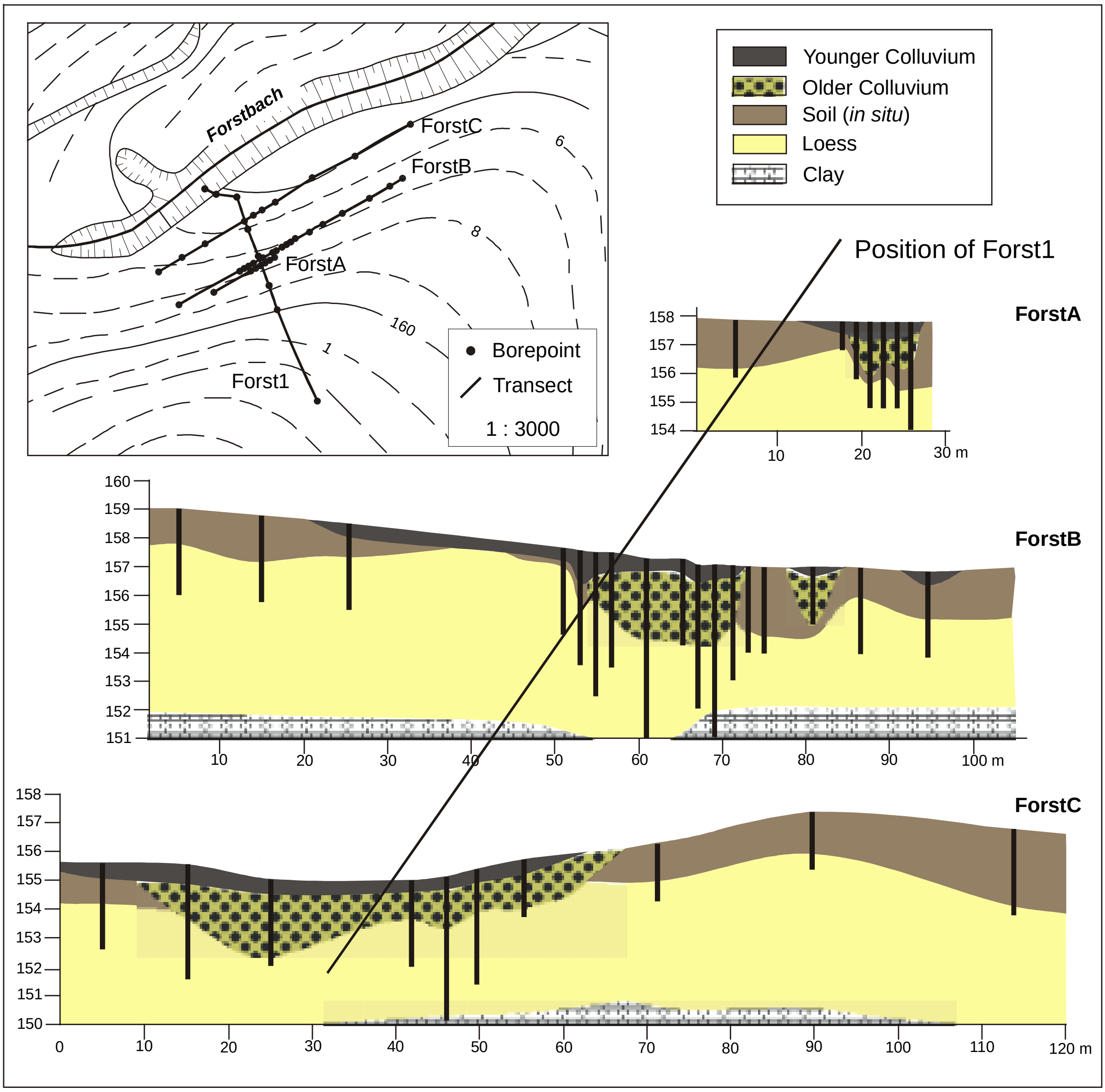


Figure 5.16: Cross-slope transects, perpendicular to Forst1 (LÖWNER 2000). The position of transect Forst1 (Fig. 5.15) is indicated.

Samples for OSL dating were taken from the channel exposure of the Forst1 transect (Fig. 5.15, Table 5.5). Samples from the base of the accumulated sediment adjacent to the channel (4.57-4.62 m and 4.78-4.83 m) yield consistent ages of 1,220 ± 100a – 1,380 ± 100 a and 1,200 ± 130a

– 1,350 ± 150 a respectively. Sediments at depths of 2.43-2.48 m and 0.79-0.85 m yield ages of 890 ± 60 a – 930 ± 60 a and 450 ± 90 a – 500 ± 100 a respectively. Three samples for OSL dating were also recovered from a drilling (Forst2) carried out by LÖWNER (2000); the location is indicated on Figure 5.14. A sample from the base of the older colluvial generation (1.52-1.58 m) returns ages of 1,200 ± 110 – 1,280 ± 110 a. A second sample from within this colluvium (0.69-0.75 m) gives ages of 610 ± 50 – 670 ± 50 a. The younger colluvium was not dated. The deepest sample (2.37-2.42 m) with an age of 13,640 ± 1,230 a is clearly late Pleistocene sediment. Because of their location and the almost ubiquitous presence of throughflow, all samples exhibit radioactive disequilibrium, so a range of ages is provided representing possible extremes. As with many of the Auf dem Scheid samples, all samples show evidence of anomalous fading and ages must therefore be regarded as minima. Nevertheless, they are stratigraphically consistent – recognising that the two deepest samples from the Forst1 channel exposure are identical within the 1σ error range (Table 5.5).

Table 5.5: OSL ages from Forstbach.

Sample Location	Depth below surface (cm)	Age ± 1σ error (years)	Comments	
Forst1 – Channel	79-85	450 ± 90 – 500 ± 100	Rad. Diseq., Fading	Minimum Age
	243-248	890 ± 60 – 930 ± 60	Rad. Diseq., Fading	Minimum Age
	457-462	1,220 ± 100 – 1,380 ± 100	Rad. Diseq., Fading	Minimum Age
	478-483	1,200 ± 130 – 1,350 ± 150	Rad. Diseq., Fading	Minimum Age
Forst2	69-75	610 ± 50 – 670 ± 50	Rad. Diseq., Fading	Minimum Age
	152-158	1,200 ± 110 – 1,280 ± 110	Rad. Diseq., Fading	Minimum Age
	237-242	13,640 ± 1,230		

Both OSL samples from the gully borepoint relate to the older of the two inferred Forstbach colluvia, with the older age (~1,240 a) relating to the base of this colluvium. Similarly, the deepest ages from the channel exposure (~1,285 a and ~1,300 a) relate to the base of the colluvial fill of that gully. The boundary between colluvial generations in the gully fill (i.e. Forst2) is at ~50 cm below the surface, and field diagnosis of Forst1 sediments (presence/absence of $CaCO_3$) indicated a similar depth for the younger colluvium in the Forst1 channel exposure. Thus, all ages from Forstbach relate to the older colluvium, which therefore accumulated over a period of at least ~700 years. The absence of any indication of partial bleaching certainly suggests that gully filling was not the result of colluviation associated with a catastrophic event such as those that occurred in the 14th century. If a conservative 20% is added to these minimum ages (because of anomalous fading of the OSL signal), initial filling of the Forstbach gullies – and possibly their formation – may have been associated with Frankish or very early Medieval land use.

The Forstbach study site comprises a single slope, and is thus at a lower level than Auf dem Scheid within the landscape hierarchy. It can be compared perhaps to the upper extent of the Auf dem Scheid thalweg that is thought to represent the infilled extension of earlier headward channel incision (i.e. gullying). As with the arable zone of Auf dem Scheid, there has been extensive erosion of pre-existing loess soils. Given the slow rate of accumulation within these gullies, it seems likely that this erosion was associated with low magnitude diffusive processes, that have been able to remove the morphological effects of presumed higher magnitude gully-forming process. Sediment production in fact has been greater than the local storage capacity, and a large component has been exported beyond the system boundary – LÖWNER (2000) has estimated a sediment delivery ratio of ~88% for this study site. However, unlike Auf dem Scheid, the spatial configuration of this single slope gully system with respect to the next higher order system element, i.e. the Forstbach channel, is such that this excess sediment does not appear to be stored locally in the Forstbach channel, but has been moved still further.

5.4 *Accumulation Rates: Auf dem Scheid and Forstbach*

As has already been pointed out, the imprecision associated with OSL ages is such that a detailed sedimentation chronology is not possible. Nevertheless, there is sufficient chronological information available for the development of very simple sedimentation trajectories for the Auf dem Scheid integral signal point (AdS1) and for the Forstbach gullies. Rates of accumulation at sample points have been calculated based on the OSL ages given in Tables 5.1 and 5.5 (Table 5.6). These are illustrated in Figure 5.17, indicating that the highest rates of sediment accumulation for both Auf dem Scheid and the Forstbach study site occurred within the Medieval period. For the Auf dem Scheid trajectory, an accumulation rate for the period 1954-1999 has been added. This is based on ^{137}Cs-modelled accumulation at ^{137}Cs sample point 20 which is close to AdS1. The modelled accumulation at this point is 13.18 t/ha/a, which is equivalent to ~0.01 cm/a vertical accumulation (assuming a density of 1,376 kg/m^3 (PARKNER 2000)).

Table 5.6: Rates of sediment accumulation for core AdS1 in Auf dem Scheid and for the two Forstbach gullies for which OSL ages are available. (see Tables 5.1 and 5.5 for error ranges and comments on the reliability of ages on which these rates are based).

Sample Location		**Period (years)**	**Colluvium Thickness (cm)**	**Accumulation Rate (cm/year)**
Auf dem Scheid 1	Pre-Medieval	2,360	115	0.049
	Medieval	590	302	0.512
	Recent	420	158	0.376
Forst1		380	235	0.618
		435	163	0.375
		475	82	0.173
Forst2		600	86	0.143
		640	72	0.113

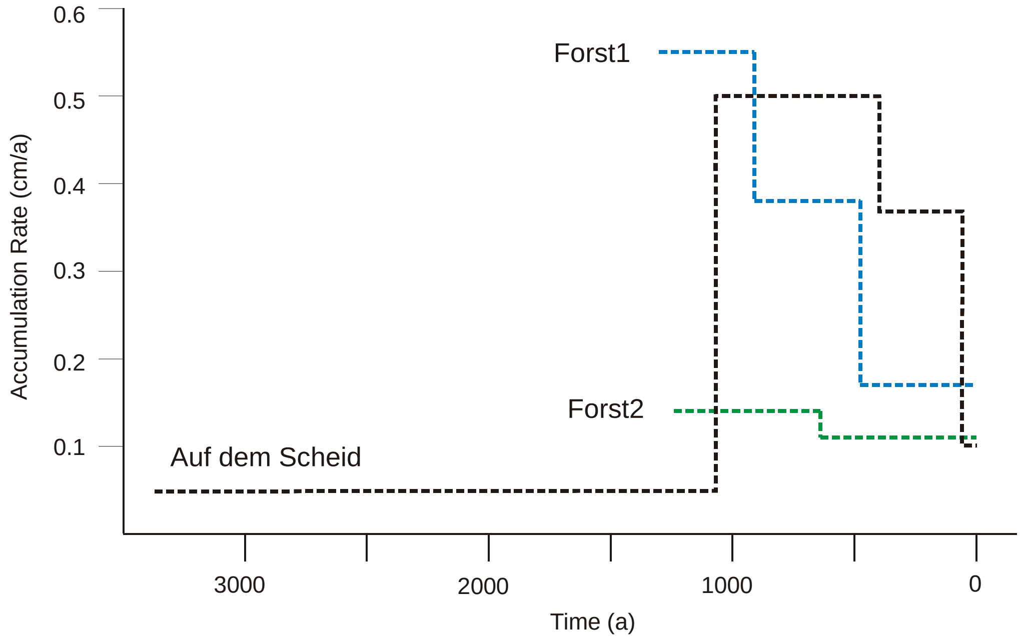


Figure 5.17: Rates of sediment accumulation for Auf dem Scheid (AdS1) and the Forstbach gullies.

While continuous deposition at a given point may occur in principle, for terrestrial accumulation sites hiatuses in erosion and deposition, interspersed with colluvial phases are more likely. Chronostratigraphic unconformities are thus to be expected within sedimentary columns. It must be emphasised, however, that the various sediments that have been dated do not necessarily faithfully represent these, i.e. they cannot always be assumed to represent the beginning or end of the colluvial phase to which they belong. Rather, they are simply ages for a point within a sedimentary sequence. While individual colluvia within sedimentary columns can be identified and described with greater or lesser accuracy, it is not always clear – *before* the sediment has been dated – to which period each belongs. For the Forstbach gullies this is not believed to be an important issue, as the deepest dated sediments are in fact from more-or-less the base of their respective gully fills, which are not thought to have been reworked and thus to represent a single – albeit slow – phase of accumulation. The accuracy of the rates plotted for Forstbach on Figure 5.17 is thus dependent principally on the sampling interval, and given the expense and labour intensive nature of OSL dating, this is necessarily coarse.

For Auf dem Scheid, this is thought to be a more relevant issue. At least three different phases of colluviation are inferred for the AdS1 site, and while the most recent of these can be relatively easily distinguished on the basis of material properties, this is not the case for the Bronze Age and Medieval colluvia. Thus, for Auf dem Scheid, the issue of sampling interval influences not only the accuracy of the rate trajectory within a given accumulation phase, but also the size of that phase. While it seems clear that there were high Medieval accumulation rates, the period over which this occurred – and therefore the accuracy of the derived rate – is not clear. On the basis of the information at hand, it is impossible to determine whether this large Medieval sediment pulse should be attributed to climatic or to land use causes. The partially bleached nature of some of these sediments provides some evidence linking their deposition to large 14th century meteorological events, but this is no more than circumstantial evidence and by no means conclusive. The laminated nature of these sediments certainly suggests that they are derived from more than one event, but the frequency of those events is not known. A further point can be made for Auf dem Scheid: the suggestion that material may have been reworked from within colluvial storage obscures the true sedimentation history still further. The rates presented in Table 5.6 and Figure 5.17 are for AdS1; extrapolation to the catchment as a whole must recognise that they are integral, and that the pattern of sediment redistribution has been somewhat more complex.

5.5 *Heidersiefen*

The Heidersiefen channel (Fig. 5.18) has formed in a loess body occupying a basin between early Pleistocene alluvial terrace sediments to the north and west and Oligocene clays to the south. Pasture is the contemporary land use on the more steeply sloping terrace sediments north of the Heidersiefen channel. Loess soils remain on the gently sloping upper part of the catchment and overlie the Oligocene clay; these areas are used for cropping of sugar beet and winter wheat. In its upper reaches the Heidersiefen bifurcates, forming two sub-catchments separated by a forested ridge formed entirely of loess. The southern of these two first order channels has been extensively influenced by recent anthropogenic earth-moving and investigations were accordingly focussed on the northern slopes.

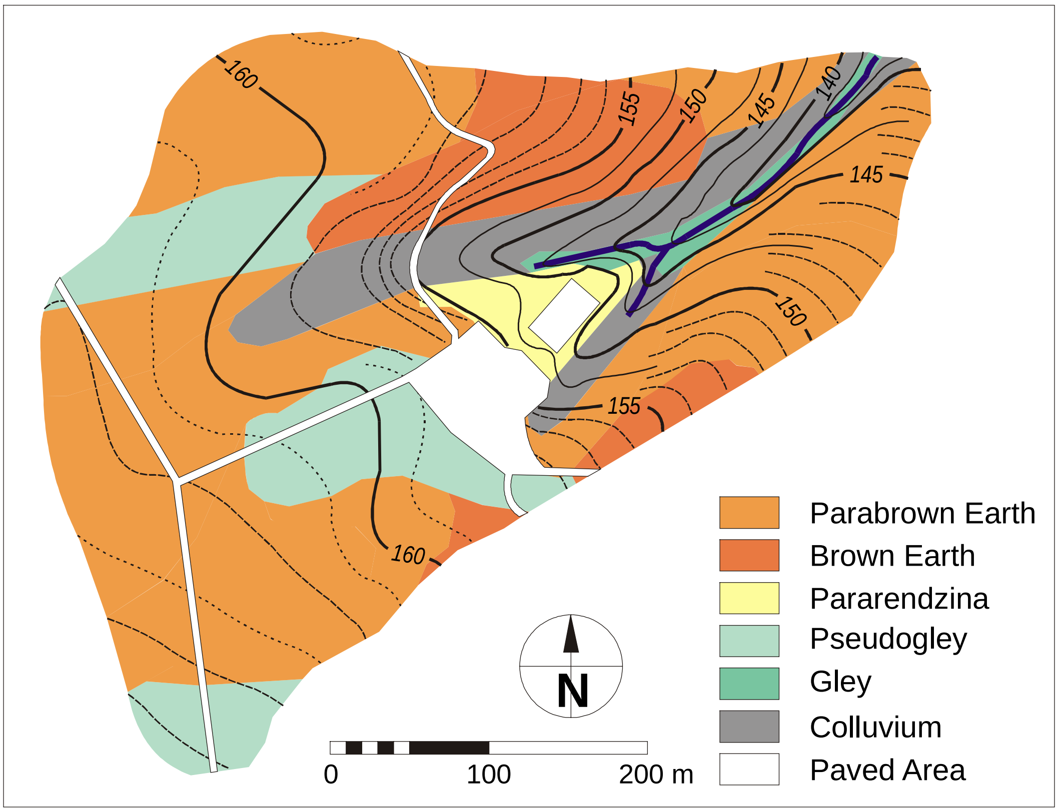


Figure 5.18: The Heidersiefen catchment.

A series of transects through the Heidersiefen basin have been constructed based on stratigraphic information provided from soil auger and percussion drilling; a representative selection of these is presented in Figure 5.19. All transects exhibit greater or lesser erosion of soils on upper slopes, and the presence of accumulated material both on the slope and within the channel itself. It is difficult to distinguish between slope and channel deposits, especially in the case of HeidA, where a considerable part of the slope is itself formed in accumulated material – to a depth of >5 m at one point. There is clear stratigraphic evidence that fluvial processes have been active, with evidence in all three transects of thalweg erosion. In HeidB this has completely removed any pre-existing loess material and colluvium lies directly over Pleistocene alluvium. Further, the colluvial bodies of HeidA and HeidB show evidence of a second generation of thalweg erosion, forming erosional terraces. This is not evident in the lower part of the catchment (HeidC). Higher on the slopes are smaller terrace features, similar to that in Auf dem Scheid, that may reflect former field boundaries. It remains unclear, however, whether this is the case or whether these also represent a further episode of fluvial erosion.

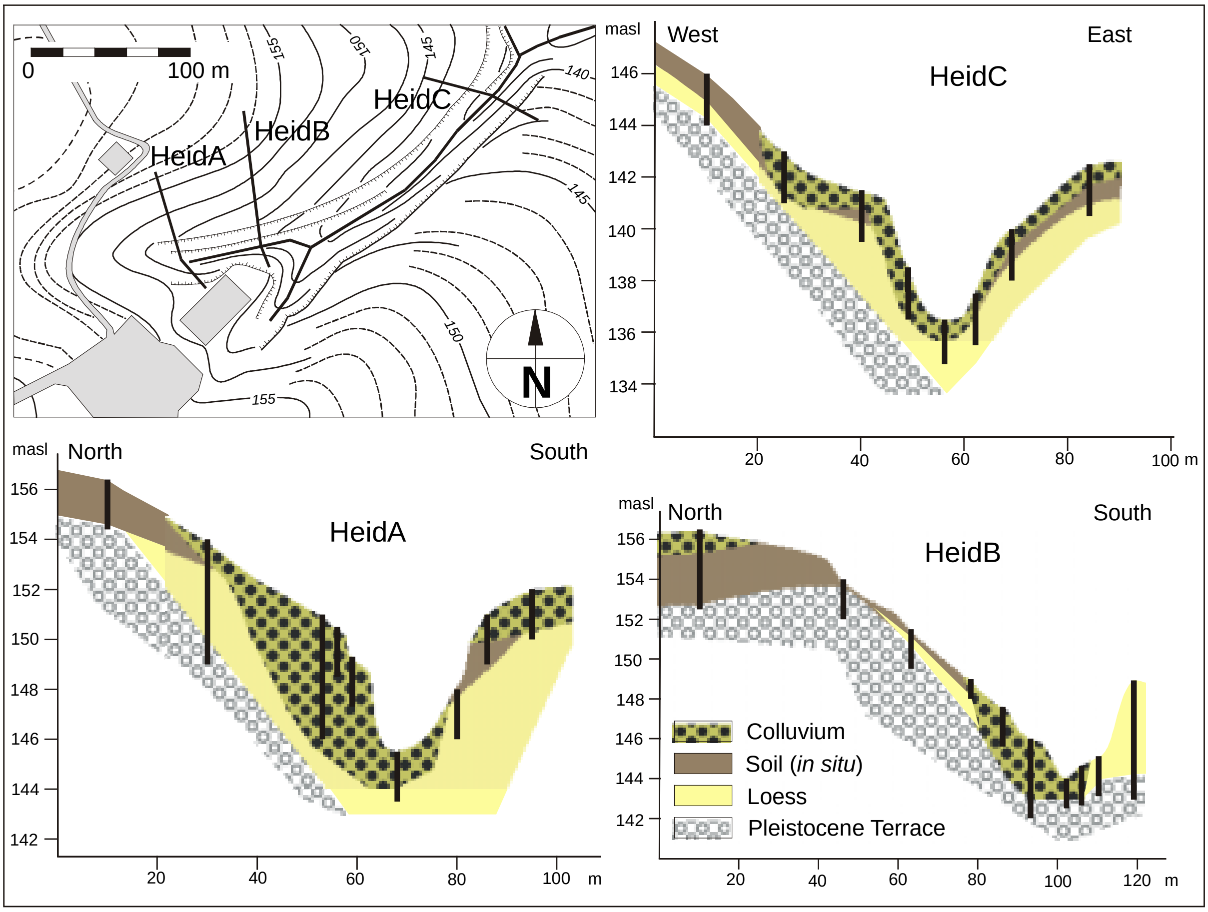


Figure 5.19: Transects HeidA, HeidB and HeidC in the Heidersiefen catchment. Locations are marked on the inset map.

In terms of their size, and to some extent the distribution of land uses, the headwater catchments of Heidersiefen are comparable to Auf dem Scheid. As with the latter, there has been considerable erosion of soils from the upper slopes and deposition within the thalweg. Using similar assumptions to those outlined above for the initial condition of Auf dem Scheid soils, FEISE (1999) has calculated Holocene sediment delivery ratios on the order of 80% for the Heidersiefen subcatchments. A more exact accounting of colluvial storage on the slopes reduces these dramatically to ~30%, although this may be unduly influenced by a greater emphasis on depositional areas. The long term sediment delivery is thus perhaps broadly comparable to that of Auf dem Scheid. There are, however, important differences between Heidersiefen and Auf dem Scheid. Human infrastructure on the one hand impedes sediment delivery from the upland arable areas to the channels, and on the other enhances the delivery of runoff to the channels. There is thus a perennial channel within the northern of the two headwater basins, and although flow is not large, it is capable of transporting sediment. Clearly, as with Auf dem Scheid, there has been quite considerable volumes of deposition within this catchment (e.g. HeidA). In contrast, to Auf dem Scheid, however, the Heidersiefen systems remain open, and the morphological effects of rainfall-runoff processes are evident within the landscape.

5.6 Summary

This chapter has presented results of field investigations – principally those in the Auf dem Scheid study area, which was the central objective of this study – and to a lesser extent those from Forstbach and Heidersiefen, which were undertaken for purposes of comparison. Inevitably, there has been some interpretation of results alongside their presentation. However, the principal interpretation of these results – with respect to the aims and objectives of the work at hand – is to be found in the following chapter. As a brief summary, these results do not deliver on the principal aims of this study: a detailed chronology for late Holocene colluviation is simply not possible given the uncertainty associated with OSL ages. This means that a long term sediment budget can only be constructed in very broad terms. Similarly, issues associated with the modelling of sediment redistribution rates on the basis of ^{137}Cs mean that closure of a sediment budget for the short term has also not been achieved. Nevertheless, the information which has been assembled does enable some useful discussion of the nature of geomorphic response to environmental change.

Chapter 6

Discussion – Geomorphic Response to Environmental Change

6.1 Introduction

Results and data from field investigation were presented and evaluated in Chapter Five. In this chapter, the implications of results for the elucidation of geomorphic response to environmental change are discussed.

In the first two sections, the two dominant processes that have been active in this landscape will be contrasted, specifically in terms of the frequency of their occurrence, and the evidence for morphological responses to these processes will be evaluated. Discussion will therefore focus on identification of process responses and the extent to which landforms and landscape have recovered from process occurrence. Change in landform morphology resulting from process occurrence can be termed *morphological response*. *Recovery time* is defined as the period within which a morphological response attributable to a given process occurrence remains as a part of the contemporary landform assemblage. Elucidation of geomorphic response to environmental change therefore involves identification of processes that have been initiated and an assessment of the extent to which the morphological response to these processes contributes to the characterisation of the contemporary landscape. This characterisation will be in the context of landscape sensitivity as expressed within the concept of the transient form ratio (BRUNSDEN & THORNES 1979).

Secondly, landscape sensitivity will be considered in a spatial context, and the importance of configuration and coupling between landscape components for controlling the development of the geomorphic landscape system will be discussed.

6.2 Frequency/Magnitude of Processes

The landscape system of the study area cannot be characterised as undisturbed; rather, it is comprised of a series of erosional and depositional landform features. Diffusive surface erosion is evidenced by the widespread occurrence of truncated soil profiles. In addition, the expression of current and/or former field boundaries represents a morphological response to both water erosion and tillage translocation processes. Secondly, all three areas exhibit evidence of gullying and/or fluvial incision. Tillage cannot alone account for the formation of gullies, such as those found in Auf dem Scheid or Forstbach, or for the erosional terraces found in Heidersiefen. These features are attributed to the occurrence of one or more intense rainfall-runoff events. There is thus evidence in all three study areas of the activity of the principal processes that are expected to be associated with post-deforestation agricultural landscapes. A question arises as to the relative timing and/or frequency of process occurrence, and their respective geomorphic effectiveness.

The deepest OSL age from AdS1 indicates that sediment accumulation in the lower part of Auf dem Scheid has been occurring for at least ~3400 years, while the OSL ages of colluvial sediments in AdS11 indicate the presence of a mid-slope gully or channel at an even earlier period. This latter feature was itself filled during this prehistoric period, which implies the contemporaneous occurrence of erosion further upslope. Similarly, there was deposition (and therefore also erosion) during the late Iron Age or Roman period. It remains open to conjecture whether these phases were associated with deforestation and agriculture.

The OSL ages from the AdS1 core indicate very high accumulation rates since ~1000 AD. The partial bleaching of the OSL signal in the sediments sampled from this colluvium certainly imply that at least some of these were deposited by a large magnitude redistributive event. There is thus circumstantial evidence that they may be correlated with an extreme rainfall-runoff event in the 14^{th} century, at which time deforestation and the introduction of agriculture had certainly occurred. The occurrence of catastrophic gullying in Auf dem Scheid associated with this event (or events) would account for the apparent removal of earlier colluvial deposits.

In Forstbach, OSL ages of gully fill give clear evidence that these features formed no later than the early Medieval period, i.e. at least ~1,250 years ago, and also that, as with Auf dem Scheid, sediment supply from upslope erosion was also occurring at this time. Chronological information from the Heidersiefen study area is not available, and there is no clear sedimentological indication within accumulated sediments of how many events they may represent. However, the inferred stratigraphy of the HeidA and HeidB transects suggests an early extreme episode of channel incision, i.e. one that removed any soil that may have been present, and indeed incised into the underlying lithology. Major accumulation then occurred within this channel, and at some subsequent time another episode of channel incision occurred, cutting through the in-channel deposits.

For Forstbach, there is thus evidence for the occurrence of a large rainfall-runoff event some 1,200-1,300 years ago that may have been coincident with deforestation and the introduction of agriculture. In Auf dem Scheid, it appears that erosion and sedimentation processes may have been occurring for considerably longer. The Heidersiefen transects indicate at least two phases of channel incision, and it appears that the more recent of these post-dates the formation of the depositional bodies, i.e. that these were formed by an earlier major erosional/depositional event.

The occurrence of at least three large magnitude rainfall-runoff perturbations in this region is inferred, i.e. one which lead to deposition of ~4,500 year old sediments in Auf dem Scheid, a second in the late Iron Age which also caused erosion-deposition in Auf dem Scheid, and a series of Medieval events supported by evidence from gullies and substantial deposition in both Auf dem Scheid and Forstbach. These events therefore occurred with low frequency, i.e. with recurrence intervals of ~1,500 years. The extent to which these events pre- or post-date deforestation and the introduction of agriculture remains uncertain. If these erosion and sedimentation events were indeed associated with agricultural land use that had already begun in the Pleiser Hügelland, this considerably pre-dates the onset of anthropogenic colluviation postulated by LESSMANN-SCHOCH *et al*. (1991) for this area. These ages are consistent, however, with evidence of severe soil erosion dating back to the Bronze Age – and earlier – that has been found in other parts of Germany (e.g. LANG in press).

The frequency of tillage perturbation was much greater – especially if it is accepted that agriculture did in fact commence in this region during a pre-historic period. Maps from the 19^{th} century indicate that agricultural land use was still widespread at that time. Reafforestation did not occur until the beginning of the 20^{th} century (ERDMANN, 1998), and the ages of trees in both Heidersiefen and Forstbach suggest that they were planted (or allowed to grow) at around this time. The complete absence of soil development under the forest of the Heidersiefen catchment divide (HeidB) suggests that this site was previously ploughed, or at least deforested, and relict gully forms can be found under the contemporary forest. Thus, although currently occurring in only restricted parts of the study sites, agricultural land use dominated the landscape for at least a millennium, and possibly as long as four millennia, with tillage probably occurring at least annually.

The two processes – linear erosion associated with large magnitude rainfall-runoff on the one hand and, on the other hand, diffusive erosion associated with tillage and low magnitude rainfall-runoff – clearly occur with very different frequencies. This difference, and especially the interaction between the two processes, has important implications for morphological response as will be discussed in the following section.

6.3 Morphological Response and Landscape Sensitivity

Heidersiefen, as its name suggests, might initially be considered to be a *Siefen* as defined by NICKE (1989) and described in Chapter Two. However, it is by no means an undisturbed form, and its genesis cannot be clearly attributed to the mechanisms postulated by NICKE (1989). The contemporary form of Heidersiefen did not develop under the present forest cover, which post-dates that development. Rather, the influence of both agricultural land use and rainfall-runoff events – and their interaction – is clear. While Heidersiefen may well have been a true *Siefen* in the past, it has not been this since the first onset of sediment delivery associated with agriculture. The same can be said of Auf dem Scheid, which in its current form does not fit the definition of a *Siefen* at all. While there is evidence that there may formerly have been a channel, or at least a greater degree of incision than at present, the late Holocene development of this catchment is characterised by sediment accumulation, although this is occurring at a decreasing rate. The wider Forstbach catchment might also be considered in this respect, but that is beyond the scope of this study. The study site that has been described here is a single zero order tributary slope and is thus not amenable to characterisation in this context.

The landforms of the study area are thus characterised as resulting directly or indirectly from sediment redistribution attributed primarily to agricultural causes. Although examples of flat-bottomed valleys with linear slopes can be found in the Pleiser Hügelland, none of the landforms discussed in this study can be considered to be *Tilken* or *Sieke* as described by HEMPEL (1954a) (see Figure 2.8) – at least not in terms of their morphometry. However, it may be useful to consider them in terms of their genesis and the processes involved in this, and in this context a qualitative similarity to the distinction between *Tilken* and *Sieke* (as discussed in Chapter Two) can be seen. Parts of the landscape under investigation show clear direct effects of agricultural land use – perhaps best exemplified by the colluviation terrace in Auf dem Scheid – and are thus qualitatively similar to *Sieke*. Other parts of the landscape are more like *Tilken*, i.e. they have not themselves been ploughed, but show a clear effect in terms of the accumulation of sediment from remote sources.

Although Auf dem Scheid today is an unchannelised first order basin, the form of the colluvial body suggests that sediments occupy a former channel or a series of gullies. In particular, the narrowly restricted lateral distribution of the deep colluvium at AdS11 indicates that this is a gully fill. Similarly, the chronostratigraphic discontinuities within the thalweg colluvium suggest the occurrence of a series of evacuations and subsequent accumulation. These features are no longer present as a part of the contemporary morphology, i.e. the morphological response to earlier linear incision has been removed. This is also the case in Forstbach, where the gullies represent a clear morphological response to rainfall-runoff perturbation, but the residence time of these forms was limited, and they exist now only as fossilised features, i.e. not as a part of the contemporary landform. Sediments produced by frequent low magnitude perturbations (tillage and low magnitude rainfall) have completely filled these gullies. In terms of morphological response, the persistence of the forms associated with the gullying process is of shorter time than the recurrence interval of the triggering process. In other words, the landform's relaxation time with respect to this process is relatively short, and both Auf dem Scheid and the Forstbach study site can therefore be characterised with a negative transient form ratio, i.e. they are insensitive to this process.

This is not the case with respect to sensitivity to agriculture and low magnitude rainfall-runoff. The effects of these remain in the form of both accumulated material and soil truncation. This is especially true in Auf dem Scheid where agricultural activity in the upper part of the catchment continues to generate and redistribute sediments. The abrupt break in slope evident between cores AdS11 and AdS12 represents the contemporary boundary between upslope agricultural activity and downslope pasture, and a clear example of a morphological response to tillage translocation. The persistence of forms associated with these high frequency/low magnitude processes is greater than their recurrence period, and thus the transient form ratio is positive and the landscape is characterised as being sensitive to these processes.

The balance of geomorphic effectiveness is less clear in Heidersiefen. While there have clearly been at least two episodes of channel incision, assessment of the extent to which contemporary morphological evidence of the earlier and larger event remains in the 1st order basin is dependent on the assumed nature of the landform prior to this event. There has, in any case, been further channel incision, and the erosional terraces thus formed represent contemporary morphological evidence of rainfall-runoff process occurrence. Furthermore, degraded gully forms remaining under forest cover represent contemporary morphological evidence of former linear erosion. Heidersiefen cannot therefore be characterised as having fully relaxed from earlier large magnitude rainfall-runoff events. Despite the long recurrence intervals of these events, the morphological responses they induced have persisted, and this landscape cannot be described as insensitive to gullying. And, although direct morphological evidence in the form of field boundaries is more obscure in Heidersiefen, a morphological response to tillage does remain in the form of both considerable volumes of accumulation and the almost ubiquitous soil truncation. But, in contrast to Auf dem Scheid and Forstbach, agricultural land use has not been able to dominate the landscape to the same extent.

There seems at first something paradoxical in describing landforms like Auf dem Scheid and the Forstbach slope, that have clearly experienced gullying, as being insensitive to this process. The definition of sensitivity must, however, be kept in mind. These landforms are only insensitive because of the low frequency of perturbation. While the *soil* may be *susceptible* to gullying and large magnitude rainfall-runoff, the *landform* is not *sensitive* to these processes. This is because of relative differences in process frequency and, importantly, because of the interaction between processes. As the ^{137}Cs analysis within the arable zone of Auf dem Scheid clearly indicates, the high frequency, low magnitude tillage process is able to erode material from all areas, whereas water erosion affects a more limited part of the land surface. In the absence of tillage, it is likely that the morphological responses to former linear erosion would have greater persistence, and the areas that are not susceptible to these processes would remain stable. Furthermore, it is possible that the supply of material in the areas susceptible to water erosion would in time be exhausted. But the effect of tillage is to mobilise sediment and to transport this to areas where it is susceptible to further mobilisation through water erosion. There is thus a continuous supply of material transported by water erosion to specific parts of the landscape, i.e. into topographic convergences and flow lines. In large magnitude rainfall-runoff events, this sediment may be transported through these areas, which may themselves be eroded. But in low magnitude rainfall-runoff events, there is insufficient energy for long distance transport, and sediment tends to be concentrated in local storage sites. So, if the recurrence intervals of high magnitude events are sufficiently long, local storage sites – gullies – will be filled in.

But this is only true for landforms in close proximity to sediment sources that are capable of facilitating the relaxation process. Landform units like Auf dem Scheid and the Forstbach study site have been able to relax or recover from gullying because of their position relative to sediment source areas; for the same reasons, Heidersiefen has been less able to do so.

To summarise, both Auf dem Scheid and Forstbach are considered insensitive to large magnitude rainfall-runoff, and to have been dominated by agriculturally generated sediment redistribution. Heidersiefen is considered more ambiguous. Agricultural land use has clearly played a major role in its development, but the effects of rainfall runoff cannot be discounted. This distinction in the degree to which agricultural land use has dominated geomorphic response to environmental change relates directly to proximity of agricultural land use. Further, because the flux of sediment through the landscape therefore becomes an important consideration, spatial and systematic hierarchies along with landscape configuration need to be considered.

6.4 Spatial Configuration and Landscape Hierarchy

Spatial configuration with respect to land use is important in determining the longer term geomorphic behaviour of landform units with respect to their sensitivity. It is also important in defining the interaction between different landscape units, and in influencing the movement of mobilised sediments throughout the landscape, i.e. the sediment flux. While both Auf dem Scheid and the Forstbach slope are insensitive to gullying and in both cases local storage sites have been filled, there are important differences between these two sites. The Forstbach slope is directly tributary to a second order perennial channel. The sediment that has been stored in the Forstbach gullies represents only ~12% of the total sediment estimated to have been eroded from within this catchment (LÖWNER 2000), the balance having been delivered to the Forstbach channel. The absence of major in-channel storage within the Forstbach indicates that the majority of this has then been further transported out of the Forstbach system. There is thus an effective coupling between sediment source and an efficient transport medium, with the slope of the study site forming a conduit from source to channel. The gullies – while they persisted – altered the nature of this coupling, and represent an interim sediment sink. In the context of the long term sediment flux from this part of the Forstbach catchment, however, the volume of this sink is small and not especially significant. The principal long term sink for material eroded from this slope is not local.

In Auf dem Scheid, the configuration of landscape components is somewhat different. Within the arable zone, there are field boundaries that impede transfer of sediment from one landscape component to the next. The land use boundary between agriculture and pasture represents a further impediment. Nevertheless, despite the storage of some material within the arable zone, ^{137}Cs analysis indicates that, over a period of some 45 years, a relatively high proportion of erosional products are exported beyond this system. There is thus a coupling between sediment source areas and a higher order landscape component. Unlike Forstbach, however, this is not an efficient transport medium in the form of a channel; rather, it is the pasture zone, which the ^{137}Cs data further indicate is a net accumulation area. The medium term (i.e. 45 a) sink of sediments generated in the Auf dem Scheid arable zone is therefore local.

The long term sediment budget for Auf dem Scheid suggests that sediment export from the catchment as a whole is of a similar magnitude to that of the arable zone. However, it is to be emphasised that this is a very approximate estimate, and some important aspects of long term sediment budgets must be considered. The long term sediment budget calculated here simply relates the estimated amount of material currently in colluvial storage to the total estimated erosional loss. However, there is evidence that accumulated material from earlier erosion-deposition phases has to an extent been removed. This means therefore that of the sediment currently in colluvial storage within Auf dem Scheid, a disproportionate amount relates to erosion that has happened in more recent periods. No account has been taken of this; there is too little available information concerning the volume of material that relates to different depositional phases, and none enabling differentiation of the total eroded volume into different erosional phases. Thus the uncertainty in approximation would be even greater than that for the approach that has been taken. The implication is that the sediment delivery ratio for more recent periods would be lower than that calculated for the longer term. This is, of course, inherent in the nature of sediment delivery ratios. If the assumptions and approximations used in its calculation are accepted, the long term sediment delivery ratio is not “wrong” (although undoubtedly imprecise!). But it does obscure information relating to the system’s internal dynamics, and in particular it may conceal a very different behaviour of the sediment flux in periods between large magnitude erosion-deposition events.

Therefore, while there may be a small lag in the transfer of sediments from the upper part of the catchment to the lower (i.e. there is deposition within the arable area), over longer terms the internal sediment delivery within Auf dem Scheid is efficient. A very large proportion of the material eroded form the upper part of Auf dem Scheid has been exported to the lower part. However, those sediments that have been delivered to the lower part of the catchment are not easily transported beyond the boundaries of Auf dem Scheid. The volume of material eroded from Auf dem Scheid has totally filled whatever channel may have been previously present, and the coupling between Auf dem Scheid and the higher order low gradient Eichenbach system is a low relief colluvial body. Further export of sediment from Auf dem Scheid is unlikely in the absence of a catastrophic event. Colluvial storage within Auf dem Scheid thus acts as a buffer between hierarchical levels of the sediment flux system. In effect the Auf dem Scheid system is closed to all but very large rainfall-runoff events.

In Heidersiefen, the extent to which sediments generated by tillage and lower magnitude rainfall-runoff have been exported from the upland agricultural area is not known. Given the current presence of infrastructural elements, this is likely to be considerably impeded. The roads and buildings of the Heiderhof farm have effectively decoupled upland sediment sources from the channels. However, the volumes of material in colluvial storage within both the first and second order basins suggests that in the past this was not the case. Delivery of sediment from the upper catchment to the channels has certainly occurred. The presence of a channel in the Heidersiefen first order basin provides a considerable contrast to the situation found in Auf dem Scheid. This means that the Heidersiefen first order system is open to much smaller rainfall-runoff events, and that the geomorphic effectiveness of these is greater. Export of material beyond this small system does not require large rainfall-runoff events.

6.5 Summary

The sensitivity of the landscape has been expressed using the concept of transient form ratios. If the recurrence interval of perturbations is greater than the persistence time of the morphological responses they engender, this ratio is negative and the landscape is characterised as insensitive. This is the case for both Auf dem Scheid and the Forstbach site with respect to rare large magnitude events. The Heidersiefen catchment is still characterised as sensitive to this process. With respect to low magnitude diffusive erosion, Auf dem Scheid is clearly still sensitive, with small scale landforms that reflect the ongoing occurrence of tillage. This is more ambiguous in the Forstbach site and in Heidersiefen. If relief reduction and denudation are included within the definition of morphological response, all three study sites clearly show an indelible morphological response and must be characterised as being sensitive to processes associated with agricultural land use.

Field evidence suggests that the geomorphic effectiveness of the different perturbations differs dependent on position within the landform hierarchy. The nature of geomorphic response to an environmental perturbation is thus dependent on the systematic scale at which it is characterised. Elucidation of geomorphic response must take account of the relative frequency/magnitude and geomorphic effectiveness of perturbing processes, the hierarchical relationship between landscape components, and the degree to which slopes and channels are coupled, which is itself not independent of temporal variation in process behaviour.

Under pre-agricultural conditions, when the landscape was protected by a forest cover, the effectiveness of external forcing processes was diminished and very little sediment was generated. There was channelised runoff, but its geomorphic effectiveness was constrained by sediment supply. With the removal of forest – and especially the introduction of tillage – sediment became more freely available. The extent to which landform change through sediment redistribution occurs is no longer supply-constrained. Rather, it is the availability of competent transport media that controls the sediment flux. In the absence of big events, agriculture dominates landform development, which is transport limited. Rare large events, with greater transport capacity, can have very significant effects for landform development. However, even this magnitude/frequency/effectiveness relationship is highly dependent on configurational phenomena. There is a feedback effect in operation: the generation of sediment following deforestation and the introduction of agriculture has been so extensive that it has blocked channels and inhibited its further redistribution. For the greater part of the study area, agriculture has dominated the landscape. In these small systems low magnitude processes have had greater geomorphic effectiveness over the longer term than the more energetic but less frequent perturbations.

Chapter 7

Conclusions and Future Perspectives

In the first section of this last chapter, the extent to which the aims of this study have been achieved will be evaluated, and the validity of its hypotheses assessed. Following this, the observations made in the previous chapter are summarised within the context both of these hypotheses and of the more general questions that were posed for this study, and some conclusions are drawn regarding the nature of geomorphic response to environmental change in the Pleiser Hügelland. The conclusions that are drawn from this work have implications for the way in which modelling of both landform development and the sediment flux are approached. Some thoughts are offered, therefore, on potential directions for future research.

7.1 Evaluation of Aims and Hypotheses

Two specific aims of this study were stated in the Introduction:

- *the development of a sedimentation chronology on the basis of a range of dating techniques, i.e. optical luminescence and the use of the radionuclide Caesium-137 as a temporal marker.*

The achievement of this aim has been only partially successful. As has been illustrated in this study, acquisition of reliable high resolution chronological information is not a trivial task. Quite apart from the cost and labour involved, there are significant methodological aspects of OSL dating that need to be addressed if the technique is to be used for the dating of feldspar-dominated colluvial sediments. Nevertheless, chronological information has been obtained, and this provides crucial support for the conclusions that have been reached.

- *the use of this temporal information in the development of historical sediment budgets for discrete spatial landscape elements.*

Again, this aim has been partially attained. Sediment budgets have been developed both for the period of ^{137}Cs (1954-1999) and for the late Holocene. The latter is inescapably approximate, and given the paucity of both spatial and temporal information, there are some drawbacks to it. It does, however, provide order of magnitude estimates, and with informed interpretation allows some qualitative inferences to be drawn. The ^{137}Cs budget is more tightly temporally constrained, and allows good differentiation between distinctive land use units.

Turning to the hypotheses that were established for this study, more success can be claimed:

1. *That two different processes have been active in the landscape, and have left morphological evidence of their occurrence.*

This hypothesis was perhaps a little simplistic. Nevertheless, it has been clearly demonstrated that this is indeed the case, and this forms the foundation on which the following hypotheses were based and tested.

2. *That human influences, i.e. tillage, dominate the landscape.*

With some qualifications this hypothesis can also be said to have been confirmed. Within the smaller low order landscape elements – Auf dem Scheid and the Forstbach site – this is clearly the case. These landforms are sensitive to the low magnitude processes that are directly and indirectly associated with agricultural land use. However, it would be an exaggeration to suggest that this is true for the whole landscape. Higher order landscape elements cannot be said to be dominated by these processes.

3. *That characterisation of geomorphic response to environmental change depends on systematic scale.*

This hypothesis can also be answered in the affirmative. While frequency and magnitude of processes is clearly very significant, this is expressed differently within landform elements of different hierarchical levels. More specifically, it is not simply the hierarchical level that is important, but rather the spatial configuration and topological relationships between landform units that determines the nature of geomorphic response and the way in which the different process types interact.

7.2 Conclusions

In the Introduction to this dissertation a number of general questions were posed. The responses to individual questions are summarised briefly, then addressed more generally within the following discussion.

- *What was the nature of environmental change?*

The nature of environmental change has been characterised as the removal of forest vegetation and the introduction of agricultural land use. This was, in fact, more an assumption underlying this work rather than a question which has been answered. Perhaps more importantly, the field evidence that has been presented for Auf dem Scheid indicates that this environmental change may well have occurred considerably earlier than might previously have been supposed. Substantial sediment redistribution was occurring in Auf dem Scheid some ~4,500 years ago. There is no clear indication that this was necessarily in conjunction with human-driven environmental change, but it is consistent with periods of human land use that have been documented for elsewhere in central Europe.

- *How has this changed the landscape system?*

This change has altered the balance of processes, firstly by changing the way in which the landscape responds to external perturbations in the form of rainfall-runoff, and secondly by introducing a new process – tillage – that was previously not present.

- *What has been the geomorphic response to environmental change?*

The geomorphic response has been characterised as the generation and transport of a large pulse of sediment, and the creation of a range of erosional and depositional landforms. Specifically, there are large volumes of colluvium that are attributed to this environmental change. These may or may not persist in the landscape. Perhaps the most significant geomorphic response has been denudation. This is essentially an indelible morphological response that has redefined the boundary conditions of the landscape system.

- *Given that there has been the introduction of a new process, i.e. tillage, to the landscape system, what are the implications of the interaction between processes for system behaviour? In other words, what is the implication of environmental change for longer term landform evolution?*

The effect of interaction between different processes has been clearly demonstrated. Most importantly, tillage provides an effectively continuous supply of material, that is further reworked by water erosion processes. This has influenced the frequency/magnitude/effectiveness of these latter processes.

- *Has environmental change caused a shift in the nature of landform development?*

Environmental change has led to a change from a supply-constrained to a transport-constrained sediment flux, and landform development that is dominated by the sediment flux. Significantly, as long as processes associated with agricultural land use continue, the system remains in a state of more-or-less constant perturbation. The landform – at least, at the scales that have been considered here – is characterised as being sensitive not to the high magnitude events, but to the ongoing low magnitude processes. Landform is a human phenomenon, and landform development is driven by human activities.

The Auf dem Scheid catchment – and the Pleiser Hügelland study area in general – shows clear evidence of geomorphic responses to both rare high magnitude rainfall-runoff events and the combined effects of diffusive processes (water and tillage erosion). Occurrence of the former is essentially independent of human induced environmental change in the form of deforestation and the introduction of agriculture. The latter, however, both indirectly and directly, relate to agricultural land use. These two process types have induced different morphological responses and it has been possible to make inferences regarding the relative significance of each, and thus to draw some conclusions about the geomorphic response to environmental change.

High magnitude rainfall-runoff events have induced major morphological responses in all the landscape elements studied. On the other hand, morphological responses to low magnitude processes are small, and remain localised due to low transport capacities. Further export of sediments can generally only occur in conjunction with higher magnitude rainfall-runoff events. This may not happen simultaneously, and there may be long lag times before the occurrence of a rainfall-runoff event of sufficient magnitude to transport the products of low magnitude processes further. In the absence of such large events, the ongoing occurrence of low magnitude processes has been able to produce large stores of material within low order transport-limited systems, and in doing so, slowly remove the morphological evidence of earlier large rainfall-runoff events from the small systems, which are thus characterised by a greater sensitivity to low magnitude processes. With no continuing export of material to higher order systems, runoff that reaches channels has greater erosive power. Indeed the concentration of energy within second order systems is such that smaller rainfall-runoff events are geomorphically effective. Thus, although unable to generate morphological responses in the small systems, they are able to maintain – and possibly to enhance – morphological evidence of earlier rainfall-runoff events in the larger systems.

Geomorphic response of the landscape system following environmental change is thus governed by the interaction between processes with different frequency/magnitude/effectiveness relationships. While there is a whole spectrum of rainfall-runoff events, most are of low magnitude, and have minimal geomorphic effect. Under "average" conditions of ongoing tillage and low magnitude rainfall-runoff, sediments remain in local storage. The extent to which systematic environmental change altered susceptibility of the landscape to rainfall-runoff events and influenced their geomorphic effectiveness is difficult to quantify. Nevertheless, for the period in which agricultural use occurred in the study area, the frequency of high magnitude rainfall-runoff perturbations has been such that the small landscape components are clearly dominated by responses to low magnitude perturbations, while the larger systems show the effects of rainfall-runoff events. Whether this continues to be the case is dependent on:

(a) The extent to which agricultural land use continues, and its nature. The present “agricultural” landscape is a product of a small but constant supply of sediment generated by tillage and supplied to water erosion. Cessation of tillage will not only immediately arrest the redistribution of a portion of the sediment flux, it will also greatly reduce the amount available for entrainment by water erosion processes. It would also bring to an end the camouflage that tillage provides for the effects of water erosion. Tillage replenishes the supply of sediments lost from water erosion source areas, by pushing material into these zones. And, in maintaining a supply it also ensures that water erosion is transport limited, i.e. runoff has high sediment concentrations, and is therefore less capable of initiating erosion downstream. The effect is to increase the likelihood of deposition rather than further erosion at downstream sites.
(b) Sediment supply. If, eventually, due to exhaustion of erodible soils and substrates, the sediment flux is once more supply constrained, a landscape dominated by incision will prevail. This will be more influenced by external factors (i.e. lithology) than by agricultural land use.
(c) Climate change. Similarly, increases in the frequency of large magnitude precipitation events will have the effect of increasing landscape dissection, similar to the effect of exhaustion of sediment supply. Alternatively, decreases in rainfall magnitude would likely enhance the current situation of sediment storage in low order basins – but possibly reduce still further the area of their distribution.

Note that, therefore, it is not simply the frequency of occurrence of large events, but also in a very real sense, their actual magnitude, that determines the spatial pattern of geomorphic response. A decrease in rainfall energy would have the effect of curtailing transport, reducing the average distance that sediments are transported from source. Other possibilities – increase in rainfall magnitudes, exhaustion of upland sediment supply, cessation of tillage or a reduction in the sediments it generates – would all have the effect of expanding the distance of transport. While it could be argued that this would be offset to an extent by reduction in sediment supply implicit within (a) and (b) above, this is only true for upland sediments. Within the contemporary landscape there are large volumes of sediment in storage in locations that may become more susceptible to erosion under changed conditions. In other words, the volumes of sediment in colluvial storage within low order landform elements like the Auf dem Scheid pasture zone, that are highly unlikely to be mobilised under contemporary conditions, may become susceptible to further redistribution.

Thus, in addition to the interaction of processes of differing frequency/magnitude, hierarchical level within the landscape system appears to be an important determinant of geomorphic response. More accurately, it is the configuration of the landscape and the spatial and topological relationships between its components that controls the behaviour of sediment in flux. Properties such as potential storage volume, drainage density, channel gradient, relative relief and basin shape are all elements of landscape configuration, that influence the coupling between sediment sources and potential sinks. For a given combination of frequency/magnitude spectra, there may be characteristic locations in the landscape where sediment is stored, and where greatest rates of various processes may be expected. Currently, diffusive processes dominate the uplands of the Pleiser Hügelland, sediment is stored in topographic convergences and, for longer periods, in unchannelised first or second order basins. Where channels exist or in still higher order basins, the influence of larger rainfall-runoff events is dominant. But, as indicated above, that distribution could change with variation in process frequency/magnitude.

For the Pleiser Hügelland, the question of whether climatic perturbations or human induced environmental change are more important in the contemporary geomorphic landscape, is answered in favour of the latter. Environmental change introduced a new form of perturbation, which has resulted in the production and propagation throughout the landscape of a pulse of sediment. Within the existing climatic confines that propagation is largely restricted to low order landform elements such as those that typify the Pleiser Hügelland. Secondly, the diffusive erosional processes that have followed this environmental change have resulted in the denudation of upland areas. The landscape has thus acquired a new condition that represents a lasting geomorphic response to environmental change. The denudation of upland sites resulting from tillage has left an indelible morphological response that forms a change in the system's state, forming new initial conditions for further system-wide perturbation.

7.3 Future Perspectives

This study formed a component of a wider research project that had an emphasis on modelling. As indicated in the Introduction, a supplementary aim of this study was to develop some concepts for the modelling of landform development in response to environmental change.

A feature of many – if not all – approaches to modelling long term geomorphic behaviour is a focus on individual process behaviour[3]. And, increasingly processes are being represented with considerable emphasis on their physical bases. A pragmatic drawback to this is the requirement for detailed and often high resolution parameterisation, which for large spatio-temporal scales is simply not available. Further, this is a deterministic approach, i.e. the model attempts to reproduce "real" quantifiable morphology. While such an approach may be able to replicate plausible patterns of landform development, there is difficulty in doing this for specific landforms (BEVEN 1996), i.e. the validation of these models is almost impossible.

In the course of the current investigation, some alternative ideas on the possibility of modelling long term sedimentary responses to environmental change have been developed. These are offered here as a comment on the future perspectives for developing further research based on the results acquired in this study. The two principal findings of this investigation form the basis of the conceptual approach that is outlined here. Firstly, a model needs to recognise that it is the frequency/magnitude of processes and thus their interaction that drives geomorphic response in terms of the spatio-temporal behaviour of the sediment flux. Secondly, the appropriate variables which control that behaviour must be identified. It has been argued here that these relate to spatial configuration and coupling between discrete sediment storage units.

The fundamental difference between existing models and the conceptual approach postulated here lies in the treatment of process. Rather than focussing on individual processes, the emphasis is placed on replication of the integrated sediment flux. This is very simply conceived of as the filling and emptying of sediment storage units. The landscape system is therefore seen as a series

[3] The range of existing models is too extensive to be adequately discussed here. A review of some of the more sophisticated long term landform evolution models that have been developed in recent years is given by COULTHARD (2001).

of units that are capable of gaining or losing sediment. Such a system is amenable to morphometric characterisation. Morphometry plays an important part in determining the behaviour of individual erosional, transport and depositional processes within individual basins. Local slope angle, for example, is very important for individual processes at smaller scales. But as spatial scale increases the significance of local morphometric properties decreases. With respect to higher order drainage basins, and the movement of sediment through these systems, different morphometric properties are considered to be more relevant. For example, volume, basin form and shape, and drainage density can be expected to control the potential for sediment storage and throughput. Similarly, as position within the basin is important at the smaller scale, determining the time taken and energy required to move sediment from source to sink, similar factors (e.g. basin order) will also be important for an integrated system. Using large scale morphometric variables such as these as internal factors addresses in part the second requirement of a model that was specified above. An additional aspect of defining the model's structure requires that consideration be given to the appropriate representation of topological relationships between units. These need to be somewhat flexible to account for the fact that at different times a given "packet" of sediment may or may not be able to bypass interim storage sites because of variation in the energy of its transport media.

A focus on the frequency/magnitude spectra of processes, reflecting variation in forcing processes – frequently climatic – represents the second aspect of the concept postulated here. In contrast to models that attempt to deterministically reproduce the behaviour of individual processes, this is a stochastic approach. It recognises that deterministic prediction of model behaviour has inherent difficulties and, importantly, that it is the interaction of processes with different frequency/magnitude spectra that has a greater influence on long term behaviour of the sediment flux. This has been shown in the current study: the pattern of sediment redistribution is a product of different processes. Deterministic modelling of gully processes parameterised with three 1,500 year recurrence interval rainfall events, and combining this with the results of several thousand iterations of a spatially distributed tillage model (if parameterisation were possible) would not necessarily capture the true essence of process interaction in the way that this has been illustrated in this work.

Thus, it is suggested that development of a modelling approach specifically for the sediment flux, and thereby indirectly for landform development might usefully pursue two aims. Firstly, the acquisition of empirical data relating to the frequency/magnitude of sediment redistribution rates of all erosional processes. Secondly, and again on an empirical basis, to identify and develop relationships between these observations and the morphometric controls of the sediment flux.

Summary

Central Europe has in many areas been subjected to continuous agricultural land use for several millennia. Deforestation and the introduction of agriculture to a previously undisturbed environment was not only a perturbation to the physical landscape system, but a shift to a qualitatively different landscape system. Within this landscape the production and redistribution of sediment has had consequences for the morphological development of the landscape. Furthermore, it has important implications for the sustainability of land use, for the design of engineering infrastructure, for contamination of waters and aquatic environments through sediment itself and as a result of associated particulate fluxes, for landform development, and for prognoses of all of these phenomena under changing climate and land use scenarios. Of particular interest, therefore, is a greater understanding of the relative significance of climatic and anthropogenic influences on the behaviour of geomorphic systems. This is important as we attempt to manage our activities so as to avoid, or at least minimise, adverse impacts on the landscape. This study deals with issues relating to geomorphic responses to environmental change.

Investigations into late Holocene colluviation took place in the Pleiser Hügelland, a region of predominantly agricultural loess-covered hill country to the east of Bonn. Widespread deforestation occurred in this area in the early to middle Medieval period, and on isolated sites probably during the Iron Age or earlier. The agricultural land use which followed this deforestation introduced a new mechanism for the generation and redistribution of sediment throughout the landscape, i.e. tillage. Colluvial sediments are principally derived from loess and loess soils, but to an extent also from basalt, trachyt and Pleistocene alluvium. This investigation has sought to characterise the geomorphic response to this environmental change. Investigation took place in three separate study areas that represent landform elements of different hierarchical magnitude: zero-, first- and second-order drainage basins.

Rates of sediment redistribution in the Auf dem Scheid catchment for the last 45 years have been modelled on the basis of 120 samples of ^{137}Cs concentration. This indicates that for this period greater rates of sediment redistribution have occurred on arable land than on pasture. The two arable zones are net sediment export areas, with high sediment delivery ratios (88%, 77%), while the pasture zone is a net accumulation area (–23%). Furthermore, modelling the effects of two different process types highlights the way in which their interaction contributes to the sediment flux. High frequency/low magnitude tillage prepares sediment for further transport by water erosion processes. There is thus a constant supply of material for sediment redistribution. Water erosion is also the mechanism by which sediment is exported beyond the boundaries of arable areas.

An attempt was made to develop a high resolution late Holocene sedimentation chronology in the Auf dem Scheid catchment using Optically Stimulated Luminescence (OSL) dating. Because of the mineral composition of the sediments in Auf dem Scheid, only limited success was achieved, and a high resolution chronology was not possible. Nevertheless, a considerable body of chronological information for colluvial sedimentation in a small area has been acquired. This and the stratigraphic information revealed during sample recovery indicates a rather complex history for the small (~5.4 ha) Auf dem Scheid catchment. At least four different phases of erosion-deposition can be inferred on the basis of OSL ages. The earliest of these is from sediments dated at ~4,400 a. The greatest rates of accumulation are associated with a Medieval

event, which may be correlated with widely reported episode of catastrophic gullying. A long term sediment budget gives an estimated sediment delivery ratio of 74%. However, when it is recognised that many of the sediments associated with earlier erosional phases have been themselves eroded and exported in the meantime, this sediment delivery ratio can be considered to be an overestimate. In the absence of high magnitude events, further reworking of colluvial sediments stored in the Auf dem Scheid catchment is unlikely. Thus, although there is a reasonably efficient mid- to long term coupling of source and sink within the Auf dem Scheid, the external coupling is weak and Auf dem Scheid can be considered to be a closed system.

OSL ages were also acquired from the fill of two fossil gullies in a single slope study area in the nearby Forstbach catchment. They have been filled with sediments eroded from the formerly agricultural slopes. The ages of gully fill indicate that these features are ~1,300 years old. In general, the ages of colluvia in the both Auf dem Scheid and Forstbach give evidence of considerable erosional activity occurring at a considerably earlier period than had previously been thought. An inference is that deforestation and the introduction of agriculture may have occurred much earlier than has previously been thought in at least this part of the Pleiser Hügelland. Further, both study sites are dominated by the evidence of agricultural processes. Although gullying associated with large scale rainfall-runoff has occurred in both, there is no evidence of this in the contemporary landscape. Thus, expressed in terms of transient form ratios, both are considered insensitive to gullying, but sensitive to low magnitude diffusive erosional processes.

Stratigraphic evidence of process behaviour was derived on the basis of a series of core transects in the Heidersiefen basin (2nd order). Large volumes of agriculturally initiated sediment are also present in this area. A long term sediment budget (FEISE 1999) indicated relatively low sediment delivery ratios (~30%) for first and second order drainage basins. However, construction of infrastructure in more recent times has caused a decoupling of sediment source areas from channel deposition sites, and sediment delivery within the Heidersiefen catchment has been reduced. This has influenced the geomorphic effectiveness of rainfall-runoff, which is capable of eroding in-channel sediment storage in even relatively low magnitude events. The presence of a perennial channel means that the sediments in storage in Heidersiefen are more susceptible to reworking than those in Auf dem Scheid or the Forstbach study site. Thus, more than the other study sites, Heidersiefen does not exhibit the same sensitivity to agricultural land use.

The two principal processes of sediment generation and redistribution that operate within this landscape (tillage and rainfall-runoff) are markedly different with respect to their frequency/magnitude/effectiveness. Tillage occurs with high frequency, i.e. on a regular basis, 2-3 times per year. Tillage is a very effective transport mechanism in terms of the volume of material it moves over longer periods, but its effects remain localised as transport is only over very small distances. More significantly, tillage increases the susceptibility of soils to water erosion processes. There is greater variability in the frequency/magnitude/effectiveness of rainfall-runoff events. Those with sufficient energy to erode and transport some small amount of sediment (i.e. through overland flow and rilling) probably occur at least as frequently as tillage. These events are able to transport small amounts of material over small distances. But those with sufficient energy to cause gullying – and thus potentially the erosion and transport of volumes of material comparable with a single ploughing operation – are considerably less frequent. Not only does the magnitude of rainfall-runoff influence the amount of material moved, it also determines the distance of transport. The effects of small magnitude events remain relatively localised, just as with ploughing. Sediment may simply remain within the field and be reincorporated into the plough horizon with the next ploughing operation; or it may be transported to a local depositional zone. At the other extreme, gullies generated by high magnitude rainfall-runoff events are potentially capable of transporting sediment out of the system entirely. The relative frequency of rainfall-runoff events of varying magnitude, and their temporal sequence, is thus an important aspect in determining the pattern of sediment generation and redistribution. There is evidence that high magnitude rainfall-runoff events have formed gullies. However, the age of these features – as revealed by the luminescence-derived ages of their fills – indicates that this has not happened very frequently. In the intervening period between the recurrence of high magnitude events, their morphological effects have been removed by the sediment generated by smaller events.

Of equal importance are configurational aspects of the landscape system. These relate to the spatial distribution of the individual process domains, both relative to each other and within the landscape system. It also relates to the spatial distribution of sediment sources/sinks and of the different components of the system hierarchy, and importantly the extent to which (a) sources and sinks and (b) systematic elements are coupled. This is influenced by both the magnitude of each of these elements, and by the energy available for transporting material from one element to the next.

The principal geomorphic response to environmental change has been the generation of large amounts of sediment through (a) initial deforestation and (b) the subsequent effects of tillage and rainfall-runoff processes. However, the low levels of energy available for transport of this sediment – due to both low relief and a low frequency of high energy rainfall events – and sometimes weak coupling between components of the sediment flux have restricted the amount of sediment entering the regional sediment flux. The post-deforestation, agricultural landscape can thus be characterised with a transport limited sediment flux. This contrasts with a generally assumed stable pre-deforestation landscape which exhibited low rates of process behaviour and therefore a supply limited sediment flux.

Zusammenfassung

Viele Regionen Mitteleuropas werden seit einigen Jahrtausenden durch kontinuierliche Ackernutzung geprägt. Entwaldung und die Einführung der Landwirtschaft in eine zuvor unberührte Umwelt bedeutete nicht nur die Störung des physischen Systems der Landschaft, sondern auch den Übergang in ein Landschaftssystem neuer Prägung. Innerhalb dieser Landschaft hatte die Produktion und Umlagerung von Sediment Auswirkungen auf die morphologische Entwicklung der Landschaft. Darüber hinaus ist der Eingriff bedeutungsvoll bezüglich die Nachhaltigkeit der Landnutzung, den Bau infrastruktureller Einrichtungen, bezüglich der Verunreinigung von Wasser und Wasserreservoirs durch das Sediment selbst und durch den damit verbundenem Stofftransport, bezüglich der Landschaftsentwicklung und der Vorhersage all dieser Erscheinungen unter sich ändernden Landnutzungs- und Klimaszenarien. Es ist daher von besonderem Interesse, klimatische und anthropogene Einflüsse in ihrer relativen Bedeutung für das Verhalten der geomorphologischen Systeme besser zu verstehen. Dieses Verstehen ist besonders dann wichtig, wenn wir versuchen, unsere Aktivitäten so zu steuern, dass Eingriffe vermieden oder zumindest reduziert werden. Diese Untersuchung beschäftigt sich

Themen, die sich auf die Reaktion des geomorphologischen Systems auf Umweltveränderungen beziehen.

Gegenstand sind spät-holozäne Kolluvien, die hauptsächlich aus Löss, aber auch aus Basalt, Trachyttuff und Schotter hervorgegangen sind. Die Untersuchungen haben in der überwiegend landwirtschaftlich genutzten Region des Pleiser Hügelland östlich von Bonn stattgefunden. Die Rodung in diesem Gebietes begann im frühen bis mittleren Mittelalter, an einigen Stellen vermutlich bereits während der Eisenzeit oder früher. Die darauffolgende Ackernutzung führte mit dem Pflügen einen neuen Prozess der Sedimentmobilisierung und -umverteilung innerhalb der Landschaft ein. Die vorliegende Untersuchung ist darauf ausgerichtet, die Reaktionen der beteiligten geomorphologischen Einheiten auf diese Umweltveränderung zu charakterisieren. Die Arbeiten wurden in drei räumlich getrennten Untersuchungsgebieten durchgeführt, die Landschaftselemente unterschiedlicher hierarchischer Ordnung repräsentieren: Einzugsgebiete nullter („Forstbach", 0,9 ha), erster („Auf dem Scheid", ~5.4 ha) und zweiter Ordnung („Heidersiefen", ~14 ha).

Auf Basis von ^{137}Cs Konzentration im Oberboden wurden die Sedimentumverteilungsraten im Einzugsgebiet „Auf dem Scheid" für die letzten 45 Jahre modelliert. Diese zeigen, daß die Sedimentumlagerung auf Ackerland jene auf Grünland bedeutend überstiegen hat. Es gibt zwei Ackerlandzonen, die Netto-Sedimentaustragsgebiete mit hohen Sedimentaustragsraten (88%, 77%) sind, während die Grünland-Zone mit einer Sedimentaustragsrate von –23% ein Netto-Akkumulationsgebiet darstellt. Weiterhin konnte durch den Einsatz numerischer Modelle veranschaulicht werden, in welcher Weise die beiden Prozesstypen Pflügen und Wassererosion zum Sedimenttransfer beitragen. Mit hoher Frequenz und geringer Magnitude stellt Pflügen Sediment für den Weitertransport durch Wassererosionsprozesse bereitet. Somit steht zu jedem Zeitpunkt Sediment für die Umverteilung zur Verfügung. Wassererosion hingegen ist der Prozeß, der Sediment über die Feldgrenzen hinweg transportiert.

Mit der Datierungsmethode der Optisch Stimulierten Lumineszenz (OSL) wurde versucht, eine hochauflösende Chronologie für die spät-holozänen Sedimente im Einzugsgebiet 'Auf dem Scheid' zu erstellen. Aufgrund der Mineralzusammensetzung der Sedimente, war dies nur in begrenzt erfolgreich und eine hochauflösende Chronologie konnte nicht erstellt werden. Trotzdem konnte eine beachtliche Menge chronologischer Informationen zur Kolluvienbildung zusammengetragen werden, die zusammen mit den stratigraphischen Befunden, ein komplexes Bild für die Entwicklung des kleinen Einzugsgebiets ergeben. Mindestens vier Erosions- bzw. Akkumulations-Phasen können auf der Grundlage der OSL-Alter identifiziert werden. Die älteste wird durch Sedimente repräsentiert, die etwa 4,400 a alt sind. Die höchsten Akkumulationsraten gehen auf mittelalterliche Ereignisse zurück, die mit mehrfach beschriebenen Perioden katastrophalen Schluchtenreißens korreliert werde können. Eine Abschätzung der holozänen Sedimentbilanz ergibt ein Sedimentaustragsverhältnis von 74%. Dieser Wert sollte jedoch als Maximalwert angesehen werden, da ein Großteil der Sedimente aus früheren Erosionsphasen in der Zwischenzeit erodiert und ausgeräumt wurden. Eine weitere Umverteilung von kolluvialem Material im Einzugsgebiet Auf dem Scheid ist lediglich durch Ereignisse hoher Magnitude zu erwarten. Daher ist trotz der eher effizienten mittel- bis langfristigen Kopplung von Quellen und Senken innerhalb des Einzugsgebiets die externe Ankopplung schwach und das Gebiet Auf dem Scheid kann als ein geschlossenes System angesehen werden.

Innerhalb des nahegelegenen Einzugsgebietes 'Forstbach' wurden an einem Einzelhang die Sedimentfüllungen zweier fossiler Gräben untersucht und mit OSL datiert. Die Sedimente sind Korrelate früherer landwirtschaftlicher Nutzung der angrenzenden Hänge. Ihre Akkumulation begann vor etwa 1,300 Jahren. Die Alter der Kolluvien, sowohl von Auf dem Scheid als auch von Forstbach, weisen auf eine beachtliche Erosionsaktivität hin, die erheblich früher stattgefunden hat als bislang angenommen. Daher muß geschlossen werden, daß die Abholzung und die Einführung des Ackerbaus sehr viel früher erfolgte, als für diesen Teil des Pleiser Hügellandes bisher angenommen wurde. Beide Untersuchungsgebiete sind dominiert von den Auswirkungen landwirtschaftlicher Prozesse. Obwohl in beiden Einzugsgebieten das mit großen Niederschlags-/Erosionsereignissen einhergehende Schluchtenreissen stattgefunden hat, gibt es hierfür an der heutigen Landschaftsoberfläche keine Hinweise. Bezüglich der "transient form ratios" müssen deshalb beide Untersuchungsgebiete als insensitiv für Schluchtenreissen bezeichnet werden. Hingegen sind beide aber als sensitiv für diffuse Erosionsprozesse mit geringer Magnitude einzustufen.

Stratigraphische Befunde für das Prozeßverhalten wurden aus einer Reihe von Catenen im Heidersiefen Einzugsgebiet (2. Ordnung) gewonnen. Auch hier sind große Mengen landwirtschaftlich verursachten Sediments vorhanden. Eine langfristige Sedimentbilanz (FEISE 1999) erbrachte mit ~30% eine relativ niedrige Sedimentaustragsrate für Einzugsgebiete erster und zweiter Ordnung. Allerdings wurden durch den Bau von Infrastruktur in jüngerer Zeit die Sedimentquellen von den Sedimentspeichern am Gerinne entkoppelt und der Sedimentaustrag reduziert. Dies beeinflußte auch die geomorphologische Wirksamkeit von Niederschlags/Abflussereignissen, die bereits bei geringer Magnitude zur Erosion von Sediment im Gerinne führen. Das perennierende Gerinne bedeutet für das Heidersiefen-Gebiet, dass die darin gespeicherten Sedimente gegenüber Aufarbeitung anfälliger sind als jene im Gebiet Auf dem Scheid. Verglichen mit den anderen Untersuchungsgebieten ist Heidersiefen daher weniger sensitiv für ackerbaulicher Nutzung.

Die beiden Hauptprozesse der Bodenerosion und -umverteilung, die in dieser Landschaft wirksam sind (Pflügen und Wassererosion) unterscheiden sich sehr stark in ihrer Frequenz/Magnitude/Effektivität. Das Pflügen geschieht mit hoher Frequenz, d.h. in regelmäßigen Abständen 2-3 mal pro Jahr, womit über längere Zeiträume große Volumina bewegen werden. Die Auswirkung des Pflügens bleibt jedoch lokal begrenzt, da der Transport nur über geringe Distanzen hinweg erfolgt. Entscheidender jedoch ist, dass Pflügen die Anfälligkeit des Bodens für Wassererosion erhöht. Die Variabilität der Frequenz/Magnitude/Effektivität bei Niederschlags/Abflussereignissen ist höher. Niederschlagsereignisse deren Energie für Erosion und Transport geringer Bodenmengen ausreichend ist (das heißt durch Oberflächenerosion und Rillenerosion), treten wahrscheinlich mindestens so häufig auf wie das Pflügen des Ackers. Diese Ereignisse können geringe Mengen Bodenmaterial über kurze Distanzen transportieren. Dagegen sind solche Niederschlagsereignisse erheblich seltener, die genügend Energie zur Erzeugung von Rinnen haben und damit eine Sedimentumverteilung vergleichbar der eines einzigen Pflügens bewirken. Die Stärke des Niederschlages beeinflußt nicht nur die Menge des erodierten Materials, sondern auch die Transportstrecke. Die Auswirkungen von schwachen Niederschlagsereignissen bleiben auf einen relativ kleinen Raum beschränkt, wie auch die des Pflügens. Das erodierte Bodenmaterial verbleibt auf dem Feld und wird mit dem nächsten Pflügen wieder in den Pflughorizont eingearbeitet oder in örtlichen Ablagerungszonen gespeichert. Das andere Extrem sind Rinnen und Gräben, die durch Starkregenereignisse entstehen, und die potentiell fähig sind, Sediment aus dem Gesamtsystem hinaus zu transportieren. Die relative Häufigkeit von Niederschlagsereignissen unterschiedlicher Stärke und deren zeitliche Abfolge, ist daher ein wichtiger Aspekt bei der Bestimmung von Mustern der Sedimentbildung und Sedimentverteilung. Es gibt Hinweise dafür, dass durch Starkregen/-abflussereignisse Gullies geformt wurden. Jedoch spricht das Alter dieser Formen – wie durch die OSL-Alter der Füllungen erwiesen – dafür, dass dies nicht sehr häufig geschehen ist. In den Zeiträumen zwischen dem Auftreten dieser Starkregenereignisse, sind ihre geomorphologischen Auswirkungen durch Sedimente beseitigt worden, die von kleinen Ereignissen stammen.

Von ähnlicher Bedeutung sind Aspekte der räumlichen Anordnung des Landschaftssystems. Diese betreffen die Verteilung der einzelnen Prozeßdomänen, sowohl relativ zu einander als auch innerhalb des Landschaftssystems. Sie beziehen sich auf die räumliche Verteilung der Sedimentquellen und –senken und auf die verschiedenen Komponenten der Systemhierarchien, wie auch auf das Ausmaß der Kopplung von a) Quellen und Senken und b) einzelnen Systemkomponenten. Dies wird beeinflußt von der Größe jedes einzelnen Elements, wie auch der vorhandenen Energie für den Materialtransport von einem zum nächsten Element.

Die grundlegende geomorphologische Reaktion auf eine Umweltveränderung war die Erzeugung von großen Sedimentmengen durch a) die erstmalige Abholzung und b) die nachfolgenden Auswirkungen von Pflügen und Niederschlag/Abfluss-Prozessen. Jedoch hat das geringe zum Sedimenttransport zur Verfügung stehende Energieniveau die Menge an Sediment, das in den regionalen Sedimenttransfer eingebracht wird, begrenzt. Dies liegt sowohl an den geringen Hangneigungen und der geringen Häufigkeit von Starkregenereignisse, als auch an der schwachen Kopplung einzelner Komponenten des Sedimenttransfers. Die entwaldete und agrarisch genutzte Landschaft ist deshalb durch einen transportbegrenzten Sedimenttransfer charakterisiert. Sie hebt sich von der ursprünglichen Waldlandschaft ab, deren Zustand allgemein als stabil angenommen wird und die sich durch geomorphologische Stabilität und einen nachschubbegrenzten Sedimenttransfer auszeichnet.

Bibliography

ABRAHAMS, A.D. 1968. Distinguishing between the concepts of steady state and dynamic equilibrium in geomorphology. *Earth Science Journal* **2(2)**, 160-166.

AG BODEN 1994. *Bodenkundliche Kartieranleitung*. (4th edn.) Hannover. 392 pp.

AHNERT, F. 1981. Über die Beziehung zwischen quantitativen, semiquantitativen und qualitativen Methoden in der Geomorphologie. *Zeitschrift für Geomorphologie (Supp.)* **39**, 1-28.

AHNERT, F. 1994. Equilibrium, scale and inheritance in geomorphology. *Geomorphology* **11**, 125-140.

AHNERT, F. 1996. *Introduction to Geomorphology*. Arnold, London. 352 pp.

AITKEN, M.J. 1998. *An Introduction to Optical Dating. The Dating of Quaternary Sediments by the Use of Photon-stimulated Luminescence*. Oxford Science Publications, Oxford. 267 pp.

AMAYO, C. 1979. Holozäne Reliefentwicklung im mittleren Rheingau (Hessen). *Geologisches Jahrbuch Hessen* **107**, 179-191.

ANDREWS, E.D. 1980. Effective and bankfull discharges of streams in the Yampa River basin, Colorado and Wyoming. *Journal of Hydrology* **46**, 311-330.

BACHHUBER, H., BUNZL, K. & SCHIMMACK, W. 1987. Spatial variability of fallout-^{137}Cs in the soil of a cultivated field. *Environmental Monitoring and Assessment* **8**, 93-101.

BACHHUBER, H., BUNZL, K., SCHIMMACK, W. & GANS, I. 1982. The migration of ^{137}Cs and ^{90}Sr in multilayered soils: results from batch, column and fallout investigations. *Nuclear Technology* **59**, 291-301.

BAUER, A.W. 1993. *Bodenerosion in den Waldgebieten des östlichen Taunus in historischer und heutiger Zeit - Ausmaß, Ursachen und geoökologische Auswirkungen*. Frankfurter Geowissenschaftliche Arbeiten, Serie D - Physische Geographie **14**. 194 pp.

BELL, M. & BOARDMAN, J. (Eds.) 1992. *Past and Present Soil Erosion*. Oxbow Monograph **22**. Oxbow Books, Oxford. 250 pp.

BEVEN, K. 1996. Equifinality and uncertainty in geomorphological modelling. *In*: RHOADS, B.L. & THORN, C.E. (Eds.) *The Scientific Nature of Geomorphology*. Wiley, Chichester. 289-313.

BLAIKIE, P. & BROOKFIELD, H. (Eds.) 1987. *Land Degradation and Society*. Methuen, London. 296 pp.

BOARDMAN, J. & FAVIS-MORTLOCK, D. (Eds.) 1998a. *Modelling Soil Erosion by Water*. NATO ASI Series **55**. Springer, Berlin. 531 pp.

BOARDMAN, J. & FAVIS-MORTLOCK, D. 1998b. Modelling soil erosion by water: some conclusions. *In*: BOARDMAN, J. & FAVIS-MORTLOCK, D. (Eds.) *Modelling Soil Erosion by Water*. Springer, Berlin. 515-517.

BOARDMAN, J., FOSTER, I.D.L. & DEARING, J.A. (Eds.) 1990. *Soil Erosion on Agricultural Land*. British Geomorphological Research Group Symposia Series, Wiley, Chichester. 687 pp.

BORK, H.-R. 1983. Die holozäne Relief- und Bodenentwicklung in Lößgebieten - Beispiele aus dem sudöstlichen Niedersachsen. *Catena (Supp.)* **3**, 1-93.

BORK, H.-R. 1989a. The history of soil erosion in southern Lower Saxony. *Landschaftsgenese und Landschaftsökologie* **16**, 135-163.

BORK, H.-R. 1989b. Soil erosion during the past millennium in central Europe and its significance within the geomorphodynamics of the Holocene. *Catena (Supp.)* **15**, 121-131.

BORK, H.-R. & BORK, H. 1987. Extreme jungholozäne hygrische Klimaschwankungen in Mitteleuropa und ihre Folgen. *Eiszeitalter und Gegenwart* **37**, 109-118.

BORK, H.-R., BORK, H., DALCHOW, C., FAUST, B., PIORR, H.-P. & SCHATZ, T. 1998. *Landschaftsentwicklung in Mitteleuropa*. Klett-Perthes, Gotha. 328 pp.

BOTSCHEK, J. 1991. Bodenerodierbarkeit in Nordrhein-Westfalen. *Arbeiten zur Rheinischen Landeskunde* **60**, 81-92.

BOTSCHEK, J., GRUNERT, J. & SKOWRONEK, A. 1991. Bodenerosionsforschung an der landwirtschaftlichen Fakultät und am geographischen Institut der Universität Bonn - eine kommentierte Bibliographie. *Arbeiten zur Rheinischen Landeskunde* **60**, 55-69.

BOTSCHEK, J., GRUNERT, J. & SKOWRONEK, A. 1994. Bodenerosion in Nordrhein-Westfalen - Voraussetzungen, Prozesse und Schutzmaßnahmen. *Berichte zur deutschen Landeskunde* **68(1)**, 33-56.

BRÄUER, F., BOTSCHEK, J. & SKOWRONEK, A. 1996. Reliefveränderung durch historische Bodenerosion auf dem landwirtschaftlichen Versuchsgut Frankenforst (Pleiser Hügelland). *Mitteilungen der Deutschen Bodenkundlichen Gesellschaft* **79**, 363-366.

BRINKMANN, J. & SKOWRONEK, A. 1999. Bodengeomorphologie und Bodenverteilung auf dem Landwirtschaftlichen Versuchsgut Frankenforst, Pleiser Hügelland. *Mitteilungen der Deutschen Bodenkundlichen Gesellschaft* **91**, 937-940.

BROOKFIELD, H. 1999. Environmental damage: distinguishing human from geophysical causes. *Environmental Hazards* **1**, 3-11.

BROWN, A.G. & QUINE, T.A. 1999. Fluvial processes and environmental change: an overview. *In*: BROWN, A.G. & QUINE, T.A. (Eds.) *Fluvial Processes and Environmental Change*. Wiley, London. 1-27.

BROWN, R.B., KLING, G.F. & CUTSHALL, N.H. 1981. Agricultural erosion indicated by ^{137}Cs redistribution: II. Estimates of erosion rates. *Soil Science Society of America Journal* **45**, 1191-1197.

BRUNNACKER, K. & BOENIGK, W. 1983. The Rhine Valley between the Neuwied Basin and the Lower Rhenish

Embayment. *In*: FUCHS, K., VON GEHLEN, K., MÄLZER, H., MURAWSKI, H. & SEMMEL, A. (Eds.) *Plateau Uplift. The Rhenish Shield - A Case History*. Springer, Berlin. 62-72.
BRUNSDEN, D. 1993a. Barriers to geomorphological change. *In*: THOMAS, D.S.G. & ALLISON, R.J. (Eds.) *Landscape Sensitivity*. Wiley, Chichester. 7-12.
BRUNSDEN, D. 1993b. The persistence of landforms. *Zeitschrift für Geomorphologie (Supp.)* **93**, 13-28.
BRUNSDEN, D. & THORNES, J.B. 1979. Landscape sensitivity and change. *Transactions of the Institute of British Geographers* **4**, 463-484.
BUNZL, K., KRACKE, W., SCHIMMACK, W. & AUERSWALD, K. 1995. Migration of fallout $^{239+240}$Pu, ^{241}Am and ^{137}Cs in the various horizons of a forest soil under pine. *Journal of Environmental Radioactivity* **28(1)**, 17-34.
BURGHARDT, O. 1997. Das Siebengebirge - Veränderung einer Landschaft durch Bergbau, Forstwirtschaft, Weinbergsflurbereinigung und Verkehrs-Trassen. *Berichte zur deutschen Landeskunde* **71(2)**, 229-254.
CAMBRAY, R.S., PLAYFORD, K. & CARPENTER, R.C. 1989. *Radioactive fallout in air and rain: results to the end of 1988*. UK Atomic Energy Authority Report **10155**.
CAMPBELL, B.L., LOUGHRAN, R.J., ELLIOTT, G.L. & SHELLY, D.J. 1986. Mapping drainage basin sediment sources using caesium-137. *In*: HADLEY, R.F. (Ed.) *Drainage Basin Sediment Delivery*. IAHS Publ. **159**, 437-446.
CHORLEY, R.J. & KENNEDY, B.A. 1971. *Physical Geography - A Systems Approach*. Prentice-Hall, London. 370 pp.
CLEMENS, G. & STAHR, K. 1994. Present and past soil erosion rates in catchments of the Kraichgau area (SW Germany). *Catena* **22**, 153-168.
COOKE, R.U. & DOORNKAMP, J.C. 1997. *Geomorphology in Environmental Management*. (2nd edn.) Clarendon Press, Oxford. 403 pp.
COULTHARD, T.J. 2001. Landscape evolution models: a software review. *Hydrological Processes* **15**, 15-173.
CROZIER, M.J. 1989. *Landslides: Causes, Consequences and Environment*. (2nd edn.) Routledge, London. 252 pp.
CROZIER, M.J. 1996. Magnitude/frequency issues in landslide hazard assessment. *In*: MÄUSBACHER, R. & SCHULTE, A. (Eds.) *Beiträge zur Physiogeographie. Festschrift für Dietrich Barsch*. Heidelberger Geographische Arbeiten **104**, Heidelberg. 221-236.
CROZIER, M.J. 1999. The frequency and magnitude of geomorphic processes and landform behaviour. *Zeitschrift fur Geomorphologie (Supp.)* **115**, 35-50.
CROZIER, M.J. & PILLANS, B.J. 1991. Geomorphic events and landform response in south-eastern Taranaki, New Zealand. *Catena* **18**, 471-487.
CROZIER, M.J. & PRESTON, N.J. 1999. Modelling changes in terrain resistance as a component of landform evolution in unstable hill country. *In*: HERGARTEN, S. & NEUGEBAUER, H.J. (Eds.) *Process Modelling and Landform Evolution*. Lecture Notes in Earth Sciences **78**, Springer, Berlin. 267-284.
CRUDEN, D.M. & HU, X.Q. 1993. Exhaustion and steady state models for predicting landslide hazards in the Canadian Rocky Mountains. *Geomorphology* **8**, 279-285.
CUNLIFFE, B. 1994a. Iron Age societies in western Europe and beyond, 800-140 BC. *In*: CUNLIFFE, B. (Ed.) *Prehistoric Europe. An Illustrated History*. Oxford University Press, Oxford. 336-372.
CUNLIFFE, B. 1994b. The impact of Rome on barbarian society, 140 BC - AD 300. *In*: CUNLIFFE, B. (Ed.) *Prehistoric Europe. An Illustrated History*. Oxford University Press, Oxford. 411-446.
DALGLEISH, H.Y. & FOSTER, I.D.L. 1996. ^{137}Cs losses from a loamy surface water gleyed soil (Inceptisol); a laboratory simulation experiment. *Catena* **26**, 227-245.
DAVIS, W.M. 1899. The geographical cycle. *Geographical Journal* **14**, 481-504.
DE JONG, E., BEGG, C.B.M. & KACHANOWSKI, R.G. 1983. Estimates of soil erosion and deposition for some Saskatchewan soils. *Canadian Journal of Soil Science* **63**, 607-617.
DEMEK, J. & EMBLETON, C. 1984. Rhineland. *In*: EMBLETON, C. (Ed.) *Geomorphology of Europe*. Macmillan Press, London. 201-209.
DIETRICH, W.E. & DUNNE, T. 1978. Sediment budget for a small catchment in mountainous terrain. *Zeitschrift für Geomorphologie (Supp.)* **29**, 191-206.
DIKAU, R. 1989. The application of a digital relief model to landform analysis in geomorphology. *In*: RAPER, J. (Ed.) *Three Dimensional Applications in Geographical Information Systems*. Taylor & Francis, London. 51-77.
DIKAU, R. 1999. The need for field evidence in modelling landform evolution. *In*: HERGARTEN, S. & NEUGEBAUER, H.J. (Eds.) *Process Modelling and Landform Evolution*. Lecture Notes in Earth Sciences **78**, Springer, Berlin. 3-12.
DÖRR, H. & MÜNNICH, K.O. 1987. Spatial distribution of soil ^{137}Cs and ^{134}Cs in West Germany after Chernobyl. *Naturwissenschaften* **74**, 249-251.
DULLER, G.A.T. 2000. Dating methods: geochronology and landscape evolution. *Progress in Physical Geography* **24(1)**, 111-116.
ERDMANN, K.H. 1998. *Untersuchungen zur Bodenerosion im südlichen Nordrhein-Westfalen*. MAB-Mitteilungen **43**. Deutsches Nationalkomitee, UNESCO Programm "Der Mensch und die Biosphäre", 391 pp.
ERDMANN, K.-H. & ROSCHER, S. 1991. Untersuchungen zur Bodenerosion im Bonner Raum unter Einsatz eines geographischen Informationssystems. *Arbeiten zur Rheinischen Landeskunde* **60**, 93-105.
ERDMANN, K.-H. & SAUERBORN, P. 1991. Die Erositivität der Niederschläge in Nordrhein-Westfalen. *Arbeiten zur Rheinischen Landeskunde* **60**, 71-80.

EVANS, R. 1990. Soil erosion: its impact on the English and Welsh landscape since woodland clearance. *In*: BOARDMAN, J., FOSTER, I.D.L. & DEARING, J.A. (Eds.) *Soil Erosion on Agricultural Land*. Wiley, Chichester. 231-254.

EVERDING, C., KEHL, M., BOTSCHEK, J. & SKOWRONEK, A. 1996. Erosionsstatus, Erosionsverhalten und Erosionsanfälligkeit verschieden texturierter Ackerböden Nordrhein-Westfalens. *Mitteilungen der Deutschen Bodenkundlichen Gesellschaft* **79**, 371-374.

FAVIS-MORTLOCK, D. & BOARDMAN, J. 1995. Nonlinear responses of soil erosion to climate change: a modelling study on the UK South Downs. *Catena* **25**, 365-387.

FAVIS-MORTLOCK, D., BOARDMAN, J. & BELL, M. 1997. Modelling long-term anthropogenic erosion of a loess cover: South Downs, UK. *The Holocene* **7**, 79-89.

FAVIS-MORTLOCK, D.T. & SAVABI, M.R. 1996. Shifts in rates and spatial distributions of soil erosion and deposition under climate change. *In*: ANDERSON, M.G. & BROOKS, S.M. (Eds.) *Advances in Hillslope Processes*. Wiley, Chichester. 529-560.

FEISE, A. 1999. *Sedimentbilanzierung eines kleinen Einzugsgebietes im Pleiser Hügelland und ihre Bedeutung für Sedimenthaushalt und Landschaftsgenese*. unpublished Diplom thesis, Universität Bonn. 110 pp.

FIRESTONE, R.B., SHIRLEY, V.S., BAGLIN, C.M., CHU, S.Y.F. & ZIPKIN, J. 1996. *Table of Isotopes*. (8th edn.) Wiley, New York. 3168 pp.

FLOHN, H. 1949. Klimaschwankungen im Mittelalter und ihre historisch-geographischen Bedeutung. *Berichte zur deutschen Landeskunde* **7**, 347-358.

FLOHN, H. 1958. Klimaschwankungen der letzten 1000 Jahre und ihre geophysikalischen Ursachen. *Deutscher Geographentag Würzburg, Tagungsberichte und wissenschaftliche Abhandlungen*. Steiner, Wiesbaden. 201-214.

FLOHN, H. 1967. Klimaschwankungen in historischer Zeit. *In*: VON RUDLOFF, H. (Ed.) *Die Schwankungen und Pendelungen des Klimas seit Beginn der regelmäßigen Instrumenten-Beobachtung*. Vieweg, Braunschweig. 81-90.

FLOHN, H. 1993. Climatic evolution during the last millennium: what can we learn from it? *In*: EDDY, J.A. & OESCHGER, H. (Ed.) *Global Changes in the Perspective of the Past*. Wiley, Chichester. 295-316.

GLADE, T. 1998. Establishing the frequency and magnitude of landslide-triggering rainstorm events in New Zealand. *Environmental Geology* **35**, 160-174.

GOVERS, G., QUINE, T.A., DESMET, P.J.J. & WALLING, D.E. 1996. The relative contribution of soil tillage and overland flow erosion to soil redistribution on agricultural land. *Earth Surface Processes and Landforms* **21**, 929-946.

GOVERS, G., VANDAELE, K., DESMET, P., POESEN, J. & BUNTE, K. 1994. The role of tillage in soil redistribution on hillslopes. *European Journal of Soil Science* **45**, 469-478.

GRANT, P.J. 1985. Major periods of erosion and alluvial sedimentation in New Zealand during the late Holocene. *Journal of the Royal Society of New Zealand* **15(1)**, 67-121.

GREENWAY, D.R. 1987. Vegetation and slope stability. *In*: ANDERSON, M.G. & RICHARDS, K.S. (Eds.) *Slope Stability*. Wiley, Chichester. 187-230.

GRUNERT, J. 1988. Geomorphologische Entwicklung des Bonner Raumes. *Arbeiten zur Rheinischen Landeskunde* **58**, 165-180.

GRUNERT, J. 1994. Hangabtragung und Bodenerosion im Bonner Raum in histroischer Zeit. *In*: VON KÖNIGSWALD, W. & MEYER, W. (Eds.) *Erdgeschichte in Rheinland - Fossilien und Gesteine aus 400 Millionen Jahren*. Pfeil, München. 215-222.

HARD, G. 1970. Exzessive Bodenerosion um und nach 1800. *Erdkunde* **24**, 290-308.

HARDING, A. 1994. Reformation in barbarian Europe, 1300-600 BC. *In*: CUNLIFFE, B. (Ed.) *Prehistoric Europe. An Illustrated History*. Oxford University Press, Oxford. 304-335.

HE, Q. & WALLING, D.E. 1997. The distribution of fallout ^{137}Cs and ^{210}Pb in undisturbed and cultivated soils. *Applied Application and Radioisotopes* **48**, 677-690.

HE, Q., WALLING, D.E. & OWENS, P.N. 1996. Interpreting the ^{137}Cs profiles observed in several small lakes and reservoirs in southern England. *Chemical Geology* **129**, 115-131.

HEIDE, G. 1988. Boden und Bodennutzung. *Geologie am Niederrhein*. (4th edn.) Geologisches Landesamt Nordrhein-Westfalen, Krefeld. 73-78.

HEMPEL, L. 1954a. Tilken und Sieke - ein Vergleich. *Erdkunde* **8**, 198-202.

HEMPEL, L. 1954b. Flurzerstörungen durch Bodenerosion in früheren Jahrhunderten. *Zeitschrift für Agrargeschichte und Agrarsoziologie* **2**, 114-122.

HENNINGSEN, D. & KATZUNG, G. 1992. *Einführung in der Geologie Deutschlands*. Ferdinand Enke, Stuttgart. 228 pp.

HIGGITT, D.L. 1991. Soil erosion and soil problems. *Progress in Physical Geography* **15**, 91-100.

HIROSE, K., AOYAMA, M., KATSURAGI, Y. & SUGIMARA, Y. 1987. Annual deposition of Sr-90, Cs-137 and Pu-239,240 from the 1961-1980 nuclear explosions: a simple model. *Journal of the Meteorological Society of Japan* **65**, 259-277.

HOMBITZER, A. 1913. *Beiträge zur Siedlungskunde und Wirtschaftsgeographie des Siebengebirges und seiner Umgebung*. Heeg, Oberkassel. 152 pp.

HOOKE, R.L. 2000. On the history of humans as geomorphic agents. *Geology* **28(9)**, 843-846.
KACHANOWSKI, R.G. 1987. Comparison of measured soil caesium-137 losses and erosion rates. *Canadian Journal of Soil Science* **67**, 199-203.
KADEREIT, A., LANG, A. & WAGNER, G.A. in press. Colluvial sediments near archaeological sites as a key to the past landscape evolution under human impact. *In*: JEREM, E. & BIRO, K. (Eds.) *Proceedngs of the 31st International Symposium on Archaeometry*.
KELLERMANN, V. & HAVERMANN, K. 1973. *800 Jahre Vinxel*. Uelpenich, Königswinter. 28 pp.
KIRKBY, M.J. 1998. Modelling across scales: the MEDALUS family of models. *In*: BOARDMAN, J. & FAVIS-MORTLOCK, D. (Eds.) *Modelling Soil Erosion by Water*. NATO ASI Series **55**, Springer, Berlin. 161-173.
KIRKBY, M.J. 1999. Landscape modelling at regional to continental scales. *In*: HERGARTEN, S. & NEUGEBAUER, H.J. (Eds.) *Process Modelling and Landform Evolution*. Lecture Notes in Earth Sciences **78**, Springer, Berlin. 189-203.
KIRKBY, M.J., ABRAHART, R., MCMAHON, M.D., SHAO, J. & THORNES, J.B. 1998. MEDALUS soil erosion models for global change. *Geomorphology* **24**, 35-49.
KÜSTER, H. 1998. *Geschichte der Landschaft in Mitteleuropa. Von der Eiszeit bis zur Gegenwart*. C.H. Beck Verlag, 423 pp.
LAMB, H.H. 1984. Climate in the last thousand years: natural climatic fluctuations and change. *In*: FLOHN, H. & FANTECHI, R. (Eds.) *The Climate of Europe: Past, Present and Future*. Reidel, Dordrecht. 25-64.
LAMOTHE, M. & AUCLAIR, M. 1999. A solution to anomalous fading and age shortfalls in optical dating of feldspar minerals. *Earth and Planetary Science Letters* **171**, 319-323.
LANCE, J.C., MCINTYRE, S.C., NANEY, J.W. & ROUSSEVA, S.S. 1986. Measuring sediment movement at low erosion rates using cesium-137. *Soil Science Society of America Journal* **50**, 1303-1309.
LANE, S.N. & RICHARDS, K.S. 1997. Linking river channel form and process: time, space and causality revisited. *Earth Surface Processes and Landforms* **22**, 249-260.
LANG, A. 1994. Infra-red stimulated luminescence dating of Holocene reworked silty sediments. *Quaternary Geochronology (Quaternary Science Reviews)* **13**, 525-528.
LANG, A. 1996. *Die Infrarot-Stimulierte-Lumineszenz als Datierungsmethode für holozäne Lössderivate*. Heidelberger Geographische Arbeiten **103**. 137 pp.
LANG, A. in press. A frequency analysis of phases of colluviation in the loess hills of south Germany. *Catena*.
LANG, A., BORK, H.-R., MÄCKEL, R., PRESTON, N.J. & DIKAU, R. 2000. Land use and climate impacts on fluvial systems during the period of agriculture - examples from the Rhine catchment. *PAGES Newsletter* **8(3)**, 11-13.
LANG, A., BORK, H.-R., MÄCKEL, R., PRESTON, N.J., WUNDERLICH, J. & DIKAU, R. in press. Changes in sediment flux and storage within a fluvial system - some examples from the Rhine catchment. *Hydrological Processes.*
LANG, A. & HÖNSCHEIDT, S. 1999. Age and source of colluvial sediments at Vaihingen-Enz, Germany. *Catena* **38**, 89-107.
LANG, A. & NOLTE, S. 1999. The chronology of Holocene alluvial sediments from the Wetterau, Germany, provided by optical and ^{14}C dating. *The Holocene* **9**, 207-214.
LANG, A., REISER, U., HABERMANN, J. & WAGNER, G.A. 1998. Luminescence dating of sediments. *Naturwissenschaft* **85**, 515-523.
LANG, A. & WAGNER, G.A. 1996. Infrared stimulated luminescence dating of archaeosediments. *Archaeometry* **38**, 129-141.
LAUX, H.D. & ZEPP, H. 1997. Bonn und seine Region. Geoöklogische Grundlagen, historische Entwicklung und Zukunftperspektiven. *Arbeiten zur Rheinischen Landeskunde* **66**, 9-31.
LESSMANN-SCHOCH, U., KAHRER, R. & BRÜMMER, G.W. 1991. Pollenanalytische und ^{14}C-Untersuchungen zur Datierung der Kolluvienbildung in einer lößbedeckten Mittelbirgslandschaft (Nördlicher Siebengebirgsrand). *Eiszeitalter und Gegenwart* **41**, 16-25.
LINDSTROM, M.J., NELSON, W.W. & SCHUMACHER, T.E. 1992. Quantifying tillage erosion rates due to moldboard ploughing. *Soil and Tillage Research* **24**, 243-255.
LINKE, M. 1976. Ein Beitrag zur Erklärung des Kleinreliefs unserer Kulturlandschaft. *In*: RICHTER, G. (Ed.) *Bodenerosion in Mitteleuropa*. Weg der Forschung **430**, Wissenschaftliche Buchgesellschaft, Darmstadt. 278-329.
LIVENS, F.R. & LOVELAND, P.J. 1988. The influence of soil properties on the environmental mobility of caesium in Cumbria. *Soil Use and Management* **4**, 69-75.
LOUGHRAN, R.J., CAMPBELL, B.L. & WALLING, D.E. 1987. Soil erosion and sedimentation indicated by caesium 137: Jackmoor Brook catchment, Devon, England. *Catena* **14**, 201-212.
LÖWNER, M.-O. 2000. *Geophysikalische und sedimentologische Untersuchungen zu Sedimentspeichern auf Gut Frankenforst bei Bonn*. unpublished Diplom thesis, Universität Bonn. 144 pp.
LOWRANCE, R., MCINTYRE, S. & LANCE, C. 1988. Erosion and deposition in a field/forest system estimated using cesium-137 activity. *Journal of Soil and Water Conservation* **43(2)**, 195-199.
LÜNING, J., JOCKENHÖVEL, A., BENDER, H. & CAPELLE, T. 1997. *Deutsche Agrargeschichte. Vor- und Frühgeschichte*. Ulmer, Stuttgart. 479 pp.
MACHAN, R. & SEMMEL, A. 1970. Historische Bodenerosion auf Wüstungsfluren deutscher Mittelgebirge.

Geographische Zeitschrift **58**, 250-266.
MALANSON, G.P., BUTLER, D.R. & GEORGAKAKOS, K.P. 1992. Non-equilibrium geomorphic processes and deterministic chaos. *Geomorphology* **5**, 311-322.
MCHENRY, J.R., RITCHIE, J.C. & GILL, A.C. 1973. Accumulation of fallout cesium-137 in soils and sediments in selected watersheds. *Water Resources Research* **9(3)**, 676-686.
MORGAN, R.P.C. 1995. *Soil Erosion & Conservation*. (2nd edn.) Longman, Harlow. 198 pp.
MORGAN, R.P.C., QUINTON, J.N., SMITH, R.E., GOVERS, G., POESEN, J.W.A., AUERSWALD, K., CHISCI, G., TORRI, D. & SYCZEN, M.E. 1998. The European Soil Erosion Model (EUROSEM): a dynamic approach for predicting sediment transport from fields and small catchments. *Earth Surface Processes and Landforms* **23**, 527-544.
MURRAY, A.S. 1996. Developments in optically stimulated luminescence dating and photo-transferred thermoluminescence dating of young sediments: application to a 2000-year sequence of flood deposits. *Geochimica et Cosmochimica Acta* **60(4)**, 565-576.
NEARING, M.A., FOSTER, G.R., LANE, L.J. & FINKNER, S.C. 1989. A process-based soil erosion model for USDA-Water Erosion Prediction Project technology. *Transactions of the American Society of Agricultural Engineers* **32**, 1587-1593.
NICHOLAS, A.P., ASHWORTH, P.J., KIRKBY, M.J., MACKLIN, M.G. & MURRAY, T. 1995. Sediment slugs: large scale fluctuations in fluvial sediment transport rates and storage volumes. *Progress in Physical Geography* **19**, 500-519.
NICKE, H. 1989. Siefen - Geomorphologische Untersuchungen an einer Sonderform der Talanfänge im Bergischen Land. *Decheniana* **142**, 147-156.
ODINIUS, B. & ERDMANN, K.-H. 1991. Der Einfluss unterschiedlicher Hanglängen auf die Bodenerosion - experimentelle Untersuchungen im Bonner Raum. *Arbeiten zur Rheinischen Landeskunde* **60**, 107-117.
OWENS, P.N., WALLING, D.E. & HE, Q. 1996. The behaviour of bomb-derived Caesium-137 fallout in catchment soils. *Journal of Environmental Radioactivity* **32**, 169-191.
OWENS, P.N., WALLING, D.E. & LEEKS, G.J.L. 2000. Tracing fluvial suspended sediment sources in the catchment of the River Tweed, Scotland, using composite fingerprints and a numerical mixing model. *In*: FOSTER, I.D.L. (Ed.) *Tracers in Geomorphology*. Wiley, Chichester. 291-308.
PAAS, W. 1968. Stratigraphische Gliederung des Niederrheinischen Lösses und seiner fossilen Böden. *Decheniana* **121(1/2)**, 9-38.
PAGE, M.J. & TRUSTRUM, N.A. 1997. A late Holocene lake sediment record of the erosion response to land use change in a steepland catchment, New Zealand. *Zeitschrift für Geomophologie* **41**, 369-392.
PAGE, M.J. & TRUSTRUM, N.A. 2000. High resolution lake sediments from New Zealand - a record of late Holocene storm history, vegetation change and landscape response. *PAGES Newsletter* **8(3)**, 17-18.
PAGE, M.J., TRUSTRUM, N.A. & DYMOND, J.R. 1994. Sediment budget to assess the geomorphic effect of a cyclonic storm, New Zealand. *Geomorphology* **9**, 169-188.
PARKNER, T. 2000. *Modelling soil erosion at Gut Frankenforst near Bonn between 1954 and today*. unpublished Diplom thesis, Universität Bonn. 126 pp.
PENGNAN, L. 1994. *Die Entwicklung der Forschung zu Bodenerosion und Bodenschutz in Mitteleuropa*. ZALF-Berichte **10**. Zentrum für Agrarlandschafts- und Landnutzungsforschung, Müncheberg. 143 pp.
PFISTER, C. 1980. Klimaschwankungen und Witterungsverhältnisse im schweizerischen Mittelland und Alpenvorland zur Zeit des "Little Ice Age". *In*: OESCHGER, H., MESSERLI, B. & SILVAR, M. (Eds.) *Das Klima, Analysen und Modelle, Geschichte und Zukunft*. Springer, Berlin. 175-190.
PFISTER, C. 1985. Veränderungen der Sommerwitterung im südlichen Mitteleuropa von 1270-1400 als Auftakt zum Gletscherhochstand der Neuzeit. *Geographica Helvetica* **4**, 186-195.
PHILLIPS, J.D. 1992. The end of equilibrium? *Geomorphology* **5**, 195-201.
PHILLIPS, J.D. 1997. Humans as geologic agents and the question of scale. *American Journal of Science* **297**, 98-115.
PRESTON, N.J. 1996. *Spatial and temporal changes in terrain resistance to shallow translational regolith landsliding*. unpublished M.Sc. (Hons) thesis, Victoria University of Wellington. 110 pp.
PRESTON, N.J. 1999. Event-induced changes in landsurface condition - implications for subsequent slope stability. *Zeitschrift für Geomorphologie (Supp.)* **115**, 157-173.
PRESTON, N.J. 2000. Feedback effects of rainfall-triggered shallow landsliding. *In*: BROMHEAD, E., DIXON, N. & IBSEN, M.-L. (Eds.) *Landslides in Research, Theory and Practice*. Thomas Telford, London. 1239-1244.
QUINE, T.A. 1989. Use of a simple model to estimate rates of soil erosion from ^{137}Cs data. *Journal of Water Resources* **8**, 54-81.
QUINE, T.A. 1995. Estimation of erosion rates from ^{137}Cs data: the calibration question. *In*: FOSTER, I.D.L. (Ed.) *Sediment and Water Quality in River Catchments*. Wiley, Chichester. 307-329.
QUINE, T.A., DESMET, P.J.J., GOVERS, G., VANDAELE, K. & WALLING, D.E. 1994. A comparison of the roles of tillage and water erosion in landform development and sediment export on agricultural land near Leuven, Belgium. *In*: OLIVE, L.J., LOUGHRAM, R.J. & KESBY, J.A. (Eds.) *Variability in Stream Erosion and Sediment Transport*. IAHS Publ. **224**, 77-86.
QUINE, T.A., GOVERS, G., WALLING, D.E., ZHANG, X., DESMET, P.J.J., ZHANG, Y. & VANDAELE, K. 1997. Erosion

processes and landform evolution on agricultural land - new perspectives from caesium-137 measurements and topographic-based erosion modelling. *Earth Surface Processes and Landforms* **22**, 799-816.
QUINE, T.A. & WALLING, D.E. 1992. Patterns and rates of contemporary soil erosion derived using caesium-137: measurement, analysis and archaeological significance. *In*: BELL, M. & BOARDMAN, J. (Eds.) *Past and Present Soil Erosion*. Oxbow Monograph **22**, Oxbow Books, Oxford. 185-196.
QUINE, T.A. & WALLING, D.E. 1993. Assessing recent rates of soil loss from areas of arable cultivation in the UK. *In*: WICHEREK, S. (Ed.) *Farm Land Erosion in Temperate Plains Environment and Hills*. Elsevier, Amsterdam. 357-371.
QUINE, T.A., WALLING, D.E. & Govers, G. 1996. Simulation of radiocaesium redistribution on cultivated hillslopes using a mass-balance model: an aid to process interpretation and erosion rate estimation. *In*: ANDERSON, M.G. & BROOKS, S.M. (Eds.) *Advances in Hillslope Processes*. Wiley, Chichester. 561-588.
RECH, M. 1983. Vor- und Frühgeschichte. *In*: KIERAS, P. (Ed.) *Der Rhein-Sieg-Kreis*. Theiss, Stuttgart. 55-77.
REHAGEN, H.-W. 1963. Spät- und nacheiszeitliche Vegetationsbilder aus dem Niederrheingebiet. *Niederrheinische Jahrbuch* **6**, 31-46.
REICHMANN, C. 1988. Vorgeschichte. *Geologie am Niederrhein*. (4th edn.) Geologisches Landesamt Nordrhein-Westfalen, Krefeld. 63-72.
REID, L.M. 1982. The use of flow charts in sediment routing analysis. *In*: SWANSON, F.J., JANDA, R.J., DUNNE, T. & SWANSTON, D.N. (Eds.) *Sediment Budgets and Routing in Forested Drainage Basins*. General Technical Report PNW-141, US Department of Agriculture, Forest Service, Pacific Northwest Forest and Range Experiment Station, Portland. 154-156.
RENWICK, W.H. 1992. Equilibrium, disequilibrium, and nonequilibrium landforms in the landscape. *Geomorphology* **5**, 265-276.
RICHARDS, K. 1999. The magnitude-frequency concept in fluvial geomorphology: a component of a degenerating research programme? *Zeitschrift für Geomorphologie (Supp.)* **115**, 1-18.
RICHTER, G. 1965. Bodenerosion - Schäden und gefährdete Gebiete in der Bundesrepublik Deutschland. *Forschungen zur deutschen Landeskunde* **152**, 592 pp.
RICHTER, G. 1981. Bodenerosion in Mitteleuropa - Landschaften, Faktoren, Forschungsaufgaben. *Mitteilungen der Deutschen Bodenkundlichen Gesellschaft* **30**, 195-212.
RICHTER, G. 1998. Changes in erosion rates present and past - do we fully understand the reasons? *Presentation at Workshop of the ESSC Taskforce on Long-term Effects of Land Use on Soil Erosion in a Historical Perspective, Müncheberg, Germany.*
RICHTER, G. & SPERLING, W. 1967. Anthrpogen bedingte Dellen und Schluchten in der Lößlandschaft. Untersuchungen im nördlichen Odenwald. *Mainzer naturwissenschaftliches Archiv* **5/6**, 136-176.
RITCHIE, J.C. & MCHENRY, J.R. 1990. Application of radioactive fallout cesium-137 for measuring soil erosion and sediment accumulation rates and patterns - a review. *Journal of Environmental Quality* **19**, 215-233.
RITCHIE, J.C., MCHENRY, J.R. & Gill, A.C. 1974a. Fallout caesium-137 in the soils and sediments of three small watersheds. *Ecology* **55**, 887-890.
RITCHIE, J.C., SPABERRY, J.A. & MCHENRY, J.R. 1974b. Estimating soil erosion from the redistribution of fallout ^{137}Cs. *Soil Science Society of America Proceedings* **38**, 137-139.
ROGOWSKI, A.S. & TAMURA, T. 1965. Movement of ^{137}Cs by runoff, erosion and infiltration on the alluvial captina silt loam. *Health Physics* **11**, 1333-1340.
ROGOWSKI, A.S. & TAMURA, T. 1970. Erosional behavior of ^{137}Cs. *Health Physics* **18**, 467-477.
ROHDENBURG, H. 1971. *Einführung in die Klimagenetische Geomorphologie*. Lenz-Verlag, Gießen. 352 pp.
SCHIMMACK, W., AUERSWALD, K. & BUNZL, K. 2001. Can $^{239+240}$Pu replace ^{137}Cs as an erosion tracer in agricultural landscapes contaminated with Chernobyl fallout? *Journal of Environmental Radioactivity* **53**, 41-57.
SCHMIDT, J. 1991. A mathematical model to simulate rainfall erosion. *Catena (Supp.)* **19**, 101-109.
SCHUMM, S.A. 1973. Geomorphic thresholds and complex response of drainage systems. *In*: MORISAWA, M. (Ed.) *Fluvial Geomorphology*. Suny, Binghamton. 299-310.
SCHUMM, S.A. 1979. Geomorphic thresholds: the concept and its applications. *Transactions of the Institute of British Geographers* **4**, 485-515.
SCHUMM, S.A. & LICHTY, R.W. 1965. Time, space, and causality in geomorphology. *American Journal of Science* **263**, 110-119.
SEMMEL, A. 1972. *Geomorphologie der Bundesrepublik Deutschland*. Franz Steiner, Wiesbaden. 149 pp.
SEMMEL, A. 1995. Development of gullies under forest cover in the Taunus and Crystalline Odenwald Mountains, Germany. *Zeitschrift für Geomorphologie (Supp.)* **100**, 115-127.
SEMMEL, A. 1996. The historic-genetic approach in applied geomorphology. *Zeitschrift für Geomorphologie* **40**, 289-303.
SHERRATT, A. 1994a. The transformation of early agrarian Europe: the later Neolithic and Copper Ages 4500-2500 BC. *In*: CUNLIFFE, B. (Ed.) *Prehistoric Europe. An Illustrated History*. Oxford University Press, Oxford. 167-201.
SHERRATT, A. 1994b. The emergence of elites: earlier Bronze Age Europe, 2500-1300 BC. *In*: CUNLIFFE, B. (Ed.) *Prehistoric Europe. An Illustrated History*. Oxford University Press, Oxford. 244-276.
SIAKEU, J. & OGUCHI, T. 2000. Soil erosion analysis and modelling: a review. *Transactions of the Japanese*

Geomorphological Union **21**, 413-429.
SIDLE, R.C. 1985. *Hillslope Stability and Land Use*. AGU Water Resources Monograph. 140 pp.
SIEGBURG, W. 1987. Talasymmetrien in der Umgebung von Bonn. *Decheniana* **140**, 204-217.
SIEGBURG, W. 1988. Periglaziale Täler und andere eiszeitliche Formen im Bonner Raum. *Arbeiten zur Rheinischen Landeskunde* **58**, 181-193.
SKOWRONEK, A., GRUNERT, J. & BOTSCHEK, J. 1994. Bodenerosionsforschung und Entwicklung von Bodenerhaltungsmassnahmen an der Universität Bonn. *In*: SCHMIDT, R.G. (Ed.) *Bodenerosion und Bodenschutz*. Forschungsstelle Bodenerosion **12**. 31-45.
SLAYMAKER, O. 1991. Mountain geomorphology: a theoretical framework for measurement programmes. *Catena* **18**, 427-437.
STOKES, S. 1999. Luminescence dating applications in geomorphological research. *Geomorphology* **29**, 153-171.
STOLZ, W. 1996. *Radioaktivität. Grundlagen, Messung, Anwendungen*. (3rd edn.) Teubner, Leipzig. 212 pp.
STRAHLER, A.N. 1958. Dimensional analysis applied to fluvially eroded landforms. *Bulletin of the Geological Society of America* **69**, 279-300.
STUIVER, M. & REIMER, P.J. 1993. Radiocarbon calibration program REV 3.0.3. *Radiocarbon* **35**, 215-230.
SUTHERLAND, R.A. 1998. The potential for reference site resampling in estimating sediment redistribution and assessing landscape stability by the caesium-137 method. *Hydrological Processes* **12**, 995-1007.
SUTHERLAND, R.A. & DEJONG, E. 1990. Quantification of soil redistribution in cultivated fields using caesium-137, Outlook, Saskatchewan. *Catena (Supp.)* **17**, 177-193.
SWANSON, F.J., FREDRIKSEN, R.L. & MCCORISON, F.M. 1982. Material transfer in a western Oregon forested watershed. *In*: EDMONDS, R.L. (Ed.) *Analysis of Coniferous Forest Ecosystems in the Western United States*. Hutchison Ross, Stroudsburg, Pennsylvania. 233-266.
TACKENBERG, K. 1954. *Fundkarten zur Vorgeschichte der Rheinprovinz*. Bonner Jahrbucher **2**. Rudolf Habelt, Bonn. 107 pp.
THOMAS, M.F. 2001. Landscape sensitivity in time and space - an introduction. *Catena* **42**, 83-98.
THORN, C.E. & WELFORD, M.R. 1994. The equilibrium concept in geomorphology. *Annals of the Association of American Geographers* **84**, 666-696.
TODD, M. 1994. Barbarian Europe, AD 300-700. *In*: CUNLIFFE, B. (Ed.) *Prehistoric Europe. An Illustrated History*. Oxford University Press, Oxford. 447-482.
TRIMBLE, S.W. 1993. The distributed sediment budget model and watershed management in the Paleozoic Plateau of the upper midwestern United States. *Physical Geography* **14**, 285-303.
TRIMBLE, S.W. 1999. Decreased rates of alluvial sediment storage in the Coon Creek basin, Wisconsin, 1975-93. *Science* **285**, 1244-1246.
TRUSTRUM, N.A. & PAGE, M.J. 1992. The long-term erosion history of Lake Tutira watershed: implications for sustainable land use management. *In*: HENRIQUES, P.R. (Ed.) *The Proceedings of the International Conference on Sustainable Land Management, Napier, Hawke's Bay, New Zealand, 17-23 November, 1991*. 212-215.
UNSCEAR 1982. *Ionizing Radiation: Sources and Biological Effects*. Report to the General Assembly, United Nations, New York United Nations Scientific Committee on the Effects of Atomic Radiation.
VANDEN BERGHE, I. & GULINCK, H. 1987. Fallout 137-Cs as a tracer for soil mobility in the landscape framework of the Belgian loamy region. *Pedologie* **37(1)**, 5-20.
VAN OOST, K., GOVERS, G. & DESMET, P. 2000. Evaluating the effects of changes in landscape structure on soil erosion by water and tillage. *Landscape Ecology* **15**, 577-589.
VAN ROMPAEY, A.J.J., GOVERS, G. & PUTTERMANS, C. in press. Modelling land use changes and their impact on soil erosion and sediment supply to rivers. *Earth Surface Processes and Landforms*.
VAN VLIET-LANOE, B., HELLUIN, M., PELLERIN, J. & VALADAS, B. 1992. Soil erosion in western Europe: from the last interglacial to the present. *In*: BELL, M. & BOARDMAN, J. (Eds.) *Past and Present Soil Erosion*. Oxbow Monograph **22**, Oxbow Books, Oxford. 101-114.
VIETEN, K. 1983. Tertiary volcanism in the Siebengebirge mountains. *In*: FUCHS, K., VON GEHLEN, K., MÄLZER, H., MURAWSKI, H. & SEMMEL, A. (Eds.) *Plateau Uplift. The Rhenish Shield - A Case History*. Springer, Berlin. 131-132.
VIETEN, K., HAMM, H.-M., GRIMMEISEN, W. & MEYER, W. 1988. Tertiärer Vulkanismus des Siebengebirges. *Fortschritte die Mineralogie* **66(2)**, 1-42.
VON PETRIKOVITS, H. 1978. *Altertum und Mittelalter*. Rheinische Geschichte **1**. Düsseldorf. 369 pp.
VON WERNER, M. 1995. *GIS-orientierte Methoden der digitalen Reliefanalys zur Modellierung von Bodenerosion in kleinen EInzugsgebieten*. unpublished PhD thesis, Freie Universität Berlin.
WALLBRINK, P.J., MURRAY, A.S. & OLLEY, J.M. 1998. Determining sources and transit times of suspended sediment in the Murrumbidgee River, New South Wales, Australia, using fallout ^{137}Cs and ^{210}Pb. *Water Resources Research* **34**, 879-887.
WALLING, D.E. 1983. The sediment delivery problem. *Journal of Hydrology* **65**, 209-237.
WALLING, D.E. 1999. Linking land use, erosion and sediment yields in river basins. *Hydrobiologia* **410**, 223-240.
WALLING, D.E., BRADLEY, S.B. & WILKINSON, C.J. 1986. A caesium-137 budget approach to the investigation of sediment delivery from a small agricultural drainage basin in Devon, UK. *In*: HADLEY, R.F. (Ed.) *Drainage*

Basin Sediment Delivery. IAHS Publ. **159**, 423-435.

WALLING, D.E., GOLOSOV, V.N., PANIN, A.V. & He, Q. 2000. Use of radiocaesium to investigate erosion and sedimentation in areas with high levels of Chernobyl fallout. *In*: FOSTER, I.D.L. (Ed.) *Tracers in Geomorphology*. Wiley, Chichester. 183-200.

WALLING, D.E. & HE, Q. 1992. Interpretation of ^{137}Cs profiles in lacustrine and other sediments: the role of catchment derived inputs. *Hydrobiologia* **235/236**, 219-230.

WALLING, D.E. & HE, Q. 1997. *Models for converting ^{137}Cs measurements to estimates of soil redistribution rates on cultivated and uncultivated soils. Report to the International Atomic Energy Agency.* University of Exeter, U.K., 30 pp.

WALLING, D.E. & HE, Q. 1998. Use of fallout ^{137}Cs measurements for validating and calibrating soil erosion and sediment delivery models. *In*: SUMMER, W., KLAGHOFER, E. & ZHANG, W. (Eds.) *Modelling Soil Erosion, Sediment Transport and Closely Related Hydrological Processes*. IAHS Publ. **249**, 267-278.

WALLING, D.E. & HE, Q. 1999a. Changing rates of overbank sedimentation on the floodplains of British rivers during the past 100 years. *In*: BROWN, A.G. & QUINE, T.A. (Eds.) *Fluvial Processes and Environmental Change*. Wiley, Chichester. 207-222.

WALLING, D.E. & HE, Q. 1999b. Improved models for estimating soil erosion rates from ^{137}Cs measurements. *Journal of Environmental Quality* **28**, 611-622.

WALLING, D.E. & QUINE, T.A. 1990a. Use of caesium-137 measurements to investigate patterns and rates of soil erosion on arable fields. *In*: BOARDMAN, J., FOSTER, I.D.L. & DEARING, J.A. (Eds.) *Soil Erosion on Agricultural Land*. Wiley, Chichester. 33-53.

WALLING, D.E. & QUINE, T.A. 1990b. Calibration of caesium-137 measurements to provide quantitative erosion rate data. *Land Degradation & Rehabilitation* **2**, 161-175.

WALLING, D.E. & QUINE, T.A. 1991a. Recent rates of soil loss from areas of arable cultivation in the UK. *In*: PETERS, N.E. & WALLING, D.E. (Eds.) *Sediment and Stream Water Quality in a Changing Environment: Trends and Explanation*. IAHS Publ. **203**, 123-131.

WALLING, D.E. & QUINE, T.A. 1991b. Use of ^{137}Cs measurements to investigate soil erosion on arable fields in the UK: potential applications and limitations. *Journal of Soil Science* **42**, 147-165.

WALLING, D.E. & QUINE, T.A. 1992. The use of caesium-137 measurements in soil erosion surveys. *In*: BOGEN, J., WALLING, D.E. & DAY, T.J. (Eds.) *Erosion and Sediment Transport Monitoring Programmes in River Basins*. IAHS Publ. **210**, 143-152.

WALLING, D.E. & WOODWARD, J.C. 1992. Use of radiometric fingerprints to derive information on suspended sediment sources. *In*: BOGEN, J., WALLING, D.E. & DAY, T.J. (Eds.) *Erosion and Sediment Transport Monitoring Programmes in River Basins*. IAHS Publ. **210**, 153-164.

WANDEL, G. & MÜCKENHAUSEN, E. 1950. Neue vergleichende Untersuchungen über den Bodenabtrag an bewaldeten und unbewaldeten Hangflächen in Nordrheinland. *Geologisches Jahrbuch* **65**, 507-550.

WASSON, R.J. 1994. Living with the past: uses of history for understanding landscape change and degradation. *Land Degradation & Rehabilitation* **5**, 79-87.

WASSON, R.J. 1996. *Land Use and Climate Impacts on Fluvial Systems during the Period of Agriculture - Research Project and Implementation*. PAGES Workshop Report Series **96-2**. 51 pp.

WEIKINN, C. 1958. *Quellentexte zur Witterungsgeschichte Mitteleuropas von der Zeitwende bis zum 1850 - Hydrographie, Zeitwende bis 1500*. Akademie Verlag, Berlin. 531 pp.

WELP, G., ERLENKEUSER, H. & BRÜMMER, G.W. 1999. Bodennutzung und Bodenerosion seit dem Mittelalter am Beispiel einer lößbedeckten Mittelgebirgslandschaft des Bonner Raumes. *Mitteilungen der Deutschen Bodenkundlichen Gesellschaft* **91**, 1367-1370.

WHITTLE, A. 1994. The first farmers. *In*: CUNLIFFE, B. (Ed.) *Prehistoric Europe. An Illustrated History*. Oxford University Press, Oxford. 136-166.

WILMSHURST, J.M. 1997. The impact of human settlement on vegetation and soil stability in Hawke's Bay, New Zealand. *New Zealand Journal of Botany* **35**, 97-111.

WISCHMEIER, W.H. & SMITH, D.D. 1978. *Predicting Rainfall Erosion Losses - a Guide to Conservation Planning*. USDA Agricultural Research Service Handbook **537**. US Government Printing Office, Washington D.C.

WOLMAN, M.G. & GERSON, R. 1978. Relative scales of time and effectiveness of climate in watershed geomorphology. *Earth Surface Processes* **3**, 189-208.

WOLMAN, M.G. & MILLER, P. 1960. Magnitude and frequency of forces in geomorphic processes. *Journal of Geology* **68**, 54-74.

ZOLITSCHKA, B. 1998. A 14,000 year sediment yield record from western Germany based on annually laminated lake sediments. *Geomorphology* **22**, 1-17.

ZOLITSCHKA, B. & NEGENDANK, J.F.W. 1997. Quantitative Erfassung natürlicher und anthropogener Bodenerosion in einem Einzugsgebiet der Eifel. *Trierer Geographische Studien* **16**, 61-78.

Appendix A

Soil Properties – Auf dem Scheid

Key: Soil Texture: (*Italicised values* indicate >5% error associated with sedimentation analysis.)

Ut2	*schwach toniger Schluff*	weak clayey loam
Ut3	*mittel toniger Schluff*	middle clayey loam
Ut4	*stark toniger Schluff*	strong clayey loam
Lu	*schluffiger Lehm*	silty loam
Uls	*sandig-lehmiger Schluff*	sandy-loamy silt
Slu	*schluffig-lehmiger Sand*	silty-loamy sand
Tu4	*stark schluffiger Ton*	strong silty clay

Key: Humus %:

0%	humus free
<1%	very weakly humic
1-2%	weakly humic
2-4%	moderately humic
4-8%	strongly humic
8-15%	very strongly humic

Key: $CaCO_3$ %:

0%	carbonate free
<0.5%	very weak carbonates
0.5-2%	weak carbonates
2-10%	contains carbonate

Core	**Depth**			**Soil Texture**			**Humus %**	**$CaCO_3$ %**
		% >2mm	**Sand**	**Silt**	**Clay**			
AdS1	0-11		13.53	65.90	20.57	**Ut4**	7.061	0.712
	22-34		15.53	67.91	16.56	**Ut3**	0.945	0.068
	39-51		18.86	63.78	17.37	**Lu**	0.858	0.410
	56-65		10.19	72.29	17.51	**Ut4**	0.841	0.660
	74-83		8.50	72.06	19.44	**Ut4**	0.610	0.402
	93-100	4.86	*13.37*	*74.76*	*11.87*	***Ut2***	0.270	0.459
	103-109		22.43	62.01	15.55	**Uls**	0.355	3.921
	122-138		6.81	72.19	21.00	**Ut4**	0.462	0.306
	138-146		11.01	73.69	15.30	**Ut3**	0.326	0
	195-200		*4.24*	*76.25*	*19.51*	***Ut4***	1.411	3.293
	216-220		10.33	72.15	17.52	**Ut4**	1.444	0.413
	221-224		5.77	70.54	23.69	**Ut4**	2.661	
	227-231		12.63	69.83	17.55	**Ut4**	0.929	0
	238-241	1.76	8.03	71.48	20.49	**Ut4**	2.214	2.889
	255-260		7.24	71.06	21.69	**Ut4**	1.145	0
	268-274		16.11	69.99	13.90	**Ut3**	0.467	0
	277-283	2.41	4.15	79.86	15.99	**Ut3**	0.976	2.122
	286-292		*9.42*	*76.51*	*14.07*	***Ut3***	0.666	0
	292-300		6.29	80.71	13.00	**Ut3**	0.458	2.837
	300-319		12.26	74.49	13.25	**Ut3**	0.806	0.566
	349-353		*15.82*	*69.35*	*14.83*	***Ut3***	0.845	0.707
	383-386		*16.60*	*61.52*	*21.88*	***Lu***	4.115	
	387-391		18.48	68.04	13.47	**Ut3**	0.611	0.403
	400-414		10.53	72.28	17.19	**Ut4**	2.362	1.893
	417-429	7.98	28.63	61.18	10.19	**Uls**	0.868	0.859
	435-440		14.07	72.53	13.40	**Ut3**	0.580	0.916
	443-448		10.15	75.12	14.73	**Ut3**	0.575	0
	470-476		*16.46*	*61.83*	*21.71*	***Lu***	2.356	0
	477-483		17.48	62.28	20.24	**Lu**	0.884	0
	484-487	17.92	40.67	46.55	12.78	**Slu**	0.377	0
	487-495		8.90	75.67	15.44	**Ut3**	1.436	0.504
	495-500		19.47	66.70	13.83	**Ut3**	0.637	0.463
	502-510		8.00	74.21	17.79	**Ut4**	1.118	0.914
	512-523	13.34	7.50	65.87	26.64	**Tu4**	1.796	1.883
	525-530	10.99	23.79	60.63	15.58	**Uls**	1.199	
	535-546	1.81	25.22	60.58	14.20	**Uls**	0.685	0.517
	548-554		12.94	67.99	19.08	**Ut4**	1.938	0.720
	557-561		22.04	67.89	10.07	**Ut2**	0.634	0.255
	562-566		11.63	75.87	12.49	**Ut3**	1.268	0.507
	566-570		17.92	71.98	10.10	**Ut2**	0.662	0.508
	570-573		10.69	71.82	17.49	**Ut4**	1.370	1.086
	579-581		12.96	69.11	17.93	**Ut4**	1.550	
	582-586		10.90	77.37	11.73	**Ut2**	1.546	0.407
	587-592		15.24	67.94	16.82	**Ut3**	0.989	0.155
	594-598		4.83	77.21	17.95	**Ut4**	2.102	0
	598-600		*11.49*	*73.96*	*14.55*	***Ut3***	0.733	0

Core	Depth		Soil Texture				Humus %	$CaCO_3$ %
		% >2mm	Sand	Silt	Clay			
AdS2	0-23	2.84	*11.07*	*68.73*	*20.20*	***Ut4***	5.445	0.154
	23-35	1.63	10.73	69.41	19.85	**Ut4**	1.293	1.031
	35-72	6.43	13.15	66.72	20.13	**Ut4**	0.928	0.829
	72-89	3.36	10.08	69.22	20.70	**Ut4**	0.681	0.518
	89-100							
	100-108		12.98	67.42	19.60	**Ut4**	0.720	0
	107-116	1.74	13.14	66.73	20.13	**Ut4**	0.535	0
	131-141		10.68	71.08	18.24	**Ut4**	0.408	0
	146-153		10.37	70.09	19.54	**Ut4**	0.393	0
	154-161		9.93	70.60	19.47	**Ut4**	0.397	0
	168-174	8.44	17.07	64.79	18.13	**Lu**	0.410	0
	176-184		10.48	70.56	18.96	**Ut4**	0.410	0
	197-200	5.28					1.130	
AdS 3	5-15	1.6178	11.10	73.25	15.66	**Ut3**	4.520	
	26-40	0.3272	*8.19*	*70.80*	*21.01*	***Ut4***	1.350	
	49-62	0.36	*9.54*	*69.80*	*20.66*	***Ut4***	0.467	
	74-86		10.02	74.05	15.93	**Ut3**	0.330	
	95-100		8.89	74.03	17.09	**Ut4**	0.393	
	121-135		7.75	73.14	19.12	**Ut4**	0.348	
	149-163	0.1008	8.28	70.79	20.93	**Ut4**	0.362	
	196-200		5.79	70.84	23.37	**Ut4**	0.194	
	208-215		6.77	71.79	21.43	**Ut4**	0.170	
	221-227		*6.77*	*74.70*	*18.53*	***Ut4***	0.151	
	234-240		9.12	77.54	13.33	**Ut3**	0.087	
	370-380	0.8047					0.221	
	389-400	17.395					0.139	
AdS 4	7-15	0.189	9.39	71.31	19.30	**Ut4**	6.192	
	24-47	2.0607	8.19	73.87	17.94	**Ut4**	1.390	
	53-63	0.7785	7.75	73.97	18.28	**Ut4**	0.858	
	68-82	0.5594	7.53	75.94	16.53	**Ut3**	0.659	
	84-97	0.5974	9.57	74.26	16.17	**Ut3**	0.541	
	97-100							
	107-118		7.36	73.26	19.38	**Ut4**	0.582	
	130-142		6.71	73.15	20.13	**Ut4**	0.473	
	160-171		7.46	73.13	19.42	**Ut4**	0.446	
	196-200		5.66	72.80	21.54	**Ut4**		
AdS 5	33-47							
	60-73						0.499	
	80-93						0.249	
	114-129						0.161	
AdS 6	42-56	2.06954					0.625	
	120-141						0.203	
	161-171						0.167	
	220-233						0.152	
AdS 8	22-34	0.68966	9.58	70.07	20.35	**Ut4**	0.920	
	49-61		8.16	70.87	20.98	**Ut4**	0.448	
	75-87	0.36675	*9.99*	*65.61*	*24.40*	***Ut4***	0.475	
	90-100		5.93	72.63	21.45	**Ut4**	0.472	
	103-116		6.67	70.64	22.70	**Ut4**	0.398	
	116-127		8.49	70.28	21.23	**Ut4**	0.384	
	136-149		6.79	71.64	21.58	**Ut4**	0.217	
	152-165		5.74	67.76	26.50	**Tu4**	0.152	
	177-197		*7.30*	*67.92*	*24.78*	***Ut4***	0.107	
	218-231		*10.50*	*66.31*	*23.19*	***Ut4***	0.083	
	248-261	0.09107	7.08	74.13	18.78	**Ut4**	0.090	
	269-282		*7.54*	*72.55*	*19.91*	***Ut4***	0.077	
	282-292		8.22	73.58	18.20	**Ut4**	0.097	
AdS 9	8-20						3.167	
	32-44						2.534	
	56-68		7.05	73.04	19.91	**Ut4**	1.098	
	71-83		7.47	72.45	20.07	**Ut4**	0.917	
	110-115						0.681	
	130-134						0.666	
	140-150		8.27	71.28	20.45	**Ut4**	0.694	
	153-163		6.92	72.72	20.36	**Ut4**	0.764	
	175-185		7.30	70.90	21.80	**Ut4**	0.581	

Core	Depth	% >2mm	Soil Texture Sand	Silt	Clay		Humus %	$CaCO_3$ %
AdS 10	14-28						3.201	
	37-48						1.271	
	78-89		5.80	71.82	22.39	**Ut4**	0.990	
	111-123		7.60	71.28	21.12	**Ut4**	0.889	
	154-167		9.74	69.18	21.08	**Ut4**	1.146	
	178-191		10.56	67.48	21.96	**Ut4**	1.014	
AdS 11	6-17						3.737	
	23-34						3.890	
	46-57		8.75	70.09	21.16	**Ut4**	2.937	
	75-86		9.26	72.77	17.97	**Ut4**	1.837	
	106-113		7.28	75.17	17.55	**Ut4**	1.241	
	123-131		7.76	74.67	17.57	**Ut4**	1.299	
	138-147		7.54	73.77	18.69	**Ut4**	0.964	
	155-165		6.93	74.82	18.25	**Ut4**	1.222	
	185-195		8.70	69.26	22.04	**Ut4**	0.782	
	205-215		8.34	67.14	24.52	**Ut4**	0.995	
	235-245		7.35	67.07	25.58	**Ut4**	0.434	
	270-280		5.29	72.04	22.67	**Ut4**	0.334	
	305-315		5.31	69.90	24.80	**Ut4**	0.424	
	340-350		7.29	72.03	20.68	**Ut4**	0.375	
	363-368		11.12	65.84	23.05	**Ut4**	0.417	
	382-392		*7.49*	*72.78*	*19.72*	***Ut4***	0.426	
	422-427		6.33	76.67	17.00	**Ut4**	0.406	
	432-437		5.24	78.00	16.76	**Ut3**	0.397	
	442-446		6.41	77.12	16.47	**Ut3**	0.459	
AdS 12	9-22						6.178	
	24-33						3.444	
	47-64						2.619	
	64-81						1.563	
	81-100						1.101	
	101-119						0.944	
	133-145						0.576	
	145-158						0.866	
	158-174						0.884	
	186-200						0.613	
	200-220						0.753	
	229-239						0.668	
	239-259						0.536	
	259-275						0.620	
	285-300						0.523	
	300-318		7.04	73.37	19.60	**Ut4**	0.757	
	328-343		10.01	66.42	23.57	**Ut4**	0.564	
	343-360		9.27	69.18	21.55	**Ut4**	0.530	
	360-379		8.11	69.03	22.86	**Ut4**	0.555	
	389-400		8.54	69.65	21.81	**Ut4**	0.628	
	400-416		8.09	71.19	20.72	**Ut4**	1.021	
	425-440		7.81	72.18	20.01	**Ut4**	1.059	
	440-460		6.12	77.26	16.62	**Ut3**	0.762	
	460-476		6.78	76.61	16.61	**Ut3**	0.808	
	486-500		7.24	77.26	15.50	**Ut3**	0.943	
AdS 13	0-12						5.409	
	12-33						2.327	
	45-73						1.793	
	73-95						0.950	
	95-100						1.385	
	100-109						1.984	
	109-123						0.768	
	133-155						1.269	
	155-178						1.018	
	187-200						0.853	
	200-224		6.88	69.15	23.97	**Ut4**	1.047	
	224-251		6.09	72.62	21.29	**Ut4**	1.035	
	262-280		7.13	73.17	19.70	**Ut4**	0.906	
	280-300						1.393	
	300-324		9.41	70.91	19.68	**Ut4**	1.037	
	324-345		10.13	72.09	17.78	**Ut4**	1.173	

Core	Depth	% >2mm	Soil Texture Sand	Silt	Clay		Humus %	$CaCO_3$ %
AdS 14	0-17						8.646	
	17-49						2.778	
	49-61						2.168	
	76-96						1.425	
	96-100							
	100-105		8.34	71.64	20.02	**Ut4**	1.221	
	105-127		9.16	73.72	17.12	**Ut4**	1.069	
	137-157		7.52	75.38	17.11	**Ut4**	0.753	
	157-163		6.77	74.30	18.93	**Ut4**	0.579	
	174-200		10.39	70.21	19.40	**Ut4**	0.555	
	200-206						0.967	
	206-229						0.586	
	240-244						0.773	
	244-263						0.526	
	273-300						0.515	
	300-312						0.624	
	312-323						0.592	
	323-334						0.507	
	343-351						0.556	
	351-355						0.492	
	355-372						0.477	
	377-385						0.540	
	389-400						0.472	
	400-417						0.535	
	431-437						0.529	
	437-444						0.498	
	444-454						0.493	
	454-479						0.434	
	479-494						0.447	

Sample Point Locations:

Longitude and latitude are given in Gauß-Krüger co-ordinates. Elevations are m above sea level. Three dimensional co-ordinates were measured using a high resolution electronic theodolite, referenced to two mapped (DGK 1:5,000) survey points within the Auf dem Scheid catchment.

Sample Point	Longitude	Latitude	Elevation
Auf dem Scheid 1	$^{25}85338$	$^{56}20256$	156.85
Auf dem Scheid 2	$^{25}85373$	$^{56}20201$	160.18
Auf dem Scheid 3	$^{25}85369$	$^{56}20240$	158.78
Auf dem Scheid 4	$^{25}85356$	$^{56}20270$	156.80
Auf dem Scheid 5	$^{25}85353$	$^{56}20203$	159.35
Auf dem Scheid 6	$^{25}85328$	$^{56}20211$	158.86
Auf dem Scheid 7	$^{25}85316$	$^{56}20239$	157.81
Auf dem Scheid 8	$^{25}85371$	$^{56}20263$	158.67
Auf dem Scheid 9	$^{25}85499$	$^{56}20053$	182.31
Auf dem Scheid 10	$^{25}85481$	$^{56}20078$	179.43
Auf dem Scheid 11	$^{25}85457$	$^{56}20108$	175.54
Auf dem Scheid 12	$^{25}85433$	$^{56}20132$	171.64
Auf dem Scheid 13	$^{25}85414$	$^{56}20152$	167.91
Auf dem Scheid 14	$^{25}85396$	$^{56}20174$	163.89
Soil Auger 1 (AdSP1)	$^{25}85318$	$^{56}20260$	157.42
Soil Auger 2 (AdSP2)	$^{25}85314$	$^{56}20223$	158.58
Soil Auger 3 (AdSP3)	$^{25}85327$	$^{56}20206$	159.32

Appendix B

^{137}Cs Data

The first two columns represent the sample point number and the date on which activities were measured at the Max-Planck-Institut in Heidelberg. Their raw data – corrected for radioactive decay to 1st January 2000 – are listed in the following four columns. These were converted to values appropriate to 1st January 1999, and inventories of ^{137}Cs activity (Bq/m^2) calculated using these corrected values. The final three columns list modelled rates of erosion or deposition (t/ha/a). For points within the arable zone, in addition to net values, the relative contributions of tillage translocation and water erosion are also listed. The geographic co-ordinates of each sample point are tabulated separately.

		Raw Data from Max-Planck-Institut (corrected for radioactive decay to 1st January 2000)				Corrected for radioactive decay to 1st January 1999			Sediment Redistribution Rates		
		Concentration ppm	Error ppm	%	Activity Bq/kg	Concentration ppm	Activity Bq/kg	Inventory Bq/m^2	Tillage t/ha/a	Water t/ha/a	Net t/ha/a
1	24/08/9	2.556E-09	1.115E-10	4.36	8.218E+0	2.603E-09	8.369E+0	**5519.038**			-0.03
2	03/02/9	2.256E-09	9.822E-11	4.35	7.252E+0	2.268E-09	7.291E+0	**5063.493**			-1.01
3	01/02/9	3.025E-09	1.294E-10	4.28	9.726E+0	3.041E-09	9.777E+0	**6062.027**			1.19
4	19/04/9	2.830E-09	1.221E-10	4.32	9.099E+0	2.859E-09	9.192E+0	**6392.928**			1.93
5	31/03/9	2.593E-09	1.121E-10	4.32	8.338E+0	2.617E-09	8.413E+0	**5489.328**			-0.09
6	27/04/9	2.729E-09	1.174E-10	4.30	8.773E+0	2.758E-09	8.866E+0	**5785.273**			0.57
7	12/08/9	2.995E-09	1.277E-10	4.26	9.630E+0	3.048E-09	9.798E+0	**6741.349**			2.71
8	30/06/9	4.081E-09	1.724E-10	4.22	1.312E+0	4.142E-09	1.332E+0	**9160.961**			8.12
9	08/09/9	4.010E-09	1.702E-10	4.24	1.289E+0	4.088E-09	1.314E+0	**9041.246**			7.85
10	16/06/9	2.692E-09	1.163E-10	4.32	8.654E+0	2.729E-09	8.774E+0	**6036.444**			1.13
11	08/07/9	3.297E-09	1.407E-10	4.27	1.060E+0	3.347E-09	1.076E+0	**7403.725**			4.19
12	02/02/9	2.157E-09	9.493E-11	4.40	6.936E+0	2.169E-09	6.973E+0	**4598.895**			-2.04
13	04/08/9	3.895E-09	1.651E-10	4.24	1.252E+0	3.962E-09	1.274E+0	**8762.740**			7.23
14	26/04/9	2.709E-09	1.168E-10	4.31	8.711E+0	2.738E-09	8.803E+0	**6056.606**			1.18
15	08/02/9	2.622E-09	1.134E-10	4.32	8.430E+0	2.637E-09	8.478E+0	**5833.026**			0.68
16	26/08/9	3.344E-09	1.430E-10	4.28	1.075E+0	3.406E-09	1.095E+0	**7533.009**			4.48
17	05/07/9	2.739E-09	1.189E-10	4.34	8.805E+0	2.780E-09	8.938E+0	**6149.260**			1.38
18	28/01/9	3.365E-09	1.442E-10	4.29	1.082E+0	3.383E-09	1.087E+0	**7481.887**			4.36
19	07/07/9	2.464E-09	1.073E-10	4.36	7.922E+0	2.502E-09	8.042E+0	**5533.120**			0.01
20	06/04/9	5.116E-09	2.150E-10	4.20	1.645E+0	5.164E-09	1.660E+0	**11422.735**			13.18
21	20/08/9	2.533E-09	1.063E-10	4.20	8.144E+0	2.579E-09	8.291E+0	**5704.115**			0.39
22	04/02/9	1.617E-09	7.358E-11	4.55	5.200E+0	1.626E-09	5.228E+0	**3596.860**			-4.38
23	01/07/9	2.218E-09	9.822E-11	4.43	7.129E+0	2.250E-09	7.235E+0	**5129.857**			-0.87
24	06/07/9	2.416E-09	1.063E-10	4.40	7.767E+0	2.453E-09	7.885E+0	**5590.677**			0.13
25	28/07/9	1.409E-09	6.422E-11	4.56	4.530E+0	1.432E-09	4.605E+0	**3264.713**			-5.19
26	07/04/9	3.147E-09	1.348E-10	4.28	1.012E+0	3.177E-09	1.021E+0	**7026.562**			3.35
27	25/08/9	4.934E-09	1.984E-10	4.02	1.586E+0	5.025E-09	1.615E+0	**11113.965**			12.49
28	23/09/9	2.914E-09	1.249E-10	4.28	9.370E+0	2.973E-09	9.560E+0	**6237.600**			1.58
29	05/08/9	2.583E-09	1.118E-10	4.33	8.304E+0	2.627E-09	8.446E+0	**5511.021**			-0.05
30	13/09/9	2.223E-09	9.853E-11	4.43	7.148E+0	2.267E-09	7.288E+0	**5014.214**			-1.12
31	31/08/9	2.088E-09	9.380E-11	4.49	6.712E+0	2.127E-09	6.838E+0	**4847.805**			-1.49
32	30/08/9	3.625E-09	1.549E-10	4.27	1.165E+0	3.693E-09	1.187E+0	**8168.026**			5.90
33	23/08/9	1.906E-09	8.482E-11	4.45	6.129E+0	1.941E-09	6.241E+0	**4293.592**			-2.74
34	27/09/9	3.829E-09	1.643E-10	4.29	1.231E+0	3.907E-09	1.256E+0	**4917.959**			-1.33
35	22/11/9	1.813E-09	8.333E-11	4.60	5.831E+0	1.857E-09	5.971E+0	**4660.534**	-0.13	-13.33	-13.46
36	01/12/9	2.389E-09	1.034E-10	4.33	7.680E+0	2.448E-09	7.870E+0	**6142.301**	0.06	9.87	9.93
37	23/11/9	1.735E-09	7.747E-11	4.47	5.577E+0	1.777E-09	5.712E+0	**4458.276**	.	-17.09	-17.09
38	09/09/9	2.103E-09	9.356E-11	4.45	6.761E+0	2.144E-09	6.892E+0	**5379.283**	-0.14	-15.63	-15.77
39	10/08/9	1.477E-09	6.482E-11	4.39	4.750E+0	1.503E-09	4.832E+0	**3771.670**	-0.29	-31.06	-31.35
40	15/09/9	2.115E-09	9.365E-11	4.43	6.801E+0	2.157E-09	6.935E+0	**5412.683**		-1.64	-1.64
41	24/11/9	1.977E-09	8.245E-11	4.17	6.355E+0	2.025E-09	6.509E+0	**5096.772**	-0.26	-6.12	-6.38
42	14/09/9	2.418E-09	1.049E-10	4.34	7.774E+0	2.466E-09	7.927E+0	**6206.802**	-0.23	10.79	10.56
43	22/09/9	2.150E-09	9.356E-11	4.35	6.914E+0	2.194E-09	7.053E+0	**5522.741**	-0.19	0.01	-0.18
44	14/02/0	2.366E-09	1.041E-10	4.40	7.606E+0	2.433E-09	7.823E+0	**6125.792**		9.75	9.75
45	15/02/0	1.761E-09	7.940E-11	4.51	5.663E+0	1.812E-09	5.826E+0	**4561.504**	-0.43	-14.93	-15.36
46	16/02/0	2.012E-09	8.890E-11	4.42	6.469E+0	2.070E-09	6.655E+0	**4412.317**	-0.25	-17.59	-17.84
47	17/02/0	1.675E-09	7.526E-11	4.49	5.384E+0	1.723E-09	5.539E+0	**4323.563**		-19.73	-19.73
48	17/04/0	1.441E-09	6.731E-11	4.67	4.632E+0	1.488E-09	4.783E+0	**3733.228**	-0.51	-31.75	-32.26
49	03/02/0	1.622E-09	7.247E-11	4.47	5.215E+0	1.667E-09	5.360E+0	**3553.823**		-36.81	-36.81
50	31/01/0	1.717E-09	7.852E-11	4.57	5.522E+0	1.765E-09	5.675E+0	**4443.203**	-0.17	-17.19	-17.36
51	01/02/0	1.764E-09	8.082E-11	4.58	5.672E+0	1.813E-09	5.829E+0	**4564.292**	-0.38	-14.85	-15.23
52	08/02/0	1.529E-09	7.028E-11	4.60	4.916E+0	1.572E-09	5.055E+0	**3957.727**	-0.08	-27.20	-27.28

53	02/02/0	1.619E-09	7.470E-11	4.62	5.204E+0	1.664E-09	5.349E+0	**4075.917**	-0.41	-24.21	-24.62
54	23/03/0	1.755E-09	7.951E-11	4.53	5.642E+0	1.809E-09	5.817E+0	**4432.812**	-0.31	-17.31	-17.62
55	02/03/9	1.565E-09	7.395E-11	4.73	5.032E+0	1.576E-09	5.067E+0	**3749.846**	0.05	-31.89	-31.84
56	01/03/9	1.766E-09	7.863E-11	4.45	5.678E+0	1.779E-09	5.718E+0	**4434.286**	-0.16	-17.25	-17.41
57	20/05/9	1.915E-09	8.554E-11	4.47	6.157E+0	1.939E-09	6.232E+0	**4833.178**	-0.35	-10.10	-10.45
58	15/06/9	1.806E-09	8.075E-11	4.47	5.805E+0	1.831E-09	5.885E+0	**4564.159**	-1.86	-13.58	-15.44
59	17/06/9	1.965E-09	8.762E-11	4.46	6.317E+0	1.992E-09	6.405E+0	**4966.964**	2.51	-10.51	-8.00
60	18/03/9	2.434E-09	1.072E-10	4.41	7.826E+0	2.454E-09	7.890E+0	**5617.617**	-2.51	4.80	2.29
61	18/02/9	2.602E-09	1.128E-10	4.34	8.365E+0	2.619E-09	8.419E+0	**5993.989**	0.08	8.38	8.46
62	17/02/9	3.189E-09	1.365E-10	4.28	1.025E+0	3.210E-09	1.032E+0	**8260.279**	-0.50	47.10	46.60
63	29/06/9	2.396E-09	1.044E-10	4.36	7.705E+0	2.432E-09	7.818E+0	**5785.270**	-0.83	5.75	4.92
64	11/03/9	2.534E-09	1.105E-10	4.36	8.148E+0	2.554E-09	8.211E+0	**6256.649**	-1.13	13.20	12.07
65	14/06/9	1.665E-09	7.517E-11	4.52	5.353E+0	1.688E-09	5.426E+0	**4134.774**	-2.90	-20.89	-23.79
66	15/03/9	1.594E-09	6.928E-11	4.35	5.125E+0	1.607E-09	5.166E+0	**3936.223**	0.53	-28.08	-27.55
67	18/04/0	1.807E-09	8.148E-11	4.51	5.810E+0	1.866E-09	6.000E+0	**4572.374**	-0.24	-14.69	-14.93
68	21/02/0	4.318E-09	1.828E-10	4.23	1.388E+0	4.444E-09	1.429E+0	**4660.904**			-1.90
69	22/02/0	2.158E-09	9.429E-11	4.37	6.937E+0	2.221E-09	7.139E+0	**5440.160**	-0.15	-0.77	-0.92
70	22/03/0	2.523E-09	1.090E-10	4.32	8.113E+0	2.602E-09	8.364E+0	**6695.667**	1.48	17.87	19.35
71	08/04/9	3.322E-09	1.428E-10	4.30	1.068E+0	3.354E-09	1.078E+0	**8631.656**	13.28	36.62	49.90
72	20/03/0	1.504E-09	6.906E-11	4.59	4.835E+0	1.550E-09	4.985E+0	**3598.909**	5.77	-40.85	-35.08
73	09/03/0	1.240E-09	5.944E-11	4.80	3.985E+0	1.277E-09	4.106E+0	**2964.350**		-55.11	-55.11
74	21/03/0	1.523E-09	6.979E-11	4.58	4.898E+0	1.571E-09	5.049E+0	**3645.663**	-0.14	-34.70	-34.84
75	02/12/9	2.789E-09	1.198E-10	4.29	8.966E+0	2.858E-09	9.188E+0	**6321.435**			1.77
76	06/12/9	3.605E-09	1.389E-10	3.85	1.159E+0	3.695E-09	1.188E+0	**4651.195**			-1.92
77	08/12/9	3.179E-09	1.379E-10	4.34	1.022E+0	3.259E-09	1.048E+0	**4101.507**			-3.18
78	27/01/0	3.111E-09	1.206E-10	3.88	1.000E+0	3.196E-09	1.028E+0	**5363.899**			-0.36
79	20/12/9	2.935E-09	1.148E-10	3.91	9.437E+0	3.011E-09	9.681E+0	**5053.599**			-1.03
80	15/12/9	2.736E-09	1.059E-10	3.87	8.796E+0	2.806E-09	9.021E+0	**5886.382**			0.80
81	21/12/9	4.276E-09	1.636E-10	3.83	1.375E+0	4.388E-09	1.411E+0	**5522.536**			-0.02
82	16/12/9	5.292E-09	2.013E-10	3.80	1.701E+0	5.428E-09	1.745E+0	**12006.536**			14.49
83	22/12/9	2.809E-09	1.200E-10	4.27	9.031E+0	2.882E-09	9.266E+0	**6375.013**			1.89
84	07/12/9	1.853E-09	8.330E-11	4.50	5.957E+0	1.899E-09	6.107E+0	**4329.526**			-2.65
85	11/01/0	2.166E-09	9.796E-11	4.52	6.963E+0	2.225E-09	7.153E+0	**5071.516**			-0.99
86	09/12/9	2.135E-09	9.435E-11	4.42	6.865E+0	2.189E-09	7.038E+0	**4989.974**			-1.17
87	24/01/0	1.619E-09	7.243E-11	4.47	5.206E+0	1.665E-09	5.353E+0	**3682.948**			-4.17
88	12/01/0	2.627E-09	1.139E-10	4.33	8.447E+0	2.699E-09	8.678E+0	**5970.490**			0.98
89	31/05/0	1.967E-09	8.407E-11	4.27	6.325E+0	2.037E-09	6.550E+0	**5112.439**	0.67	-6.58	-5.91
90	05/06/0	2.497E-09	1.083E-10	4.34	8.028E+0	2.587E-09	8.316E+0	**6491.007**	-0.12	15.35	15.23
91	06/06/0	2.343E-09	1.021E-10	4.36	7.531E+0	2.427E-09	7.802E+0	**6089.768**	-0.34	9.44	9.10
92	07/06/0	1.771E-09	8.018E-11	4.53	5.694E+0	1.835E-09	5.899E+0	**3910.880**	-0.59	-27.53	-28.12
93	08/06/0	2.268E-09	1.005E-10	4.43	7.293E+0	2.350E-09	7.557E+0	**5380.474**	0.55	-2.70	-2.15
94	14/06/0	1.608E-09	7.286E-11	4.53	5.170E+0	1.667E-09	5.359E+0	**4083.293**	-0.50	-24.58	-25.08
95	03/05/0	2.286E-09	1.002E-10	4.38	7.350E+0	2.364E-09	7.599E+0	**6082.749**		10.14	10.14
96	21/06/0	1.789E-09	7.690E-11	4.30	5.751E+0	1.855E-09	5.963E+0	**4543.897**	-2.54	-13.41	-15.95
97	26/06/0	2.531E-09	1.044E-10	4.12	8.139E+0	2.626E-09	8.442E+0	**6757.972**	4.17	17.31	21.48
98	27/06/0	1.981E-09	8.457E-11	4.27	6.369E+0	2.055E-09	6.607E+0	**5288.957**	-0.35	-3.44	-3.79
99	04/05/0	3.177E-09	1.357E-10	4.27	1.021E+0	3.284E-09	1.056E+0	**6889.349**			3.04
100	03/07/0	2.439E-09	1.016E-10	4.17	7.840E+0	2.531E-09	8.136E+0	**5308.962**			-0.48
101	28/06/0	3.338E-09	1.359E-10	4.07	1.073E+0	3.463E-09	1.113E+0	**7660.500**			4.76
102	04/07/0	2.061E-09	9.073E-11	4.40	6.626E+0	2.139E-09	6.876E+0	**4730.930**			-1.75
103	05/07/0	2.261E-09	1.004E-10	4.44	7.268E+0	2.346E-09	7.544E+0	**5189.959**			-0.74
104	08/05/0	2.122E-09	9.317E-11	4.39	6.821E+0	2.194E-09	7.053E+0	**4270.805**			-2.79
105	09/05/0	1.773E-09	8.024E-11	4.53	5.699E+0	1.833E-09	5.894E+0	**3886.995**			-3.69
106	29/06/0	7.047E-10	3.826E-11	5.43	2.266E+0	7.312E-10	2.351E+0	**1617.266**			-9.54
107	06/07/0	2.374E-09	9.910E-11	4.17	7.634E+0	2.464E-09	7.923E+0	**5451.270**			-0.17
108	10/07/0	2.021E-09	8.953E-11	4.43	6.499E+0	2.099E-09	6.747E+0	**4642.212**			-1.94
109	11/07/0	2.586E-09	1.094E-10	4.23	8.314E+0	2.685E-09	8.632E+0	**5939.051**			0.91
110	10/05/0	2.085E-09	9.143E-11	4.39	6.704E+0	2.156E-09	6.933E+0	**4915.504**			-1.34
111	17/05/0	1.703E-09	7.721E-11	4.53	5.476E+0	1.762E-09	5.666E+0	**4017.041**			-3.38
112	27/04/0	2.357E-09	1.026E-10	4.35	7.577E+0	2.436E-09	7.830E+0	**5551.738**			0.05
113	26/04/0	2.060E-09	9.219E-11	4.48	6.623E+0	2.129E-09	6.843E+0	**4851.779**			-1.48
114	11/05/0	1.717E-09	7.729E-11	4.50	5.521E+0	1.776E-09	5.710E+0	**3928.787**			-3.59
115	19/04/0	1.872E-09	8.380E-11	4.48	6.019E+0	1.934E-09	6.216E+0	**4276.797**			-2.78
116	02/05/0	2.202E-09	9.648E-11	4.38	7.079E+0	2.276E-09	7.318E+0	**5034.740**			-1.07
117	12/05/0	2.868E-09	1.229E-10	4.29	9.220E+0	2.966E-09	9.537E+0	**4978.234**			-1.20
118	25/04/0	3.506E-09	1.491E-10	4.25	1.127E+0	3.623E-09	1.165E+0	**8012.735**			5.55
119	22/05/0	2.884E-09	1.245E-10	4.32	9.274E+0	2.985E-09	9.598E+0	**6603.642**			2.40
120	18/05/0	3.831E-09	1.628E-10	4.25	1.232E+0	3.965E-09	1.275E+0	**8769.533**			7.25

Sample Point Locations:

Longitude and latitude are given in Gauß-Krüger co-ordinates. Elevations are m above sea level.

Three dimensional co-ordinates were measured using a high resolution electronic theodolite, referenced to two mapped (DGK 1:5,000) survey points within the Auf dem Scheid catchment.

Sample Point	**Longitude**	**Latitude**	**Elevation**
1	^{25}85399	^{56}20323	161.65
2	^{25}85412	^{56}20287	165.64
3	^{25}85427	^{56}20262	168.00
4	^{25}85436	^{56}20233	171.83
5	^{25}85453	^{56}20209	175.77
6	^{25}85427	^{56}20205	171.60
7	^{25}85409	^{56}20199	166.41
8	^{25}85397	^{56}20195	162.85
9	^{25}85385	^{56}20189	161.63
10	^{25}85393	^{56}20218	161.60
11	^{25}85394	^{56}20236	161.90
12	^{25}85396	^{56}20266	162.52
13	^{25}85368	^{56}20279	157.93
14	^{25}85367	^{56}20194	161.04
15	^{25}85353	^{56}20211	159.00
16	^{25}85380	^{56}20224	160.39
17	^{25}85370	^{56}20253	158.77
18	^{25}85345	^{56}20238	157.73
19	^{25}85325	^{56}20223	158.19
20	^{25}85320	^{56}20245	157.52
21	^{25}85337	^{56}20259	156.74
22	^{25}85353	^{56}20257	157.26
23	^{25}85414	^{56}20093	176.78
24	^{25}85399	^{56}20111	174.27
25	^{25}85431	^{56}20109	174.92
26	^{25}85415	^{56}20133	173.10
27	^{25}85449	^{56}20125	173.60
28	^{25}85458	^{56}20155	176.40
29	^{25}85452	^{56}20166	174.08
30	^{25}85424	^{56}20154	168.65
31	^{25}85384	^{56}20135	170.48
32	^{25}85402	^{56}20152	168.01
33	^{25}85412	^{56}20158	166.99
34	^{25}85438	^{56}20178	171.77
35	^{25}85582	^{56}19917	190.22
36	^{25}85544	^{56}19918	189.65
37	^{25}85568	^{56}19943	189.36
38	^{25}85550	^{56}19952	188.87
39	^{25}85567	^{56}19964	188.74
40	^{25}85605	^{56}19948	189.62
41	^{25}85619	^{56}19981	189.09
42	^{25}85605	^{56}19984	188.82
43	^{25}85631	^{56}20008	188.92
44	^{25}85626	^{56}20048	188.38
45	^{25}85583	^{56}20021	187.36
46	^{25}85546	^{56}19991	187.24
47	^{25}85504	^{56}19955	187.96
48	^{25}85502	^{56}19987	186.83
49	^{25}85535	^{56}20008	186.20
50	^{25}85560	^{56}20033	186.09
51	^{25}85588	^{56}20056	187.17
52	^{25}85607	^{56}20075	187.22
53	^{25}85588	^{56}20101	185.96
54	^{25}85551	^{56}20070	185.23
55	^{25}85525	^{56}20040	184.14
56	^{25}85501	^{56}20024	184.58
57	^{25}85480	^{56}20005	185.28

58	^{25}85480	^{56}20046	182.49
59	^{25}85470	^{56}20039	182.74
60	^{25}85462	^{56}20039	182.39
61	^{25}85481	^{56}20056	181.55
62	^{25}85498	^{56}20067	181.48
63	^{25}85509	^{56}20062	182.41
64	^{25}85535	^{56}20088	183.82
65	^{25}85559	^{56}20111	184.26
66	^{25}85556	^{56}20120	183.36
67	^{25}85514	^{56}20142	180.51
68	^{25}85469	^{56}20174	179.44
69	^{25}85492	^{56}20104	179.12
70	^{25}85469	^{56}20111	176.36
71	^{25}85460	^{56}20113	175.47
72	^{25}85431	^{56}20087	177.61
73	^{25}85464	^{56}20081	178.82
74	^{25}85447	^{56}20066	179.79
75	^{25}85464	^{56}20145	176.00
76	^{25}85456	^{56}20174	177.47
77	^{25}85450	^{56}20182	176.27
78	^{25}85457	^{56}20191	177.89
79	^{25}85449	^{56}20193	176.72
80	^{25}85439	^{56}20196	174.27
81	^{25}85426	^{56}20193	170.99
82	^{25}85405	^{56}20183	164.79
83	^{25}85395	^{56}20174	163.79
84	^{25}85374	^{56}20164	165.82
85	^{25}85356	^{56}20171	164.64
86	^{25}85343	^{56}20186	161.54
87	^{25}85332	^{56}20200	159.67
88	^{25}85349	^{56}20228	158.33
89	^{25}85616	^{56}19924	190.00
90	^{25}85561	^{56}19907	190.06
91	^{25}85530	^{56}19935	189.11
92	^{25}85536	^{56}20027	185.25
93	^{25}85453	^{56}20049	181.18
94	^{25}85515	^{56}20094	181.88
95	^{25}85468	^{56}20097	177.32
96	^{25}85485	^{56}20131	178.35
97	^{25}85469	^{56}20125	176.12
98	^{25}85481	^{56}20085	179.15
99	^{25}85477	^{56}20152	178.81
100	^{25}85487	^{56}20160	179.55
101	^{25}85443	^{56}20144	171.85
102	^{25}85431	^{56}20146	170.05
103	^{25}85400	^{56}20165	165.20
104	^{25}85420	^{56}20246	167.92
105	^{25}85408	^{56}20274	165.43
106	^{25}85381	^{56}20301	160.15
107	^{25}85355	^{56}20276	156.65
108	^{25}85316	^{56}20254	157.77
109	^{25}85319	^{56}20213	159.05
110	^{25}85360	^{56}20154	167.61
111	^{25}85397	^{56}20136	170.16
112	^{25}85380	^{56}20169	164.62
113	^{25}85366	^{56}20179	162.78
114	^{25}85353	^{56}20196	160.19
115	^{25}85345	^{56}20218	158.57
116	^{25}85373	^{56}20233	159.24
117	^{25}85437	^{56}20186	173.39
118	^{25}85419	^{56}20171	167.68
119	^{25}85393	^{56}20247	162.36
120	^{25}85381	^{56}20285	160.19

Appendix C

Description of ^{137}Cs Models

The two models used for estimating rates of soil erosion and sediment deposition on the basis of ^{137}Cs activities are described here. These descriptions are based on a state-of-the-art summary report produced by WALLING & HE (1997) for the International Atomic Energy Agency, and are thus based on the work of numerous researchers. The software and documentation are available at: http://www.iaea.org/programmes/nafa/d1/index.html.

Mass Balance Model

This is the most advanced of the mass balance models summarised by WALLING & HE (1997). It incorporates both water erosion and tillage translocation.

Tillage induces a net downslope sediment flux (F_Q) which, for a unit contour length, may be represented as:

$$F_Q = \varphi \sin \beta \qquad \text{(C1)}$$

β	maximum slope angle	(°)
φ	constant	(kg/m/a)

For each section (i) of a slope transect, the net tillage redistribution (R_t) can be expressed as:

$$R_t = R_{t,out} - R_{t,in} = (F_{Q,out} - F_{Q,in}) / L_i = \varphi(\sin \beta_i - \sin \beta_{i-1}) / L_i \qquad \text{(C2)}$$

R_t	net tillage redistribution	(kg/m²/a)
$F_{Q,out}$	sediment lost from section *i* due to tillage	(kg/m²/a)
$F_{Q,in}$	sediment gained by section *i* due to tillage	(kg/m²/a)
L_i	slope length of i^{th} section	(m)
β_i	output angle from section *i* (see Figure C1)	(°)
β_{i-1}	input angle to section *i* (see Figure C1)	(°)
$R_{t,out}$	net tillage output	(kg/m²/a)
$R_{t,in}$	net tillage input	(kg/m²/a)

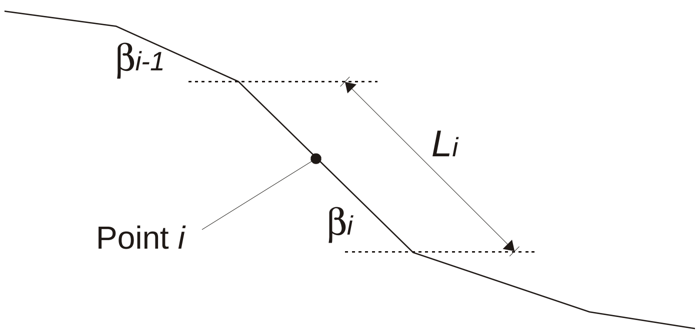


Figure C1: Definitions of β_i, β_{i-1} and L_i.

The constant φ can be estimated from the erosion rate of the first hilltop eroding point ($R_{t,out,1}$ or R_1), for which water erosion is assumed to be negligible, and for which there is no tillage input:

$$\varphi = \frac{R_{t,out,1} L_i}{\sin \beta_1} = \frac{R_1 L_1}{\sin \beta_1} \qquad \text{(C3)}$$

Thus, a value for R_1 (i.e. $R_{t,out,1}$) is required. This can be estimated by using the measured ^{137}Cs inventory of that point ($A_1(t)$) to solve the following equation for R_1:

$$A_1(t) = A_1(t_0)e^{-(R_1/d+\lambda)(t-t_0)} + \int_{t_0}^{t} I(t')e^{-(R_1/d+\lambda)(t-t')}\Delta t' \quad \text{(C4)}$$

$A(t)$	cumulative ^{137}Cs activity per unit area	(Bq/m^2)
R_1	erosion rate at point *1*	(kg/m^2/a)
d	cumulative mass depth	(kg/m^2)
λ	decay constant for ^{137}Cs	(a)
$I(t)$	annual ^{137}Cs deposition flux	(Bq/m^2/a)

Cumulative mass depth (d) is the mass of material containing ^{137}Cs below 1 m^2 of soil surface.

For a point experiencing *water erosion*, the change in ^{137}Cs inventory through time is expressed as:

$$\frac{\Delta A(t)}{\Delta t} = (1-\Gamma)I(t) + R_{t,in}C_{t,in}(t) - R_{t,out}C_{t,out}(t) - R_w C_{w,out}(t) - \lambda A(t) \quad \text{(C5)}$$

Γ	percentage of freshly deposited ^{137}Cs fallout removed by erosion before incorporation in plough horizon	
$C_{t,in}$	^{137}Cs in tillage input sediment	(Bq/kg)
$C_{t,out}$	^{137}Cs in tillage output sediment	(Bq/kg)
$C_{w,out}$	^{137}Cs in sediment lost through water erosion	(Bq/kg)
R_w	water erosion rate	(kg/m^2/a)

The factor Γ represents the proportion of ^{137}Cs that is removed by rainfall before incorporation into the plough layer. It can be expressed as:

$$\Gamma = P\gamma(1 - e^{-R/H}) \quad \text{(C6)}$$

P	particle size correction factor	
γ	proportion of annual ^{137}Cs input susceptible to pre-tillage removal	
H	cumulative mass depth of initial ^{137}Cs infiltration	(kg/m^2)

The *net* erosion rate R (kg/m^2/a), i.e. resulting from both tillage and water erosion is:

$$R = R_{t,out} - R_{t,in} + R_w \quad \text{(C7)}$$

For a point experiencing *deposition from water erosion processes*, the change in ^{137}Cs inventory through time is expressed as:

$$\frac{\Delta A(t)}{\Delta t} = I(t) + R_{t,in}C_{t,in}(t) - R_{t,out}C_{t,out}(t) + R'_w C_{w,in}(t) - \lambda A(t) \quad \text{(C8)}$$

$C_{w,in}$	^{137}Cs sediment gained through water deposition	(Bq/kg)
R'_w	deposition rate associated with water erosion	(kg/m^2/a)

The *net* erosion rate R (kg/m^2/a) is:

$$R = R_{t,out} - R_{t,in} - R'_w \quad \text{(C9)}$$

The ^{137}Cs concentration in soil within the plough layer $C_s(t')$ in Bq/kg can be expressed for a net eroding point as:

$$C_s(t') = \frac{A(t')}{d} \tag{C10}$$

and for a net depositional point as:

$$C_s(t') = \frac{1}{d}[A(t') - \frac{|R|}{d}\int_{t_0}^{t-1} A(t'')^{e-\lambda t''}\Delta t'] \tag{C11}$$

The relationships between C_s, $C_{t,in}$ and $C_{t,out}$ are as follows:

$$C_{t,in}(t') = C_{t,out}(t') = C_s(t') \tag{C12}$$

The concentration of ^{137}Cs in water eroded sediment ($C_{w,out}(t')$) in Bq/kg can be expressed as:

$$C_{w,out}(t') = PC_s(t') + \frac{I(t')}{R_w}P\gamma(1 - e^{R_w/H}) \tag{C13}$$

and in sediment deposited by water ($C_{w,in}(t')$) as:

$$C_{w,in}(t') = \frac{1}{\int_S RdS}\int_S P'C_{w,out}(t')RdS \tag{C14}$$

S	upslope contributing area	(m^2)

For a given point, the rate of tillage erosion or deposition can be determined from Equations C2 and C4, while the rates of water erosion/deposition are calculated by solving Equations C5, C7, C13 and C14.

Diffusion and Migration Model

The vertical distribution of ^{137}Cs within uncultivated soils is significantly different from that of tilled soils in which ^{137}Cs is mixed throughout the plough layer. In many cases, the vertical distribution of ^{137}Cs in the soil exhibits an exponential decline with depth. This does not remain constant, however, as ^{137}Cs slowly migrates through the soil profile. The variation in concentration of ^{137}Cs in surface soil ($C_u(t)$) over time (t) can be expressed as:

$$C_u(t) \quad \frac{I(t)}{H} + \int_0^{t-1} \frac{I(t')e^{-R/H}}{\sqrt{D\pi(t-t')}} e^{-V^2(t-t')/(4D)-\lambda(t-t')} \Delta t' \qquad \text{(C15)}$$

D	diffusion coefficient	(kg^2/m^4/a)
V	downward migration rate of $^{!37}$Cs	(kg/m^2/a)

The D and V factors describe the development of the vertical distribution profile through time. They are defined as:

$$D = \frac{(N_p - W_p)^2}{2(t-1963)} \qquad \text{(C16)}$$

$$V = \frac{W_p}{t-1963} \qquad \text{(C17)}$$

t	the year of sampling	
W_p	mass depth of maximum ^{137}Cs concentration	(kg/m^2)
N_p	mass depth of increment between depth of maximum ^{137}Cs concentration and depth at which this reduces to 1/e of the maximum	(kg/m^2)

For *eroding points*, assuming that sheet erosion is the only erosional process, loss in ^{137}Cs inventory ($A_{loss}(t)$) and the ^{137}Cs concentration in surface soil (Equation C15) can be used to estimate an erosion rate (R) by solving the following equation for R:

$$A_{loss}(t) = \int_0^t PRC_u(t')e^{-\lambda(t-t')}\Delta t' \qquad \text{(C18)}$$

The concentration of ^{137}Cs in deposited sediments ($C_d(t')$) in Bq/kg can be expressed as:

$$C_d(t') = \frac{1}{\int_S RdS} \int_S P'PC_u(t')RdS \qquad \text{(C19)}$$

This, together with the excess ^{137}Cs inventory (A_{ex}), can be used to estimate a deposition rate (R'):

$$R' = \frac{A_{ex}}{\int_{t_0}^{t} C_d(t')e^{-\lambda(t-t')}\Delta t'} \qquad \text{(C20)}$$