Understanding landscape dynamics over thousands of years: combining field and model work

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Understanding landscape dynamics over thousands of years : combining field and model work

With a case study in the Drakensberg foothills, KwaZulu-Natal, South Africa

Arnaud Josephus Alexander Maria Temme

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Then came those old-fashioned books of natural history that dealt courageously with The Universe, illustrating it with quaint engravings of strange rock formations in the Hartz Mountains, the Mammoth Caves in Kentucky, the Aurora Borealis, and eruption of Mount Etna; always with little men, armed with long staves, looking on as though they themselves were responsible for the phenomena. But none of these things was a part of the school curriculum. They could find no expression; and never for a moment did it occur to me that interest in such things might suggest a line of approach when considering the awful question, "What will I do when I grow up? ". (..) Explorers were only mythical beings that one read about, and scientists were men of vast intellect (..) So all my absorbing interests were relegated to the classification of a "hobby" .

Eric Shipton, Upon That Mountain (1943)

This thesis is dedicated to the memory of Laurent Bonhomme, who died in an ice avalanche on July 16, 1999 during our attempt to climb Khan Tengri (7010m) in the Tien-Shan mountains of Kazachstan.

DANKWOORD

Mei 2004

Het wordt donker, sneller dan ik had verwacht. Nadat ik inmiddels driemaal door mijn enkels ben gegaan, is hardlopen er echt niet meer bij. Langzaam vorder ik over de hoogvlakte terwijl de temperatuur snel omlaag duikt. Inmiddels twaalf uur bezig. Ik trek mijn jack aan en huiver. Waarom leek het ook alweer een goed idee om in één dag, alleen alle controlepunten langs te gaan? Plotseling sta ik aan de rand van de hoogvlakte, een paar meter verwijderd van de ontzaglijke diepte van het Amfitheater. Geheel onverwacht, ik dacht dat ik daar nog lang niet was. Hier voelt een mens zich overdag al alleen en nietig! Naast de Tugela rivier stort zich inmiddels ook een rivier van vrieslucht omlaag, die me zachtjes een duwtje in de rug geeft, richting de duistere afgrond. De rotsen aan de rand lijken plotseling wel extra glad. Het is een beangstigend gevoel, en snel draai ik naar links, op weg naar de kettingen van de afdaling. Op weg naar de mensenwereld.

Mei 2005

De Great Karoo doet zijn naam eer aan: de weg is oneindig en recht en het landschap is groots en open. De schaarse wegwijzers geven afstanden aan naar kleine dorpjes als Touwsrivier en Matroosberg. Afstanden van stuk voor stuk honderden kilometers. Kaapstad: 650 km. Geen mensen op de weg, en ook geen mensen naast de weg. De Karoo lijkt verlaten, zelfs de radio pikt nu geen van de zwakke lokale zenders op. De komende uren is het de Great Karoo en ik. En niet andersom.

Promoveren is het proces waarbij wetenschappelijke zelfstandigheid bereikt wordt. Het is dan ook niet verwonderlijk dat zelfstandigheid een grote rol speelt in het bereiken van dat doel. Sommige van de meest memorabele momenten van mijn promotie-traject, tijdens veldwerk of in Wageningen, kenmerkten zich door die zelfstandigheid en soms zelfs eenzaamheid waarvan ik hierboven twee voorbeelden heb gegeven.

Toch zijn er cruciale verschillen tussen zelfstandigheid en eenzaamheid. Een goede analoog is in de bergsport te vinden. Eenzame (solo-)klimmers zijn vaak gevaarlijk bezig. Zelfstandige klimmers daarentegen worden weliswaar niet aan het handje gehouden worden door gidsen of instructeurs, maar zijn juist wel op hun tochtgenoten aangewezen voor overleg, steun, wederzijdse controle, beveiliging en gezelligheid.

Overleg, steun, wederzijdse controle, beveiliging en gezelligheid dus. Dat maakt duidelijk hoe groot het belang van anderen is, zowel in de bergsport als tijdens een promotietraject. Hieronder zal ik proberen om recht te doen aan dat belang. Mocht ik mensen vergeten, bij voorbaat mijn excuses.

Het is moeilijk om het belang van mijn promotor Tom Veldkamp in woorden uit te drukken. En voordat U denkt dat dat niet bepaald een compliment is; dat komt omdat dat belang zo enorm is geweest. Tom, als aanjager, afremmer, hypothese-machine, criticus en geestelijk vader, in de breedte en in de diepte, en achter de computer en in het veld, heb je ervoor gezorgd dat ik zover ben gekomen. Overleg, steun, wederzijdse controle, beveiliging en gezelligheid – al die aspecten en meer. Het is een enorme eer dat ik langdurig zo intensief met je heb mogen werken en ik hoop dat het ons lukt om de voorwaarden te scheppen waaronder dat ook in de toekomst mogelijk blijft. Bedankt voor de kansen, het vertrouwen en de vrijheid die je me bij voortduring gaf.

Alejandra Mora Vallejo, mijn charmante Chileense kamergenote en partner-in-crime gedurende vier jaar, vriend voor het leven. Jeroen Schoorl, geestelijk vader van het LAPSUS model en smooth operator. Lieven Claessens, de 'chasseur' van Nairobi en geheim agent in het Witte Huis. Eke Buis, kamergenote en LAPSUS-collega. Jantiene Baartman, afstudeervakker en redder. Iris Peeters, mede-modeleur en Belgische counterpart. Michiel Braakhekke, op al die vlakken. Jullie waren fantastisch, bedankt voor een heel fijne tijd!

Datzelfde geldt voor collega's en studenten bij Land Dynamics en eerder bij Bodem Inventarisatie en Land Evaluatie: we spreken niet altijd dezelfde taal, maar we praten wel over dezelfde onderwerpen. Bedankt voor de discussies en de gezelligheid, vooral Bas, Dirk, Gerard, Gert, Henny, Kathleen, Linda, Luciana, Marthijn, Matthijs, Meindert, Nynke, Toine, Wieteke en Wouter!

Ik heb met veel plezier samengewerkt met mijn collega-promovendi in het PhD Student Panel van ondezoeksschool PE&RC. En wie PE&RC zegt, zegt Claudius van de Vijver. Claudius, we hebben vanaf 2003 veel goede momenten beleefd en prettig samengewerkt bij de organisatie van de Land Science cursus in Zuid-Afrika. Bedankt voor je vriendschap!

De korte periodes die ik heb samengewerkt met Jakob Wallinga en Candice Johns van het Netherlands Centre voor Luminescence dating in Delft waren intensief, prettig en waardevol. Jakob, Candice, ik kom graag nog eens terug met nieuwe monsters!

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The calm questions and answers of Greg Botha, who did most of the previous research on comparable deposits in KwaZulu-Natal, have been very important. Greg, in PMB and over e-mail, you and your encyclopaedic knowledge of literature have been invaluable for my research. Thank you!

Nchlanchla Walter Miya has been my dependable field assistant through two years of fieldwork. Nchlanchla, all the best for you and your family. I hope we can meet and do a Drakensberg walk again!

The warm welcome and help I received at the University of KwaZulu-Natal at Pietermaritzburg were invaluable. Big thanks to Monique Salomon, Terry Everson and prof. Jeff Hughes. I am similarly indebted to Louis Scott, Paul Sumner, Jay Le Roux, Marc Tadross and Werner Nel.

De afgelopen jaren ben ik zowel een sportende onderzoeker als een onderzoekende (berg-)sporter geweest. De gezonde balans tussen die twee is een van de belangrijkste redenen geweest dat mijn promotietraject zonder diepe dalen is verlopen. Sommige van de beste gedachten over mijn onderzoek kwamen vanzelf bovendrijven in de rust die overweldigende uitzichten of langdurige trainingen in mijn hoofd veroorzaken. Een uur in het bos was regelmatig meer effectief dan een week achter de laptop, en een maand in de Alpen scheelde twee maanden werk in Nederland! De mensen met wie ik die speciale momenten en periodes heb beleefd, verdienen daarom net zoveel dank als zij die meer direct bij mijn werk betrokken waren. In het bijzonder de Sperende Lama's, Knav98, Ibex, CAKK en Team Xbionic.

Mijn familie maakte alles mogelijk op een ander vlak. Dank aan mijn moeder, vader, zus en broer.

En nogmaals, als laatste maar boven alles, mijn rots: Marije.

PREFACE

The research resulting in this thesis has been carried out as PhD project "Soil-vegetation-landscape dynamics: quick and slow soil landscape feedbacks in natural and used systems (KwaZulu-Natal, RSA)" , and was funded by Wageningen University chairgroups Land Dynamics (formerly Soil Inventarization and Land Evaluation) and Earth System Science (formerly Soil Formation and Ecopedology). The project ran from September 2003 through January 2009 and was carried out within the C.T. de Wit graduate school Production Ecology and Resource Conservation and in the framework of the Global Land Project (www.globallandproject.org).

SYMBOLS AND ABBREVIATIONS

Δ	Difference / Change / Slope
BP	Before Present
da	deca-annum, decade
DEM	Digital Elevation Model
ka	kilo-annum, thousand years
LE	Landscape Element
LEM	Landscape Evolution Model
LGM	Last Glacial Maximum
MEF	Model Efficiency Factor
OIS	Oxygen Isotope Stage; a subdivision of geological time
OSL	Optically Stimulated Luminescence; a dating method
RMSE	Root Mean Square Error

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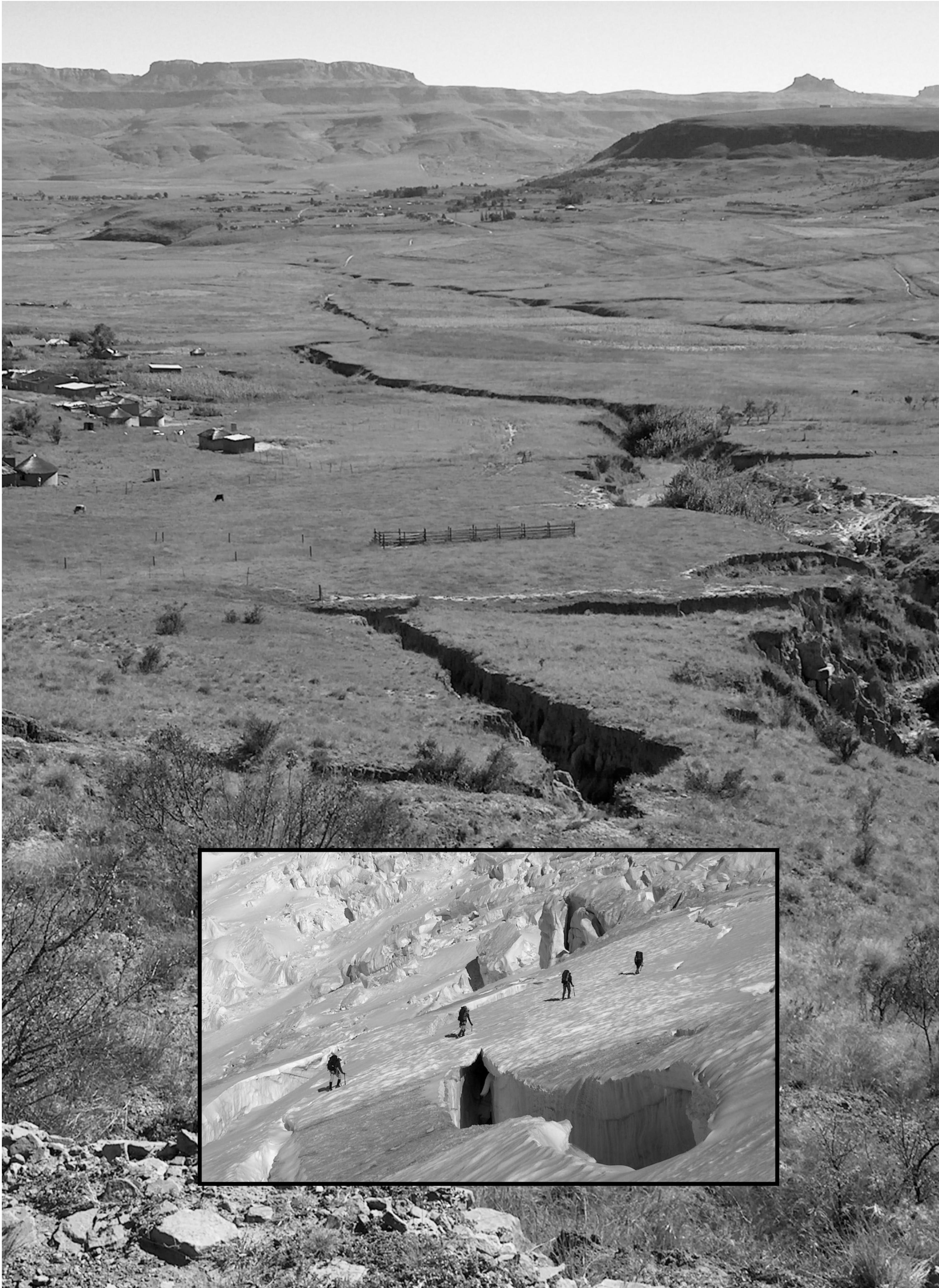


CHAPTER 1

GENERAL INTRODUCTION

Notes

CHAPTER 1

GENERAL INTRODUCTION

1.1 BACKGROUND

Landscapes change. From the slow weathering and erosion of old continental shields like in Africa and Australia, to the formation of river deltas like most of the Netherlands and from the powerful grinding of glaciers in the Alps or Himalayas, to the sudden collapse of slopes in landslides in New Zealand - landscapes change and change is paramount, even if we do not always recognize it.

People have seen and wondered about changes in landscapes for a long time. The ancient Greeks Xenophanes (570 BC–480 BC) and Aristotle (384 BC–322 BC) made observations about landscape changes, and the Chinese statesman and scientist Shen Kuo (1031–1095) wrote about changes in rivers and mountains.

In the 1680's, as Gould (1987) discusses, the first elaborate ideas about the causes and effects of changes in landscapes were published by Thomas Burnet. Written in a religious world and from a religious background (Burnet was a priest), the four-volume *Telluris Theoria Sacra* or *Sacred Theory of the Earth* (1691) presented landscape change as the result of two global catastrophes.

The first catastrophe, the Flood, occurred when the perfectly featureless world of the Paradise cracked open to allow subterranean water to cover it. Our current world was seen as the essentially static result of that cracking, with the broken pieces of crust for continents, and the water of the Flood filling the oceans[1]. The second catastrophe was a global conflagration, resulting in a cloud of burned particles that

[1] Burnet called our present world a "hideous ruin" and "a dirty little planet". Mountaineers would argue the other way around: a totally flat world in Paradise would be so much less interesting.

settled in featureless concentric circles sorted by density – which yielded the original world of the Paradise where Christ was to rule for a thousand years[2].

Burnet's ideas of landscape change may seem far-fetched to us now, but they were in fact an attempt to identify natural instead of supernatural causes for the events described in Scripture (Gould, 1987). As such, they were innovative and ground-breaking.

A radical break with catastrophist ideas was proposed around 1800, particularly by Charles Lyell, commonly seen as the father of geology, who wrote his *Principles of Geology* between 1830 and 1833. Lyell realized that past processes are unobservable, and that only their results remain as evidence. He argued that a comparison of these results with modern phenomena produced by processes that we can observe directly, would lead to increased knowledge about the landscape. Further, he recognized that current processes generally resulted in slow landscape change; ergo landscape change had always been slow. Lyell's main argument, called uniformitarianism, introduced both the notion that natural laws are constant in space and time and (unfortunately) the mistaken but at the time attractive idea that slow rates of landscape changing processes did not change over time (e.g. Gould, 1987).

The recognition that landscape changing processes may act very slowly to produce impressive results over millions of years, was crucial for the development of geology since it opened the door for an understanding of geological time. Geomorphology, defined here as the study of landscapes and the processes that change them, profited likewise[3].

Subsequent discussion about the nature of landscape change was strongly influenced by these gradualist ideas of Lyell (1830-1833) and Hutton (1795) in geology and Darwin in biology (1859). One of the most notable results was the first true geomorphological model of landscape change, by the American geomorphologist Davis (1899). Davis introduced the geographical cycle, explaining how rivers slowly erode flat uplifted land in several steps to a lower (base-)level[4]. The flat land at this new level can again be uplifted, starting the cycle anew. Climate supposedly played no role in this cycle.

Many changes and contributions to geomorphological theory have since been made. One interesting alternative to Davis' cycle was proposed by a South African geologist: Lester King. King proposed the mechanism of parallel slope-retreat instead of Davisian fluvial erosion, which enabled him to explain the widespread low-gradient surfaces of different elevation in Southern Africa.

Currently, it is recognized that landscape forming process activity is dynamic in time and space, but that laws are constant (Gould, 1965). Landscape change is seen as the sum of the gradual and sudden activity of multiple landscape forming processes. Examples of these processes are physical and chemical weathering, fluvial erosion and deposition, wind erosion, mudflows, landslides, soil creep and rockfall[5]. The rates of these processes differ between climates, parent materials and landscape positions and may

[2] This concludes the role of religion in this thesis. In science, questioning, reasoning and measuring are better than believing.

[3] Not to mention biology – Darwin used the millions-of-years paradigm to huge, well-known effect.

[4] This final result of fluvial erosion is known as a peneplain, or "almost plain". Compare peninsula, "almost island" .

[5] Among many others. It may be argued that a discrete definition of processes is subjective. Chapter 4 elaborates this point.

vary in cycles or randomly (Brunsden, 1996). Landscape response to changes in driving factors is typically non-linear (Schumm, 1977) and may be immediate or delayed. The delays (lags) range from decades up to thousands of years and are mainly caused by the buffering effects of soil and vegetation (Veldkamp and Tebbens, 2001; Thomas, 2004) and the existence of thresholds in the landscape. In summary, geomorphology sees landscapes as complex landscape-soil-vegetation systems.

Our interest as a society in understanding and quantifying such systems remains and even increases now that our own influence on landscapes and their usability becomes apparent. Soil properties change depending on landuse (e.g. Sonneveld *et al.*, 2002). Erosion is intensified when we overgraze steep slopes (Sonneveld *et al.*, 2005), or till sloping agricultural fields (Van Oost *et al.*, 2003; Heuvelink *et al.*, 2006). Landslide risk increases when we cut forests (like in Uganda, Claessens *et al*, 2007), build mountain roads (like in Taiwan, Braakhekke, 2007) or build leaking irrigation systems (like in Spain). On a global scale, we have started to change natural landscape dynamics through human-induced climate change (IPCC, 2007).

It is essential to continue building on our knowledge of both the complex natural development of landscapes and the possible changes to this development brought about by human actions. This knowledge is necessary to make well-informed policy decisions for our future in an increasingly globalized society where issues of land degradation are a grave concern. One of the most difficult aspects of this task is the translation of often long-term (ka) landscape knowledge to the shorter term that is of most interest to society (decades, Kroonenberg, 2006)[6]. In other words, it remains the task of geomorphologists to look into the past to see the future.

To perform this task, many tools are at our disposal, ranging from field investigations and laboratory dating techniques to Landscape Evolution Models (LEMs). Modern field studies of geomorphological history, aided by an array of analytical techniques, generally result in plausible hypotheses of the evolution of particular landscapes, though not always at the desired level of precision and accuracy. LEMs provide a way to test and improve landscape evolution hypotheses and can refine fieldwork results. In this thesis, I use these combined tools to advance our thematical and methodological knowledge of the landscape-soil-vegetation system.

1.2 MODELLING CHANGING LANDSCAPES

The numerical modelling of changing landscapes, or landscape evolution modelling, was recognized as a promising field of research from around 1970 (e.g. Kirkby, 1971; Ahnert, 1976). Since then, many lessons have been learned, aspects of which are discussed in the introductions of chapters 3 through 6. In this section, I briefly introduce basic technical aspects of modern LEMs. Again, these are elaborated upon in chapters 3 through 6.

The digital landscape

Landscape evolution modelling uses a digital representation of the landscape. Based on this representation, the rates of different landscape forming processes are calculated and used to change that

[6] Kroonenberg famously wonders which timescales are meant in sustainability; policy cycles or geological cycles.

digital landscape. When calculating multiple timesteps, this results in landscape dynamics that could be presented as a movie[7].

The most common digital representation of the landscape is a Digital Elevation Model (DEM), where an area is subdivided in a regular grid of rectangular cells. These cells are considered to have uniform altitude. Evidently, a small gridsize (leading to smaller cells) can capture a landscape better than a large gridsize (Temme *et al.*, 2008a)[8], but this comes at the cost of higher memory and calculation requirements.

Currently, DEMs are almost globally available at 90m resolution (SRTM DEMs, Adam *et al.*, 2000) and smaller resolution DEMs exist for many areas. The Dutch national DEM has a resolution of 5m and a South African DEM is available at 20m resolution.

Accurate DEMs can only be measured for current landscapes, not for ancient, or palaeo-landscapes. That means that when we want to model the past evolution of a landscape, two options are available: modelling backward in time from an accurate current DEM (e.g. Peeters *et al.*, 2006), or modelling forward in time from a palaeo-DEM created by making assumptions (e.g. Buis *et al.*, submitted). Modelling forward is by far the most common choice, particularly because of conceptual problems with backward modelling[9].

Landscape evolution model LAPSUS

This project used and adapted LEM LAPSUS (LandscApe ProcesS modelling at mUlti dimensions and scaleS, (Schoorl *et al.*, 2000; Schoorl *et al.*, 2002, Schoorl *et al.*, 2004). LAPSUS is an example of a reduced-complexity, multi-process landscape evolution model, that is typically used with a temporal resolution of years.

LAPSUS is a non-commercial model used only for research, that at the time of writing exists without a Graphic User Interface. Parameters and process descriptions are changed directly in the single-file model source code. This requires and ensures that users have intimate knowledge of the model but makes it difficult to quickly get to grips with the model.

Schoorl *et al.* (2002) describe the initial version of LAPSUS, with water erosion and deposition as the only landscape forming process. Claessens *et al.* (2007) implemented a description of landslide activity. Buis (2008) discusses a more recent model version in detail. Chapter 5 of this thesis discusses some aspects of the model, as well as the implementation of a number of additional landscape forming processes. Here, I sketch a picture of LAPSUS at its most general level (Fig. 1.1). Most other LEMs have the same basic structure.

7 This is attractive for educational purposes, especially when combined with the current popularisation of geo-information through e.g. Google Earth and NASA World Wind.

8 Even though this potential is not necessarily fulfilled. The accuracy of the altitude of the cells must also be taken into account. See Temme *et al*, 2008a: Geostatistical simulation and error propagation in geomorphometry. In: Hengl, T. and Reuter, H.I. (eds), Geomorphometry: concepts, software, applications. Elsevier

9 A given landscape may have originated from many different palaeo-landscapes (equifinality), and different processes may have caused its evolution (polygenesis). Therefore, modelling backwards may result in only one of a set of outcomes that may be true. Chapter 5 elaborates on this point.

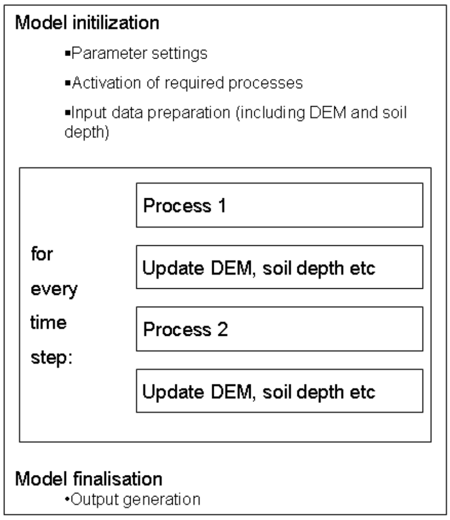


Fig. 1.1: General structure of LEM LAPSUS.

During model initialization, LAPSUS reads the user-provided parameters, activates the landscape forming processes that are needed in the current study and reads the required input data into memory. Then, starting from the initial DEM, soil depth and other inputs, the required number of timesteps is calculated. In every timestep, each landscape forming process requested by the user (not necessarily two like in Fig. 1.1) is calculated and its results are used to update landscape characteristics. After the required number of timesteps has been reached, the final output DEM and soildepth maps are written.

1.3 RESEARCH AREA

This project focussed on the landscape-soil-vegetation system in Okhombe valley ("the valley of the Khombe river") in the province of KwaZulu-Natal in the Republic of South Africa, although data from other study areas were also used to illustrate tests of landscape evolution models in Chapter 4. Here, I will introduce the Okhombe valley.

Okhombe valley is part of the Drakensberg foothills and is situated close to the border with the independent Kingdom of Lesotho and the Free State province (Fig. 1.2). The river Khombe that drains the valley is a tributary of the Thukela, the largest river catchment in KwaZulu Natal, which drains in the Indian Ocean. Nowadays, large amounts of water from the Thukela are pumped over the waterdivide with the Free State and subsequently used in providing Gauteng Province (including Johannesburg) with water. Altitude of the valley is between 1300 and 1500 m.a.s.l.

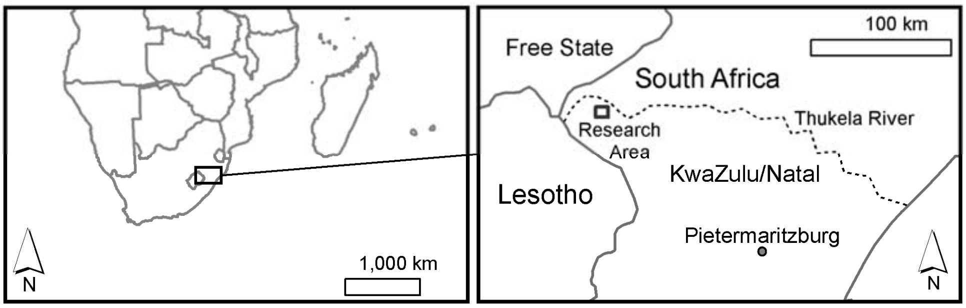


Fig. 1.2: Position of the Okhombe Valley research area.

Current annual rainfall is about 800-1000 mm (and increases with about 40 mm per 100 m of altitude as discussed by Nel and Sumner, 2005). The summer months November to March account for 70% of the annual rainfall (Schulze *et al*, 1997). Mean annual temperature is about 14°C, mean minimum daily temperatures are about 5°C in winter, frost and snow occur almost every winter (Schulze *et al*, 1997).

Vegetation is predominantly grassland, though some patches of natural forest remain. In the Acocks classification of vegetation types (Acocks, 1988), the area is under Southern Tall Grassveld and Highland Sourveld (Fig. 1.3).

Fig. 1.3: Vegetation in Okhombe Valley is grassland with some forest in protected positions. In the background, the Drakensberg mountains are visible.

The bedrock of the valley is a depositional sequence of progressive aridification from the Permian and Triassic, the Beaufort Group, that was extensively intruded by dolerite sills and dykes in the Jurassic (Verster, 1998). Since the Jurassic, the eastern part of southern Africa has been subjected to regional tilting, resulting in an uplift of over three kilometers in the research area (Partridge and Maud, 2000). This uplift has created a strongly erosional landscape. Scarce, recent sedimentary landforms are found along rivers and in structurally controlled concave positions (Tooth *et al.*, 2004), directly overlying bedrock. A number of these sedimentary landforms were found in Okhombe valley and one of them was used as our main research area.

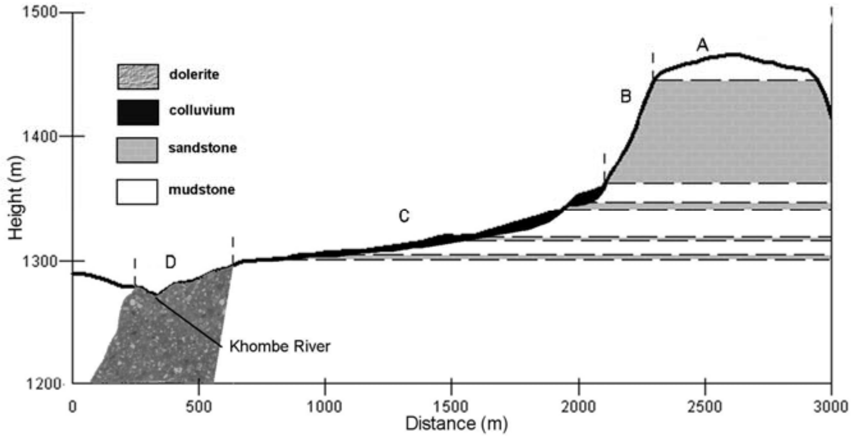


Fig. 1.4: Profile view of the research area.

The research area presents four landscape elements (LEs, Figs. 1.4 and 1.5). From top to bottom these are A. the upper slopes of predominantly mudstone with gentle slopes of 5°, B. the more resistant and steeper middle slopes of predominantly sandstone with slopes between 20° and 35°, C. the lower slopes of both lithologies, where colluvium was deposited with slopes less than 10°, and D. a small, resistant area of dolerite with slopes around 10°, in which the bed of the river Khombe is situated. Within the lower slopes (C), several alternations between mudstone and sandstone occur, creating minor steps in the bedrock.

Six permanent gullies (*sensu* Poesen, 2003) have incised the colluvia and join downstream before draining over the dolerite into the river Khombe (Fig 1.5). Erosion mainly occurs by means of headward retreat of the gullies (Fig. 1.6), often developing along existing sub-surface pipes (Beckedahl, 1996). Erosion is especially severe in the upstream deposits (zones BC, C1), where gullies develop most new tributaries (Sonneveld *et al.*, 2005).

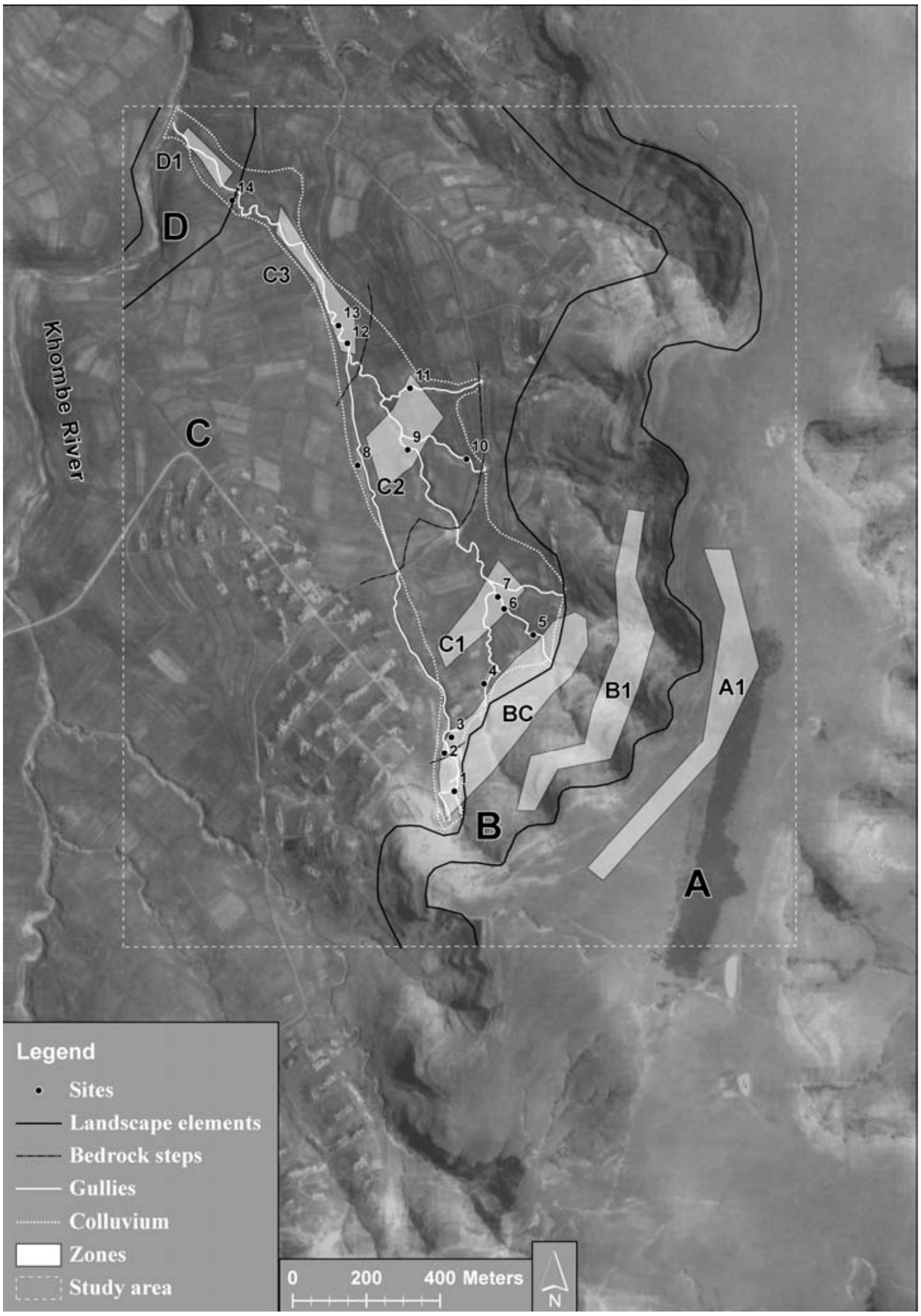


Fig. 1.5: Plan view of the research area. A-D are landscape elements, 1-14 are sites, A1-D1 are zones.

Fig. 1.6: Headward retreat of new tributaries of the gullies in Okhombe Valley.

1.4 MAIN OBJECTIVE AND RESEARCH QUESTIONS

As mentioned before, the main objective of this project was an increased understanding of the complex landscape-soil-vegetation interactions that control landscape development at the scale of millenia, with Okhombe valley as the main research area. Two research questions with sub-questions were defined:

1) How has the landscape in the Okhombe valley evolved over the last 50 ka?
    a) What is the stratigraphical architecture of the deposits in the Okhombe valley?
    b) Which sequence and combination of processes has caused deposition?
    c) How has climate controlled these processes, and how is it likely to do so in the future?
2) How can landscape evolution at temporal extents of 10^4 years be modelled with landscape evolution models?
    a) How can model-predicted, non-spurious sinks be used in landscape evolution models?
    b) How can multiple processes be combined in landscape evolution models?
    c) How can these models be best combined with fieldwork results to increase our knowledge of landscape dynamics?

1.5 THESIS OUTLINE

After the introduction, this thesis is composed of five chapters that deal with the different questions mentioned above and one chapter that combines the conclusions and tries to answer the main questions of this research on a more general level. Chapters 2 through 6 are based on scientific papers published in or prepared for peer-reviewed international scientific journals. These chapters to some extent follow the standard scientific structure, i.e. are subdivided into introduction, methods, results, discussion and conclusions. Chapter 7 has a different structure due to its more general purpose. Fig. 1.7 shows the relation of chapters 2-6 to the research questions above.

	Research question 1 Evolution of Okhombe Valley			Research question 2 Modelling landscape evolution		
	1a	1b	1c	2a	2b	2c
Chapter 2	XX	XX	XX			
Chapter 3				XX		
Chapter 4				X	XX	
Chapter 5		X	X		X	XX
Chapter 6			X			XX

Fig. 1.7: General layout of this thesis. XX indicates a strong contribution, X indicates a moderate contribution.

Chapter 2 discusses results from extensive fieldwork in 2004 and 2005 in Okhombe valley, where the long-term, 50ka scale landscape evolution of the valley was studied and reconstructed. Results from fieldwork and laboratory analyses of samples taken in the valley are presented. The chapter forms the basis for subsequent modelling exercises.

Chapters 3 and 4 deal with the development of LEMs in general and LAPSUS in particular. In chapter 3, I present an algorithm (a method) that allows LEMs to deal with non-spurious sinks and depressions, as opposed to the widely used method of removing these sinks from DEMs. In chapter 4, I present a framework that discusses the set-up of LEMs where multiple landscape forming processes are combined.

Both the ability to deal with sinks and the novel ideas about multi-process-methods are crucial for chapter 5, which presents a landscape evolution modelling study for the last 50ka in Okhombe valley, combining several landscape forming processes. The focus is on detailing the fieldwork conclusions of Chapter 2 and on developing methods to calibrate model outputs with uncertain and incomplete field data. New model descriptions of landscape forming processes were also developed in this chapter.

Chapter 6 uses the landscape evolution model from Chapter 5 to study its relevance for the study of future landscape dynamics. It studies the conditions under which the LAPSUS version of Chapter 5 can distinguish between the results of different climate-change scenarios on a 1ka temporal extent, and whether it is possible to draw general conclusions about the likely future development of the valley.

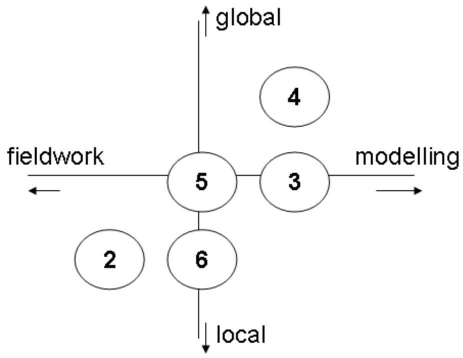
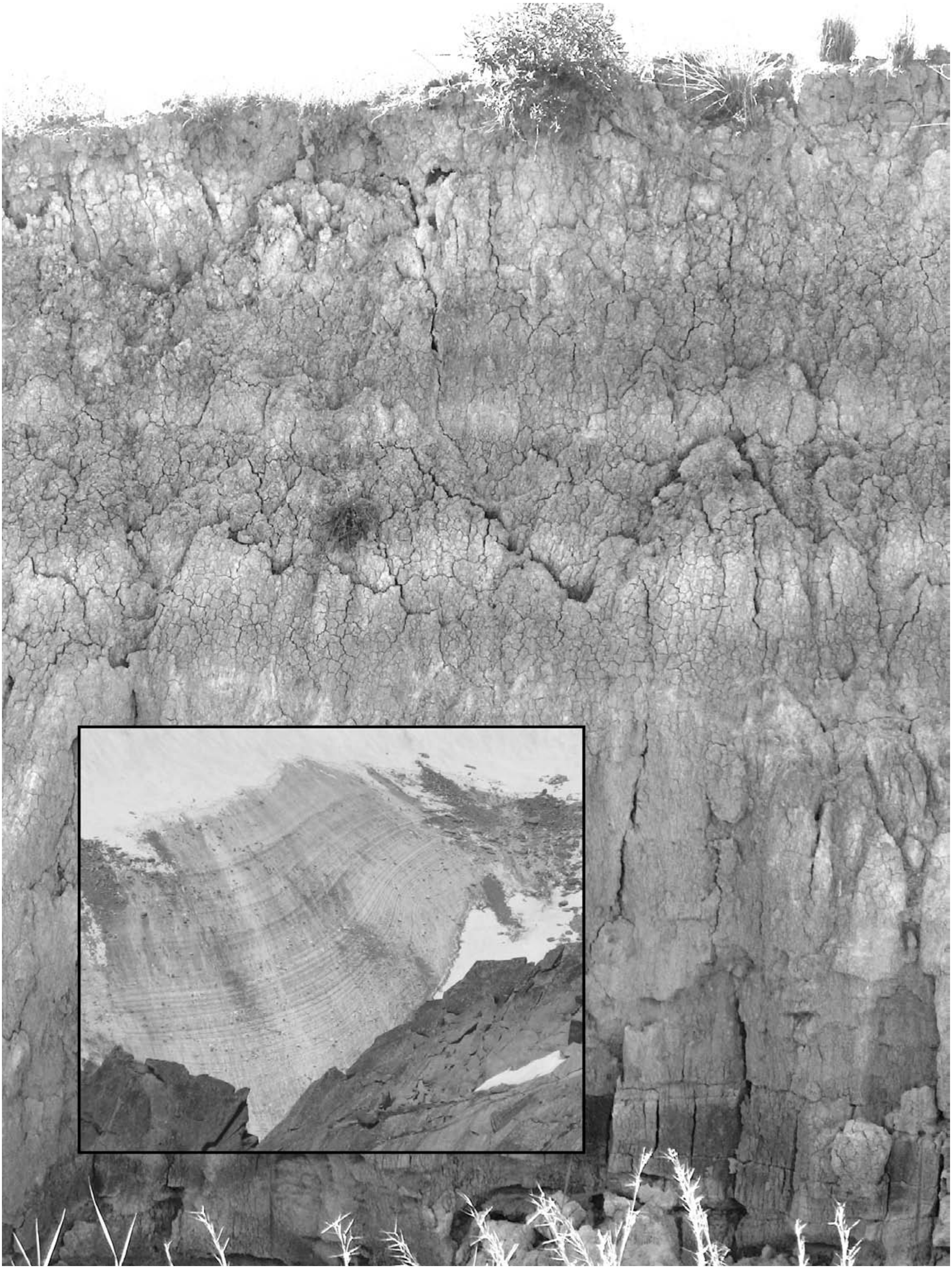


Fig. 1.8: Position of chapters 2-6 in a two-dimensional space, with the type of geomorphological work on the x-axis, and the relevant spatial scale on the y-axis. On a local scale, conclusions are strongly thematical, whereas on the global scale, they are strongly methodological.

Fig. 1.8, which positions chapters 2 to 6 in relation to each other, shows that this work presents both a mix between fieldwork and modelling, and a mix between local (thematical) and global (methodological) topics.

Chapter 7 tries to answer the main questions of this research on a more general level. First, conclusions from Chapters 2, 5 and 6 are combined to summarize the knowledge about landscape evolution of Okhombe valley. The implications of these conclusions for deposits in a wider area in KwaZulu-Natal are then discussed, and an explorative attempt is made to subdivide these deposits based on landscape and climatic characteristics. Second, the innovations and conclusions pertaining to landscape evolution modelling are listed and discussed. Combining these innovations, an iterative fieldwork-modelling setup is proposed, and implications and opportunities for future research are discussed.



CHAPTER 2

CLIMATE CONTROLS ON LATE PLEISTOCENE LANDSCAPE EVOLUTION OF OKHOMBE VALLEY

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Notes

CHAPTER 2

CLIMATE CONTROLS ON LATE PLEISTOCENE LANDSCAPE EVOLUTION OF OKHOMBE VALLEY

Hillslopes in central and western parts of KwaZulu-Natal, South Africa are often mantled by colluvial sediments of the Masotcheni Formation. These sediments have accreted in response to several cycles of deposition, pedogenesis and incomplete erosion. Climatic controls on these cycles are incompletely known. Results from fieldwork, micromorphology, stable carbon isotope analysis and Optically Stimulated Luminescence dating of Masotcheni Formation sediments from the Okhombe valley in the Drakensberg foothills are combined. Deposition in the area comprised at least 11 phases, starting before 42 ka and ending before 0.17 ka. The first six deposits (from before 42 ka to after 29 ka) resulted from the interplay between slope processes and fluvial redistribution under cold conditions. Solifluction was the most important slope process. No deposits have been found from the Last Glacial Maximum, arguably because this period was too dry. The last five deposits (from about 11 ka to before 0.17 ka) resulted from fluvial redistribution of upslope material and older deposits under increasing precipitation. Current extreme gully erosion in the Masotcheni Formation indicates a lack of available upslope material, leaving downslope deposits as the only sediment source for fluvial redistribution. This model for landscape response to climate change may be able to explain how climate controlled landscape processes in other Masotcheni Formation sites in KwaZulu Natal. In the research area and elsewhere, this proposition may be tested with numerical landscape evolution models.

2.1 INTRODUCTION

Hillslopes in central and western parts of KwaZulu-Natal, South Africa, are often mantled by colluvial sediments of the Masotcheni Formation. These sediments have accreted in response to several cycles of deposition, pedogenesis and incomplete erosion over the last 100 ka (Botha, 1996). Currently, extreme gully erosion incises deeply into these sediments, creating badland topography and causing a loss in area and accessibility of agricultural land. This erosion and associated problems severely affect the communal lands in the footslopes of the Ukhahlamba-Drakensberg Park, World Heritage Site, in the west of the province, where people rely heavily on natural resources for their daily living (Sonneveld *et al.*, 2005).

Research on colluvial sediments of the Masotcheni Formation has focussed on their stratigraphical subdivision by means of palaeosols and layers of colluvial deposits (Botha *et al.*, 1992; Botha and Fedoroff, 1995; Botha, 1996; Clarke *et al.*, 2003). The emphasis of this research was to relate the sequence of accretion (colluviation) and intervening periods of pedogenesis and erosion to late Quaternary palaeoclimatic records (particularly those of Partridge *et al.*, 1997; Scott, 2002). Radiocarbon and luminescence dating were employed for palaeosols and deposits, respectively. Results suggested that colluvium accumulated during arid stages, while pedogenesis may have occurred under periods of greater humidity. Temperature was not found to be a driving factor (Clarke *et al.*, 2003). Landscape processes and drivers that led to net accretion of Masotcheni Formation sediments have received less attention so far.

Analysis of the genesis and driving factors of recent gully erosion into Masotcheni Formation colluvia was undertaken on different spatial and temporal scales. On a provincial scale, Botha (1996) found a correlation between colluvial successions on different bedrock types and gully erosion, which indicated e.g. the extreme vulnerability of Masotcheni Formation sediments. Sonneveld *et al.* (2005) found that activity of erosion features at sub-catchment and site scale varied over time with rainfall, grazing regime and population density in Okhombe Valley. Rienks *et al.* (2000) found that erodibility of Masotcheni Formation sediments elsewhere in the province was correlated with electrical conductivity and sodium adsorption ratio, and that landscape position and geomorphic threshold conditions also co-determine erosion.

Little attention has been given to the shared landscape-process context of Masotcheni Formation deposition and current extreme gully erosion. When studying Masotcheni Formation deposition, Botha (1996) discussed the empirical model of Knox (1972) that relates 'geomorphic work' (e.g. erosion) to precipitation regime and vegetation cover, though he cautioned that it should be used on several temporal and spatial scales when studying the deposition of Masotcheni Formation colluvia. Tooth *et al.* (2004) focussed on geological controls on alluvial river behaviour in a setting similar to Okhombe Valley, and found that highly resistant dolerite intrusions co-determine river behaviour. Holistic spatial approaches of the soil-vegetation-landscape system (*sensu* Veldkamp *et al.*, 2001) that combine approaches like those of Botha (1996) and Tooth *et al.* (2004) may give us a better understanding of the processes that control both the sequential deposition of colluvia in the past and their episodic erosion in the present.

The Veldkamp *et al.* (2001) approach was adopted for a study of Masotcheni Formation colluvia in Okhombe catchment, a communal area in the foothills of the Drakensberg World Heritage Site. This chapter focusses on fieldwork and laboratory results that show the development and depositional processes of Masotcheni Formation colluvia in the area. In addition, a process model of this landscape's response to climate change is proposed.

The objective is to propose a process model of landscape response to climate change for Masotcheni Formation sediments in this area, based on field observations, micromorphology, stable carbon isotope analysis and Optical Stimulated Luminescence dating (OSL). To that end, I describe 1) the colluvial stratigraphy in the research area, 2) the sedimentary succession and erosional and depositional processes of this stratigraphy.

2.2 RESEARCH AREA

Fieldwork was conducted over several years in a 4 km² research area in Okhombe valley (Figs 1.2, 1.4 and 1.5). The research area is on the periphery of the main extent of Masotcheni Formation colluvia sites in KwaZulu Natal (Botha, 1996) and comparable sites in Swaziland (Price-Williams *et al.*, 1982; Dardis, 1990). Its relatively high altitude leads to lower temperatures and higher rainfall when compared to these sites. However, crucial similarities with these sites occur: landscape position, the fact that basal sediments were deposited on bedrock stripped of regolith, the evidence of cycles of deposition, soil formation and incomplete erosion leading to colluvia with interbedded palaeosols and their current, often extreme erosion. Therefore, the sediments in my research area were initially and tentatively assigned to the Masotcheni Formation.

2.3 METHODS

Field observations

A total of 14 sites were selected to ensure representation of the different landscape elements, gullies and areas between bedrock steps (Fig 1.5). Within this setting, site selection was based on the availability of vertical outcrops that were not covered with vegetation. Where several options were available, gully sidewall exposures with maximum thickness and clarity were chosen. Horizons at the sites were distinguished based on colour, texture and structure and described as palaeopedological master soil horizons using FAO terminology (FAO, 1990). Based on the master horizons, their morphology and the abruptness of the boundary between them, strata were defined, typically as a combination of palaeo A and B/C master horizons. Strata and horizons were traced in gully sidewalls between studied sites (Fig. 1.5). This established an overall correlated stratigraphy that orders deposits in the research area. Fig. 2.1 summarizes this procedure. Note that arabic numerals are used to distinguish strata for every site (FAO, 1990), but that roman numerals are used to indicate deposits that have been correlated between sites.

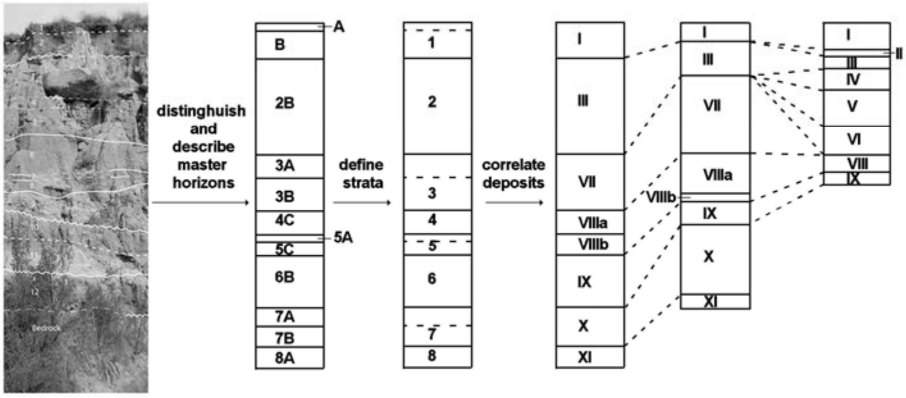


Fig. 2.1: The procedure used during fieldwork to map the extent of different colluvial layers in the research area.

Micromorphology

Micromorphological samples were taken from strata in sites 1 and 2 (Fig. 1.5) to investigate depositional processes in more detail than was possible during fieldwork. Because of the interest in depositional processes, samples were taken from horizons that had been affected by soil formation as little as possible. Structurally undisturbed samples (8x8 cm) were taken in cardboard boxes and later impregnated with a polyester resin. Thin sections were made following the method of Fitzpatrick (1970) and examined with a petrographic macro- and microscope in plane polarized and cross polarized light. The micromorphological description uses the terminology of Stoops (2003).

Stable carbon isotope analysis

Soil samples for stable carbon isotope analysis on Soil Organic Matter (SOM) were taken from sites 1 and 2 (Fig. 1.5, Balesdent *et al*, 1987). These samples were typically taken from buried A horizons. Samples were dried and sieved and roots were removed before grinding to powder. Carbon content was analysed in an element analyser and samples containing 800 mg of SOM were analysed at the Stable Isotope Facility at UC Davis, CA, USA. Isotopic composition is reported in per mil (‰) notation where

$$\delta^{13}C = \{(^{13}C/^{12}C)_{sample} / (^{13}C/^{12}C)_{standard} - 1\} x1000. \quad (2.1)$$

The standard designates the global isotopic reference standard from Pee Dee Formation Belemnites (PDB) in SC, USA.

Optically Stimulated Luminescence dating

OSL dating was used to determine the time of sediment deposition. This method determines the last time sand grains were exposed to daylight, i.e. the time of deposition and period of burial of the sediment. Two measurements are recorded for OSL dating:

1) The amount of ionizing radiation absorbed by quartz grains since last exposure to daylight. This is called the equivalent dose (D_e) and is expressed in Gray (Gy; 1 Gy = 1 J kg^{-1}).

2) The radiation dose the quartz grains receive in the natural environment per year. This is termed the dose rate ($\dot{D}$) and is expressed in Gy ka^{-1}. The age is then obtained by the equation:

$$Age(ka) = \frac{D_e(Gy)}{\dot{D}(Gy/ka)} \tag{2.2}$$

Samples were preferentially taken in A-horizons, to ensure maximum bleaching before burial (*cf.* Bush and Feathers, 2003). This means that resulting dates indicate the time of burial of a deposit, rather than the time of deposition. Samples for OSL dating were taken as 50x40x40 cm blocks from sites 1, 3 and 11 (Fig. 1.5). Blocks were reduced to 20x10x10 cm by removing their outer, light-exposed surfaces under subdued orange light.

Quartz grains in a narrow size range (125-180 µm for sample NCL-2205121, 90-180 µm for sample NCL-2205125, 180-212 µm for all other samples) were obtained using sieving and chemical treatment (HCl, H_2O_2, HF). The Single-Aliquot Regenerative-dose (SAR) procedure (Murray and Wintle, 2000; Murray and Wintle, 2003) was used for D_e determination. This procedure monitors and corrects for changes in luminescence sensitivity of samples during the measurement procedure.

2.4 RESULTS

Field observations

A summary of profile descriptions at the 14 selected sites, as well as the correlation of deposits between them, is given in Table 2.1.

Table 2.1: Summary of profile descriptions. For horizons, Guidelines for Soil Description master horizon codes are used (FAO, 1990). For correlated deposit, roman numerals indicate the consecutive deposits. For texture class, S = sand, SL = sandy loam, LS = loamy sand, L = loam, CL = clayloam, SCL = sandy clayloam. For structure type, GR = granular, AB = angular blocky, SB = subangular blocky, PR = prismatic. For structure grade, WE = weak, ST = strong. For boundary distinctness, G = gradual, C = clear, A = abrupt.

Layer	Horizon (GSD)	Correlated deposit	Depth (cm)	Texture class (SSM)	Structure type, grade (GSD)	Boundary distinctness (GSD)
Site 1						
1	A	I	0-20	SL	GR, WE	G
2	B	I	20-110	LS	GR, WE	A
3	2B	III	110-420	SL	AB, WE	A
4	3A	VII	420-490	SL	AB, ST	C
5	3B	VII	490-600	SL	GR, WE	C
6	4C	VIIIa	600-680	CL	PR, ST	C
7	5A	VIIIb	680-690	SCL	PR, ST	C
8	5C	VIIIb	690-730	CL	PR, ST	C
9	6B	IX	730-910	S	GR, WE	A
10	7A	X	910-970	SL	PR, ST	G
11	7B	X	970-1030	SL	AB, WE	A
12	8A	XI	1030-1110	LS	PR, ST	
Site 2						
1	A	I	0-30	SL	GR, WE	G
2	B	I	30-60	SL	GR, WE	C
3	2B	III	60-170	SCL	AB, ST	C
4	3A	VII	170-300	SL	AB, WE	C
5	3B1	VII	300-330	SL	AB, WE	G
6	3B2	VII	330-420	SL	SB, WE	C
7	4C	VIIIa	420-550	S	GR, WE	C
8	5B	VIIIb	550-575	SL	AB, WE	C
9	6A	IX	575-585	SCL	AB, ST	G
10	6B	IX	585-650	SCL	AB, WE	A
11	7A	X	650-770	SL	AB, ST	C
12	7B1	X	770-830	LS	AB, WE	C
13	7B2	X	830-840	SL	AB, ST	C
14	7B3	X	840-875	S	GR, WE	C
15	8A	XI	875-920	L	PR, ST	
Site 3						
1	A	I	0-70	SL	GR, WE	G
2	B	I	70-110	SL	GR, WE	A
3	2A	II	110-130	SCL	SB, ST	A
4	3B	IIII	130-180	SL	AB, WE	A
5	4A	IV	180-235	SCL	PR, ST	C
6	4B	IV	235-270	SL	AB, WE	A
7	5A	V	270-310	SCL	AB, ST	C
8	5B	V	310-415	SCL	PR, ST	A
9	6A	VI	415-480	SC	SB, WE	C
10	6B	VI	480-500	LS		
11	7C	VIIIb	to side	CL		
12	8A	IX	to side	SCL		

Layer	Horizon (GSD)	Correlated deposit	Depth (cm)	Texture class (SSM)	Structure type, grade (GSD)	Boundary distinctness (GSD)
Site 4						
1	A	I	0-30	SL	GR, WE	G
2	B	I	30-90	SL	GR, WE	C
3	2A1	IV	90-190	C	SB, WE	G
4	2A2	IV	190-230	SC	SB, WE	G
5	2B	IV	230-350	SL	AB, WE	C
6	3A	VI	350-385	SL	AB, WE	C
Site 5						
1	A	I	0-35	SL	GR, WE	G
2	B1	I	35-70	SL	GR, WE	G
3	B2	I	70-120	SL	GR, WE	C
4	2B1	III	120-160	SL	AB, WE	G
5	2B2	III	160-290	SCL	AB, WE	C
6	3A	IV	290-410	CL	AB, ST	G
7	3B	IV	410-495	LS	SB, WE	A
8	4A	V	495-510	SCL	AB, ST	G
9	4B	V	510-575	SCL	AB, ST	A
10	5A	VI	575-580	SCL	AB, ST	G
11	5B	VI	580-620	SL	AB, WE	C
12	6A	VII	620-650	LS	AB, WE	
Site 6						
1	A	I	0-30	SL	GR, WE	G
2	B1	I	30-100	SL	GR, WE	G
3	B2	I	100-145	SL	GR, WE	C
4	2B	III	145-210		GR, WE	A
5	3A	IV	210-240	SCL	AB, WE	C
6	3B	IV	240-380	SCL	AB, ST	G
7	4A	VI	380-430	SCL	SB, WE	C
8	4B	VI	430-480	SL	AB, WE	G
9	5A	VII	480-490	SL	AB, WE	
Site 7						
1	A	I	0-35	SL	GR, WE	G
2	B	I	35-120	SL	GR, WE	C
3	2B	III	120-180	SL	PR, ST	G
4	3B	IV	180-375	SL	AB, WE	C
5	4A	VI	375-390	SL	GR, WE	C
6	4B	VI	390-500	S	GR, WE	C
7	5A	VII	500-520	SCL	AB, WE	
Site 8						
1	A	I	0-35	SL	GR, WE	G
2	B	I	35-80	SL	GR, WE	G
3	2B1	III	80-115	SL	GR, WE	C
4	2B2	III	115-195	LS	GR, WE	G
5	3A	IV	195-225	SC	SB, WE	G
6	3B	IV	225-415	LS	GR, WE	A
7	4A	VI	415-435	SC	SB, ST	G
8	4B	VI	435-475	LS	GR, WE	C

Layer	Horizon (GSD)	Correlated deposit	Depth (cm)	Texture class (SSM)	Structure type, grade (GSD)	Boundary distinctness (GSD)
9	5A	VII	475-495	SC	SB, WE	G
10	5B	VII	495-545	SL	AB, ST	
Site 9						
1	A	I	0-45	SL	GR, WE	A
2	2B	III	45-90	SCL	AB, WE	C
3	3A1	IV	90-150	CL	AB, ST	C
4	3A2	IV	150-170	SCL	AB, ST	C
5	3A3	IV	170-220	CL	AB, WE	G
6	3A4	IV	220-245	LS	SB, WE	G
7	3A5	IV	245-270	SCL	AB, WE	C
8	3B	IV	270-350	LS	AB, WE	C
9	4A	VI	350-400	SCL	AB, WE	G
10	4B	VI	400-410	SL	AB, WE	C
11	5A	VII	410-440	LS	GR, WE	
Site 10						
1	A	I	0-30	LS	GR, WE	G
2	B	I	30-60	LS	GR, WE	C
3	2B	III	60-170	SCL	SB, WE	C
4	3A1	IV	170-240	SC	SB, WE	G
5	3A2	IV	240-270	SCL	AB, ST	G
6	3B1	IV	270-330	SL	SB, WE	G
7	3B2	IV	330-420	SL	SB, WE	C
8	4A	VI	420-455	SL	SB, WE	C
9	4B1	VI	455-530	LS	SB, WE	G
10	4B2	VI	530-590	LS	SB, WE	
Site 11						
1	A	I	0-25	SL	GR, WE	G
2	B1	I	25-50	SL	GR, WE	G
3	B2	I	50-75	SL	GR, WE	A
4	2A1	II	75-120	SCL	PR, ST	G
5	2A2	II	120-185	SCL	PR, ST	A
6	3B1	III	185-250	SL	SB, WE	C
7	3B2	III	250-300	LS	SS	C
8	3B3	III	300-400	LS/SC	SS	A
9	4A1	IV	400-450	CL	PR, ST	G
10	4A2	IV	450-505	SCL	PR, ST	C
11	4B	IV	505-555	SCL	SB, WE	A
12	5B	V	555-630	CL	AB, ST	
Site 12						
1	A	I	0-31	LS	GR, WE	G
2	B	I	31-60	LS	SB, ST	C
3	2B	III	60-95	LS	SB, ST	C
4	3A	IV	95-139	CL	AB, WE	C
5	3B	IV	139-173	SCL	AB, WE	G
6	4A	VI	173-191	SCL	AB, WE	G
7	4B1	VI	191-270	SCL	SB, ST	G
8	4B2	VI	270-325	SCL	SB, ST	

Layer	Horizon (GSD)	Correlated deposit	Depth (cm)	Texture class (SSM)	Structure type, grade (GSD)	Boundary distinctness (GSD)
Site 13						
1	A1	I	0-35	FS	GR, WE	G
2	A2	I	35-65	FS	GR, WE	G
3	B	I	65-110	FS	GR, WE	C
4	2B1	III	110-130	LS	GR, WE	C
5	2B2	III	130-175	FS	GR, WE	A
6	3A	IV	175-195	SCL	GR, WE	G
7	3B1	IV	195-212	SL	GR, WE	G
8	3B2	IV	212-253	SCL	GR, WE	G
9	3B3	IV	253-280	SL	GR, WE	
Site 14						
1	A	I	0-28	FS	GR, WE	G
2	B1	I	28-47	FS	GR, WE	G
3	B2	I	47-60	FS	GR, WE	C
4	2A	IV	60-102	SCL	AB, ST	C
5	2B1	IV	102-115	SL	AB, ST	G
6	2B2	IV	115-155	SL	AB, WE	C
7	3A1	VI	155-205	CL	AB, ST	G
8	3A2	VI	205-250	CL	AB, ST	

Thickness of the deposits is typically between 5 and 8 m in the most concave positions close to the uphill slopes (sites 1-5, 10, 11). Going downstream, thickness decreases and is typically 3-6m in the area around sites 6-8. There, the stepped bedrock surface has caused changes in thickness of the deposits over distances of about one hundred meters. Thickness ranges between 1 and 3 m in the most downstream deposits (sites 9 and 12-14 were taken on positions of maximum thickness).

Textures are mixtures of sand, silt and clay that reflects the combination of parent materials: sand- and mudstones (ref. landscape elements A and B in Fig. 1.4). No differences in mean texture were observed between up- and downstream sites, though deposits in downstream sites (e.g. sites 12-14) are better sorted than deposits in upstream sites (e.g. sites 1-4).

Textural differences between A and B or C horizons were not observed. Most A-horizons were Ah-horizons, with accumulation of organic matter visible as lower value colours than corresponding B or C horizons. Structure elements in A-horizons were usually smaller than in corresponding B or C horizons.

Soil structures are mostly weakly developed. Granular structure is more common in downstream sites, angular and subangular blocky structure is more common in upstream sites. Strongly developed prismatic structure is found in some horizons in upstream sites that have a higher than average amount of clay.

Identification and correlation of the colluvial sequence between sites revealed a stacked succession of eleven deposits across the study area. Variation in thickness of individual deposits and the effects of localized truncation results in partial preservation. Fig. 2.2 shows the deposits at three of the most complete sites.

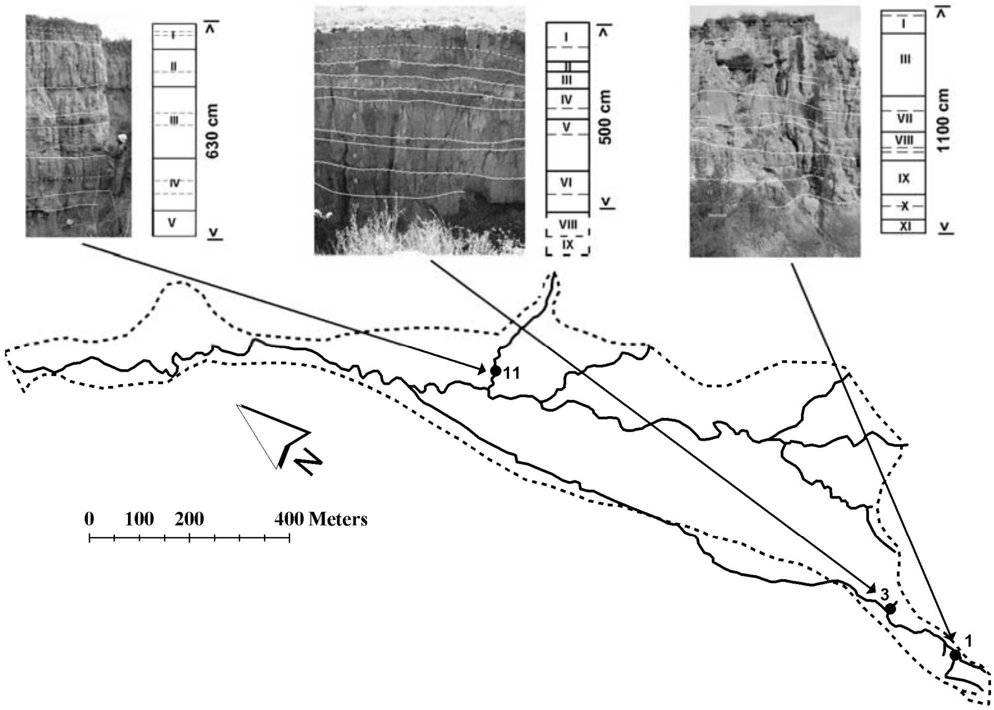


Fig. 2.2 : Deposits at three of the most complete sites. In the picture of site 3, the lowest deposits are not visible.

Fig. 2.3 shows the distribution of the stratigraphy by means of the correlated deposits in the described sites. The oldest deposit (XI) is visible only in some of the most upslope sites (1 and 2). More recent deposits are visible over more of the area, with deposits VI, IV and III present in almost all sites. Deposit II seems only of local importance, but may be difficult to observe where soil formation in deposit I has also affected the underlying deposit II.

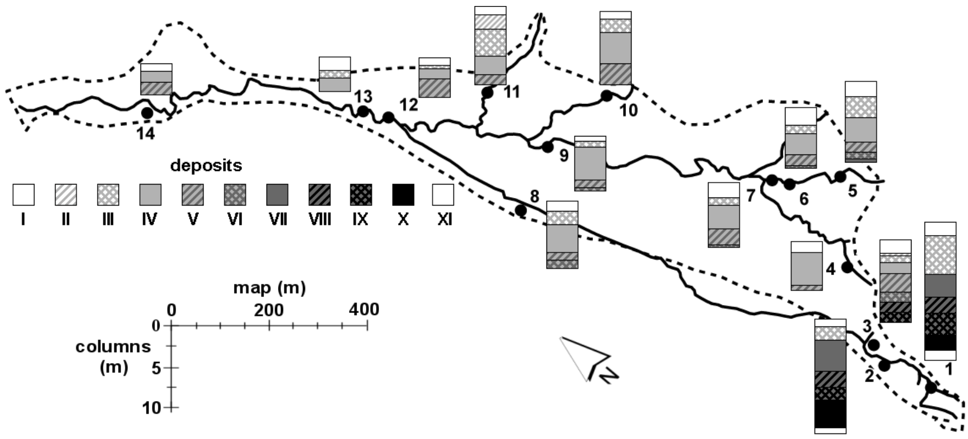


Fig. 2.3 : Distribution of the stratigraphy over the research area.

In sites 1-3, and throughout the southernmost deposits, two deposits (deposits VIIIa and VIIIb) were found that were different from other deposits in up- or downstream sites. Deposit VIII (strata 6-8 in site 1, stratum 7 in site 2 and stratum 11 in site 3) is denser and has a more reddish hue than deposits that under- and overlie it (for instance 2.5YR versus 10YR in site 1). From site 1, five micromorphological samples were taken from the strata that form this deposit.

One of the horizons of deposit VIIIa in site 1 is a 10cm thin, weakly developed palaeo A-horizon (stratum 7). Here, limited soil formation had occurred before deposit VIIIb buried this horizon, as evidenced by horizontal imprints of flattened reed-type leaves on the contact between the palaeo-A and the overlying horizon (Fig. 2.4 C). The leaf imprints are oriented in the direction of flow of deposit VIII b, which approximates current drainage direction.

In downstream sites typically two or three strata are observed. Sediments display evidence of fluvial deposition, stratification and ubiquitous infilled palaeochannels (Fig. 2.4 A and B). The downstream area shows many currently abandoned meanders, whereas interpolations between palaeochannels also indicated meandering behaviour. This is no surprise given the low-gradient position in the landscape upstream of the dolerite barrier (*cf* Tooth *et al.*, 2004). Because of the better sorting of the sediments, less permeable strata alternate with more permeable strata. This hampers downward flow of water through the profile, resulting in stagnic properties and causing frequent piping erosion in these positions (*cf* Beckedahl, 1996).

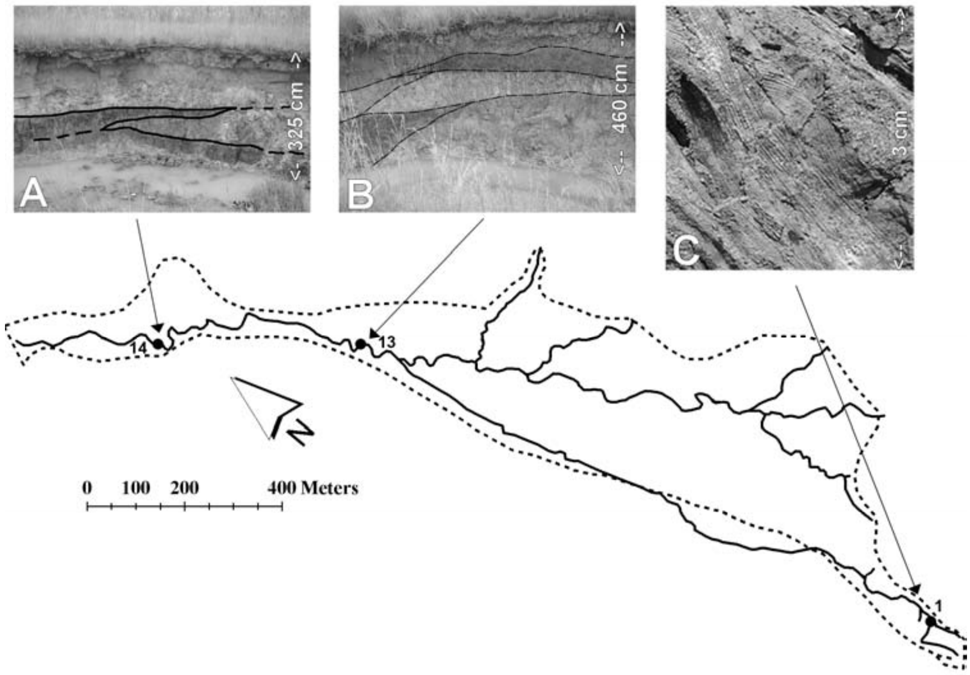


Fig. 2.4 : Evidence of fluvial deposition in downstream sites (A and B) and leaf imprints on palaeo-A horizon 7, site 1 (C).

In upstream sites 1, 2 and 5, more strata are observed. The lowest strata in these sites display no evidence of fluvial deposition; sediments here are unlayered, denser and poorly sorted. Matrix-supported gravel, stones and boulders are found in some strata. In site 1, a rectangular sandstone rock of about 2 x 1 .5 x 0.5 m was found, oriented horizontally in deposit VII. This block has been transported with the sediment given its position about 150 meters from source areas. This suggests that strata in these upstream sites have been deposited by other processes than strata in downstream sites. To get more insight in these processes, micromorphological samples were taken from sites 1 and 2.

The resolution of Fig. 2.3 does not allow for a detailed representation of stratigraphic differences close to bedrock steps within landscape element C. In some situations, the lowest stratum immediately upstream and immediately downstream a sandstone step is equally old, though that stratum is usually thicker downstream. This difference in thickness decreases in overlying layers. In other cases, the oldest strata have been eroded for up to hundred meters upstream of the step, but are visible immediately downstream of the step until they again dissappear further downstream.

Micromorphology

Micromorphological samples were taken in sites 1 and 2, where least information on depositional process was obtained from field observations. The position of the micromorphological samples is given in Fig. 2.5. A summary of the results is given in Table 2.2.

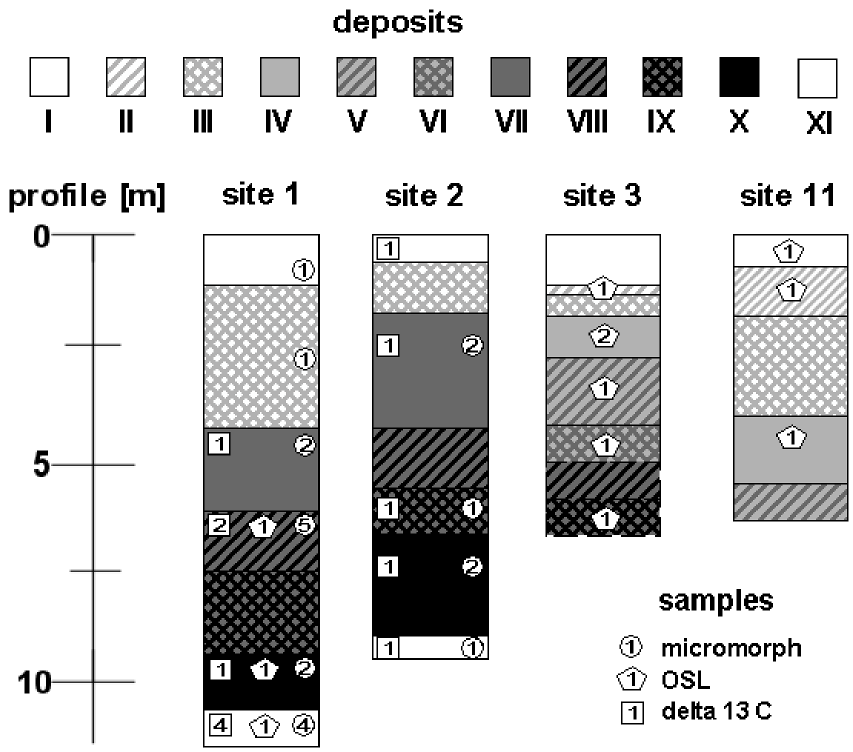


Fig. 2.5: The position of micromorphological, stable carbon isotope and Optical Stimulated Luminescence (OSL) samples in sites 1, 2, 3 and 11. Micromorphological samples are indicated with circles, stable carbon isotope samples with squares and OSL samples with pentagons. The numbers in the circles, squares and pentagons indicate the number of samples taken in a deposit.

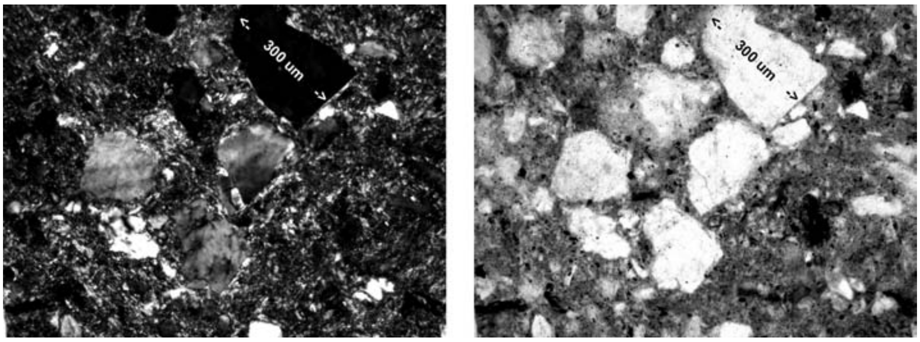


Fig. 2.6: Granostriation along the surfaces of the grains in the centre of this sample. Picture taken under cross-polarized (left) and plane-polarized light (right).

Micro-scale stratification is absent in all samples and most samples have distinct or prominent dense packing, consistent with a lack of preserved fluvial depositional structures in these sites. Related distribution patterns are almost exclusively single-spaced porphyric and samples have common and sometimes many granostriated b-fabrics (Fig. 2.6). Generally, samples have common large pores and few fine pores. Grain sizes of the deposits range from clay to small gravel (<6mm), consistent with my macromorphological observations that included stones, gravel and rocks. Samples displayed clay illuviation in different degrees, except for samples from deposit VIII, where clay illuviation is absent.

Notable exceptions are deposits X and XI in site 2, where dense packing is weaker or rare and few granostriated b-fabrics are found. Vughy microstructure is found in the three samples that were taken from these deposits. Also, these deposits have many fine pores.

The dominant origin of SOM differs between deposits and sites. In site 1, SOM is randomly distributed and stains the fine material, except in deposit VIII where organic matter fragments are scarce and occur in sharply bounded, subrounded groundmass bodies of 100-300 micron. This indicates that SOM resulted from soil formation in all deposits in site 1, except for deposit VIII, where SOM is predominantly inherited. In site 2, SOM was both inherited and a result of soil formation in deposits VII and IX and a result of soil formation in deposits X and XI.

The reddish colour of the event-based deposit VIII is caused by finely dispersed iron compounds that stain clay coatings. Consistent with the macromorphological observation of a weakly developed A-horizon and weak soil formation within this deposit, easily weatherable minerals like biotite and chlorite are present in the groundmass but give no indication of weathering. This suggests that the SOM and iron compounds were both inherited. In addition, it demonstrates that the parent material for this deposit is a mix from different sources. A likely explanation is an origin from both landscape element A (Fig. 1.4, dominated by often reddish mudstone) and landscape element B (Fig. 1.4, dominated by sandstone).

Table 2.2: Results of micromorphological analysis. For dense packing, microstratification, granostriated b-fabric, large and fine pores: - = absent, + = weak/few, ++ = common/distinct, +++ = many/prominent. For related distribution pattern: S = single spaced porphyric, D = double spaced porphyric. For SOM origin: sf = soil formation, in = inherited.

Master horizon	Correlated deposit	Dense packing	Micro-stratification	Distribution pattern	Granostriated b-fabric	large pores	fine pores	SOM origin
Site 1								
B	I	++	-	S	++	++	+	sf
2B	III	++	-	S	++	++	++	sf
3A	VII	+++	-	S/D	++	++	+	sf
3B	VII	++ -	-	S	++ -	++	++	sf
4C	VIIIa	+++	-	S	++	++	+	in
4C	VIIIa	++	-	S/D	++	++	+	in
5A	VIIIb	++	-	S	++	++	+	in
5A	VIIIb	++	-	S	++	++	+	in
5C	VIIIb	+++	-	S	++	++	+	in
7A	X	++	-	S	++	++	++	sf
7B	X	++ -	-	S	+ -	++	+++	sf
8A	XI	++	-	S	++	++	-	sf
8A	XI	++	-	S	++	++	++	sf
8A	XI	++	-	S	++	++	++	sf
8A	XI	+++	-	D/S	+++	++	+	sf
Site 2								
3A	VII	++	-	S/D	++(+)	++	+	in/sf
3B1	VII	++	-	S	++	++	++	in/sf
6B	IX	++	-	S	++	++	++	in/sf
7A	X	++	-	S	++	++	+++	sf
7B	X	-	-	S	+	++	+++	sf
8A	XI	-	-	S	+	+	+++	sf

All other deposits in upstream sites, including deposits X and XI in site 2, lack the distinct reddish colour and thus at least the majority of inherited iron compounds. This means that the influence of parent material from landscape element A on these deposits is smaller. Therefore, they must predominantly originate from landscape element B, the steeper slopes dominated by sandstone, directly above the upstream sites.

Combining these results with field observations, deposits in upstream sites, except deposits X and XI in site 2, are diamictons; very poorly sorted sediments. The fine, granostriated diamictons that are found in restricted landscape positions below steeper slopes indicate sediment deposited by solifluction mechanisms (Bertran and Texier, 1999). Note that solifluction is used *sensu lato* (Bloom, 1998) and that no periglacial climatic setting is implied. For the event-based deposit VIII, where leaf imprints (Fig 2.4 C) indicated at least two fast flows, deposition happened in multiple mudflows, rather than one earthflow.

Deposits X and XI in site 2 give a more colluvial impression and are most likely a redistribution of the material from the same deposits in site 1. This corresponds with my field observations that the oldest deposits were confined to the most upstream areas. Downstream redistribution of that material could be visible in site 2.

Stable carbon isotope analysis

The position of the samples for stable carbon isotope analysis in sites 1 and 2 is given in Fig. 2.5. A summary of the results is given in Table 2.3. Where SOM is dominantly inherited, the results give an indication of the vegetation composition in the sediment source area at the time of erosion. Where SOM is dominantly a result of soil formation *in situ*, the results give an indication of the vegetation composition during soil formation at the sampled locations. Since samples were taken in upstream sites, where sediment source areas are within a few hundred meters of sampled locations, differences between $\delta^{13}C$ values of inherited SOM and SOM resulting from soil formation must reflect an overall change in vegetation in the research area.

Baseline samples from contemporary soils indicate a clear difference between forest and grassland. Litter and A-horizon values in an old afromontane forest about four kilometers from the research area are below -26‰. Litter and A-horizon values in grassland a few hundred meters from the research area, as well as values from the A horizon (deposit I) of site 2, are above -13‰.

Table 2.3: Stable carbon isotope results. Baseline samples for forest and grassland were taken from both the litter and the A-horizon in representative sites. For SOM origin: sf = soil formation, in = inherited.

Site	Master horizon	Correlated deposit	$\delta^{13}C$ (‰)	SOM origin
Forest	Litter		-26.11	
	A-horizon		-26.17	sf
Grassland	Litter		-12.56	
	A-horizon		-12.7	sf
Site 1	3A	IV	-14.46	sf
	5A	VIII	-12.59	in
	5A	VIII	-12.48	in
	7A	X	-15.51	sf
	8A	XI	-15.12	sf
	8A	XI	-15.05	sf
	8A	XI	-14.93	sf
	8A	XI	-14.47	sf
Site 2	A	I	-12.47	sf
	3A	IV	-14.95	in/sf
	6A	IX	-16.73	in/sf
	7A	X	-14.77	sf
	8A	XI	-14.56	sf

In the samples taken from the palaeo-deposits, $\delta^{13}C$ values between -12.48‰ and -16.73‰ were found, all indicating a vegetation dominated by grassland, generally with a somewhat larger contribution of trees and shrubs than in current grassland.

Values for SOM from the event-based deposit (VIII) are higher than others (-12.48‰ and -12.59‰ versus values between -14.46‰ and -16.73‰). SOM from this deposit was dominantly inherited, whereas SOM from other deposits dominantly results from soil formation. This suggests that a grassland with somewhat more trees and shrubs than in present grassland was present in the periods of soil formation on the deposits. It also suggests that almost only grass was present during the periods of deposition.

Optically Stimulated Luminescence dating

The position of the samples for OSL dating in sites 1, 3 and 11 is given in Fig. 2.5. A summary of the results is given in Table 2.4. Dates range from 42 ka for burial of deposit XI to 0.17 ka for present-day surface deposit I.

Table 2.4: Optical Stimulated Luminescence (OSL) dating results.

Site	Lab code	Master Horizon	Correlated deposit	Age (ka)	Error (ka)
Site 1	NCL-2205119	5A	VIII	29.4	2.4
	NCL-2205127	7A	X	38.5	2.8
	NCL-2205120	8A	XI	42.4	3.7
Site 3	NCL-2205121	2A	II	7.73	0.36
	NCL-2205122	4A	IV	7.86	0.42
	NCL-2205123	4B	IV	11.6	0.9
	NCL-2205124	5B	V	10.6	0.6
	NCL-2205125	6A	VII	10.3	0.5
	NCL-2205126	8A	IX	35.5	2
Site 11	NCL-2205128	A	I	0.169	0.025
	NCL-2205129	2A1	II	8.76	0.66
	NCL-2205130	4A1	IV	9.67	0.44

In site 1 and 11, the dates are internally consistent, i.e. they are in correct stratigraphic order. In site 3, the dates are not internally consistent; samples taken in master horizons 4B and, less problematically, 5B are older than the sample from underlying master horizon 6A. To investigate the reasons for this age reversal, the scatter in single aliquot equivalent doses for these samples were compared (Wallinga *et al.*, 2002). For representation the single aliquot equivalent dose was divided by the sample dose rate, so single-aliquot ages could be plotted to allow comparison of the different samples (Fig. 2.7). Based on the greater scatter between the individual aliquot results for the samples taken from the B-horizons (4B and 5B) it was concluded that for these samples the OSL signal of some grains was not completely reset prior to deposition (*cf* Bush and Feathers, 2003). As a consequence the OSL ages for these samples slightly overestimate the burial age.

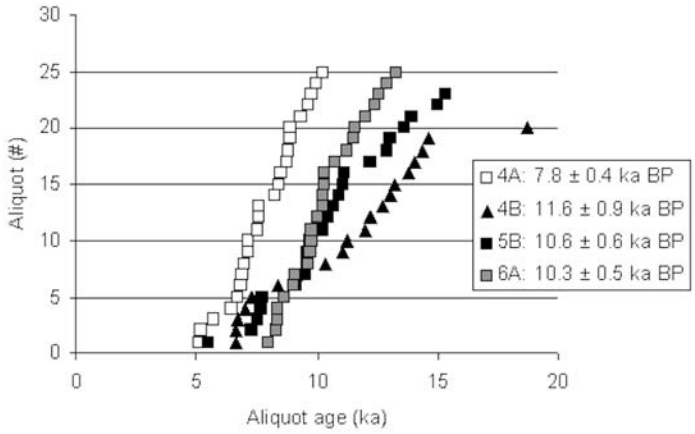


Fig. 2.7: A comparison of aliquot ages for some samples taken from site 3. To avoid bias by outliers, single aliquot estimates removed more than 2 standard deviations from the sample mean were rejected in an iterative procedure.

To check the consistency of our correlation between sites, deposit II and IV were sampled in both site 3 and site 11. Deposit II was dated to 8.76 ± 0.66 ka in site 11 versus 7.73 ± 0.36 ka in site 3. Deposit IV was dated to 9.67 ± 0.44 ka in site 11 versus 7.86 ± 0.42 ka in site 3. This may indicate that our correlation between sites 3 and 11 has been unsuccesful and that deposits in site 3 belong higher in the stratigraphic sequence. However, these differences of up to 2 ka could also be attributed to lags in landscape response, with deposition occurring earlier in upstream site 3 than in downstream site 11. No changes to the correlated stratigraphy were made.

The oldest deposits in upstream sites are from a late Pleistocene age (buried at 42.4 ± 3.7 ka - 29.4 ± 2.4 ka), before the Last Glacial Maximum, i.e. in Oxygen Isotope Stage (OIS) 3. These deposits typically result from solifluction. Younger deposits, resulting from fluvial redistribution, are of Holocene age (buried at 10.3 – 0.17 ka, OIS 1). The age of the current A horizon of site 11 likely does not reflect the time of deposition because of ongoing bleaching (Bush and Feathers, 2003). Deposition probably stopped well before 0.17 ka.

2.5 Spatial and stratigraphical development

The spatial and stratigraphical development of the deposits in the research area can now be described, and inferences about evolution of its landscape can be made.

Earliest evidenced deposition, before 42 ka, was in the most concave, upstream positions (deposit XI in sites 1 and 2) and occurred on bedrock that was bared by fluvial erosion in these positions. Depositional process was solifluction and sediment source areas were the slopes dominated by sandstone above upstream sites (landscape element B in Fig. 1.4), where soil mantles must have been present. Headcuts in these slopes must have been smaller or non-existent. Some redistribution of the material supplied by solifluction has occurred, as evidenced by the lowest deposits in site 2, but the influence of that for the rest of the research area appears limited. Soil formation in the period following this earliest deposition occurred under vegetation dominated by grasses, with some influence of shrubs or trees.

In later periods of deposition, from about 42 ka to at least 29 ka, as concavity decreased upstream, area of deposition increased and deposits covered a somewhat larger area (deposits X, IX and VII). Soils formed in periods of quiessance after deposition, without evidence of vegetation changes (*cf.* Talma and Vogel, 1992). In upstream sites, the depositional process was solifluction and sediment was still sourced from the sandstone slopes, where headcuts must have become more distinct. In downstream sites, where sediment was increasingly available, streams eroded and removed deposits.

Deposit VIII (buried at 29 ka) is an exception in terms of source area (it must have orginated in landscape element A in Fig. 1.4), extent (it is only visible in the southernmost deposits and covers less than 10% of their area) and process (fast mudflows instead of slow earthflows). Likely, causes of the events associated with this deposit are not the same as the causes of the other deposits. For instance, continuous headward erosion of the steep sandstone slopes (landscape element B in Fig. 1.4), may have oversteepened the overlying mudstones (landscape element A in Fig. 1.4). In an extreme-rainfall event, failure of these mudstone slopes may have provided parent material for the observed mudflow. Vegetation in the source area during deposition was almost purely grass, but because of the specific source of this deposit, this need not be the case for the other periods of deposition.

No deposits have been found from the LGM, and clear boundaries between Holocene and pre-LGM deposits suggest limited erosion. Truncation was not apparent from sedimentological or pedological characteristics in our sites. Soil formation on deposits underlying the Holocene deposits was limited.

In the Holocene, sediments were deposited over the whole research area (deposits VII-I, from before 10 ka to probably around 7 ka). In upstream areas, deposition was sheet-like, producing a uniform stratigraphy covering the pre-LGM solifluction and mudflow deposits. In downstream areas, deposition resulted from meandering fluvial action. Headcuts in sandstone slopes upstream (landscape element B) must have achieved their current morphology by fluvial erosion.

Streams in the research area have been superimposed on two types of resistant rock: dolerite (in landscape element D) and sandstone (in landscape element C, ref. Fig. 1.4). Upstream of these barriers, streams had a more meandering behaviour than downstream, with associated consequences for the completeness of the stratigraphy, as shown by Tooth *et al.* (2004). This effect is less clear for sandstone steps than for the dolerite barrier because sandstone steps are more erodible and sometimes laterally discontinuous. More than a control, the highly resistant dolerite is a prerequisite for the existence of the sequence, as headward erosion from Okhombe river into the research area would otherwise have been likely.

Throughout this sequence, erosion of deposits has been limited in upstream sites (preserving thick deposits) and more or less in equilibrium with deposition in downstream sites (resulting in thin deposits). Late Holocene erosion, deeply and widely incising into upstream deposits, is more severe than it has been during the whole period of deposition of our sequence (*cf.* Clarke *et al.*, 2003). When the current episode of gully erosion started is unknown, though it is likely after deposition of deposit I, around 7 ka.

Summarizing, on bedrock locally bared by erosion prior to 42 ka, solifluction of material from upstream, dominantly sandstone slopes has provided sediment that fluvial action has eroded and redistributed.

There is no evidence of erosion or deposition in the LGM. In the Holocene, erosion and redistribution of deposits by means of fluvial action continued at least until 7 ka. Over time, the presence of resistant lithologies and fluvial channel morphology have determined the expression of this landscape-forming process on our research area.

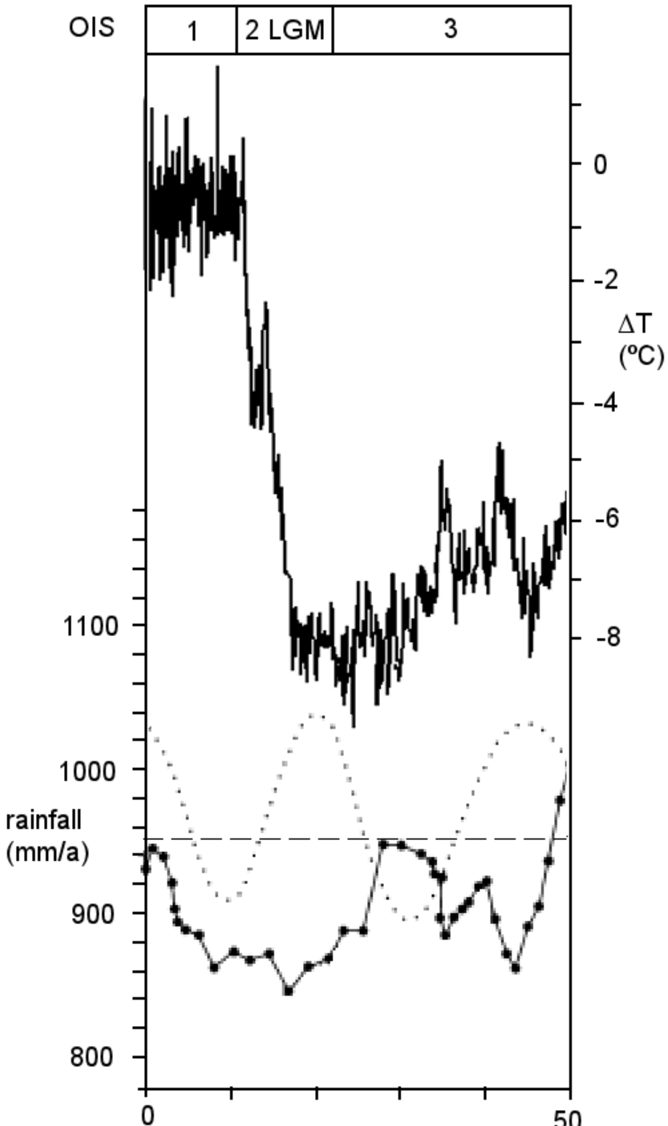


Fig. 2.8: The last 120 ka of the Vostok (temperature, Petit et al, 1999) and Pretoria Saltpan (precipitation, Partridge et al, 1997) records. The thick upper line is the temperature record, the thin lower line is the precipitation record. The dotted line is an indication of changing July insolation at 30ºS, the dashed line indicates 950 mm rainfall. Figure adapted from Clarke et al. (2003).

Other factors than lithology and topography must have determined the nature and balance of the landscape-forming processes. The fact that correlation of our deposits was generally succesful, indicates that periods of deposition and periods of soil formation alternated in the same way throughout the research area. This supports the notion of an exogenous, climatic control on nature and balance of the processes of deposition.

For our temporal extent, the most-used record of palaeo-temperature changes for South Africa is the 420 ka Vostok record (Petit *et al.*, 1999) and the most-used palaeo-precipitation record is the 200 ka Pretoria Saltpan record (Partridge *et al.*, 1997). The last 120 ka of these two records are presented in Fig. 2.8. An addition of 300 mm was made to the Pretoria Saltpan values to correct for the present-day difference between the sites, assuming that this difference has been constant in time

2.6 DISCUSSION

Combining our earlier results with climatic records (Fig. 2.8), solifluction deposits start at the beginning of the coldest phase in the climate record (around 42 ka). Temperatures in this period were typically between 6 and 7°C colder than present and rainfall was typically between 900 and 950 mm. Solifluction stopped in the LGM, when both temperature and precipitation dropped to their minimum; between 7 and 8°C colder than present with rainfall around 850 mm. No evidence for widespread erosional activity in the LGM was found. In the second phase of deposition fluvial deposits were found, dating from about 10 to about 7 ka. In this period, temperatures were comparable to present and rainfall increased from about 850 to 950 mm.

This suggests that the process of solifluction in Okhombe valley is controlled by both precipitation and temperature. Solifluction requires a saturated parent material and a slope (Bloom, 1998). A slope is obviously present in landscape elements A, B and C of the research area (Fig. 1.4). Parent material was likely supplied by physical frost-weathering of sandstone from landscape element B, given that temperatures were between 6 and 7°C colder than present, i.e. mean minimum daily winter temperatures between -2 and -3°C. Temperatures may even have been lower near our upstream sites if strong local effects like cold air drainage (Samways, 1990) are accounted for. Moreover, low temperatures must have limited vegetation and evapotranspiration, allowing for an easier saturation of parent material. Conditions were not cold enough for permafrost (*cf* Boelhouwers and Meiklejohn, 2002), but seasonal freezing and thawing of the topsoil may have increased spring saturation in this period. Saturation of the parent material is therefore likely to be a function of low temperatures and sufficient precipitation.

Fluvial redistribution of material is active whenever water flows over the surface. Botha (1996) used the model of Knox (1972, Fig. 2.9) to suggest how changes in precipitation may have influenced fluvial redistribution for Masotcheni Formation sediment elsewhere in the province. Most redistribution ('work done on the landscape') occurs after an increase in precipitation, when vegetation is still recovering from the drier phase before. Minimum redistribution occurs when vegetation is decreasing after a period of humidity. Thomas (2004), looking from a tropical perspective, proposed models for several temporal extents that can explain lag and type of landscape response to climatic change.

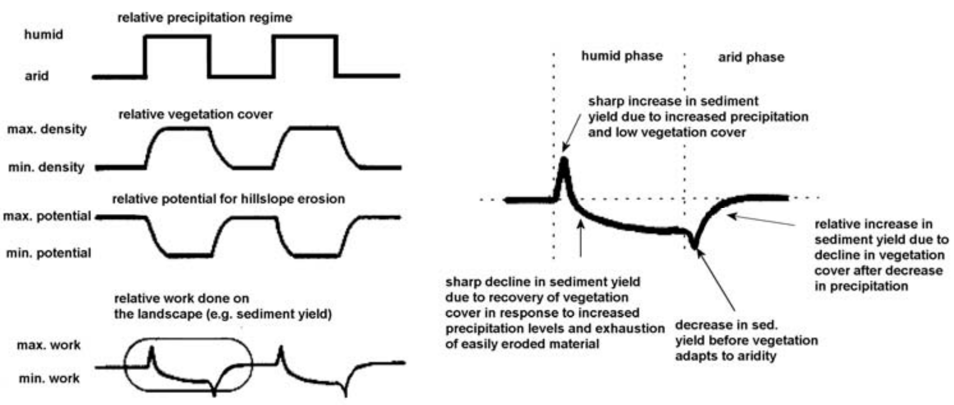


Fig. 2.9: Landscape response model, redrawn from Knox (1972) and Botha (1996).

Looking at the simultaneous changes of temperature and precipitation in the last 110 ka (Fig. 2.10, with precipitation values from the Pretoria Saltpan record), I can now summarize how climate controlled landscape evolution in Okhombe valley. Before 50 ka, three increases in precipitation occurred: an increase of almost 200mm from 105 to 90 ka, an increase of about 60mm from 80 to 70 ka, and an increase of about 100mm from 60 to 50 ka. Each of these three must have strongly increased fluvial redistribution (*cf* Knox, 1972, Thomas, 2004) and may widely have removed deposits that were present before that time. From 50 to 25 ka, changes in precipitation are less dramatic and temperatures are lower than before. Under these conditions (field 1 in Fig. 2.10), solifluction occurred in several stages but fluvial redistribution was not as active as before given the smaller and slower increases in precipitation during this period. Therefore, solifluction deposits were preserved. From 25 to 15 ka, precipitation and temperature dropped to their minimum (field 2 in Fig. 2.10). This apparently stopped both solifluction and fluvial redistribution, probably because of insufficient precipitation. Frost weathering of the sandstone slopes (landscape element B in Fig. 1.4) probably continued. In the Holocene, the strong rise in temperatures precluded solifluction and frost weathering, whereas the 50-75mm increase in precipitation increased fluvial redistribution (field 3 in Fig. 2.10). Primarily, weathered material from the mudstone and sandstone slopes must have been eroded and redistributed. Climatic variability in the Holocene (Holmgren *et al*, 2003; Mayewski *et al*, 2004) may have resulted in the observed phases of this redistribution, though their influence on precipitation in the LGM and Holocene in South-Africa is insufficiently known to make a more detailed model of landscape response. It is conceivable that exhaustion of upslope material in the last few ka (evidenced by a current lack of soil in these landscape elements) has lead to the widespread erosion of the Masotcheni Formation deposits that is observed today (field 4 in Fig. 2.10).

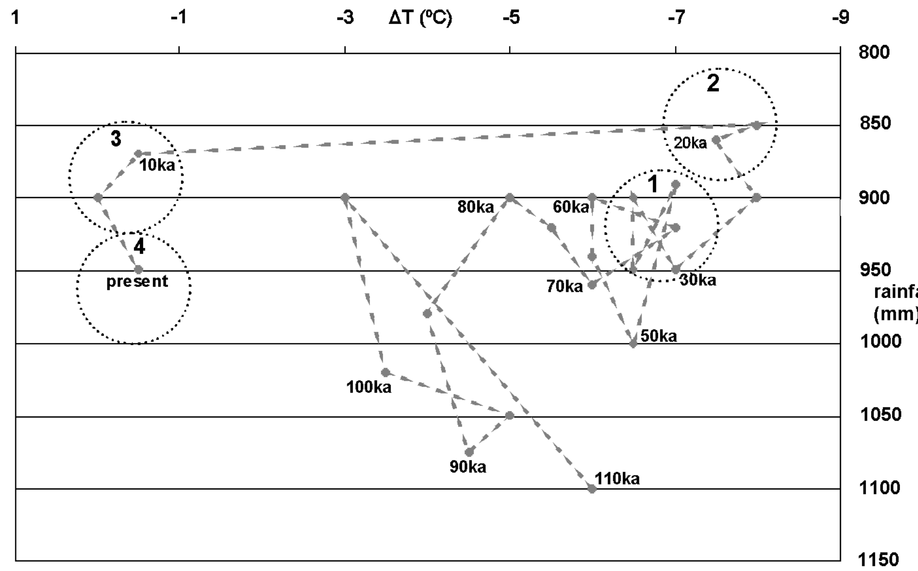


Fig. 2.10: Changing precipitation and temperature in the research area in the last 110 ka. Palaeo-precipitation and -temperature values were taken from the records in Fig. 2.8 at every 5 ka. Fields 1 to 4 approximate sets of climatic conditions under which different processes have been observed: 1) cold, solifluction, 2) dry and cold, no landscape activity, 3) warm and getting humid, active fluvial redistribution and 4) warm and getting more humid, gully erosion. Boundaries of fields are not suggesting actual boundaries to sets of climatic conditions.

This model of climatic control on Masotcheni Formation deposits extends earlier models. Botha (1996) and Clarke *et al.* (2003) suggested that deposition in their study areas resulted from increasing precipitation after drought, for records covering OIS 5 to present (including the Voordrag record, Botha, 1996; Clarke *et al*, 2003). In their study areas, situated in somewhat warmer and drier parts of the province, conditions may never have led to solifluction. Our model, developed in a valley that experienced a wide range of conditions, may be able to explain the deposition of Masotcheni Formation sediments throughout their area of occurrence.

The interactions between climatic drivers and landscape processes, operating in a landscape with structural controls, have a high degree of complexity. That makes it difficult to assess implications of different models of landscape response through space and time. Landscape evolution modelling would be a useful tool to visualize and test these models of landscape response, especially where fieldwork supplies adequate information for calibration and validation.

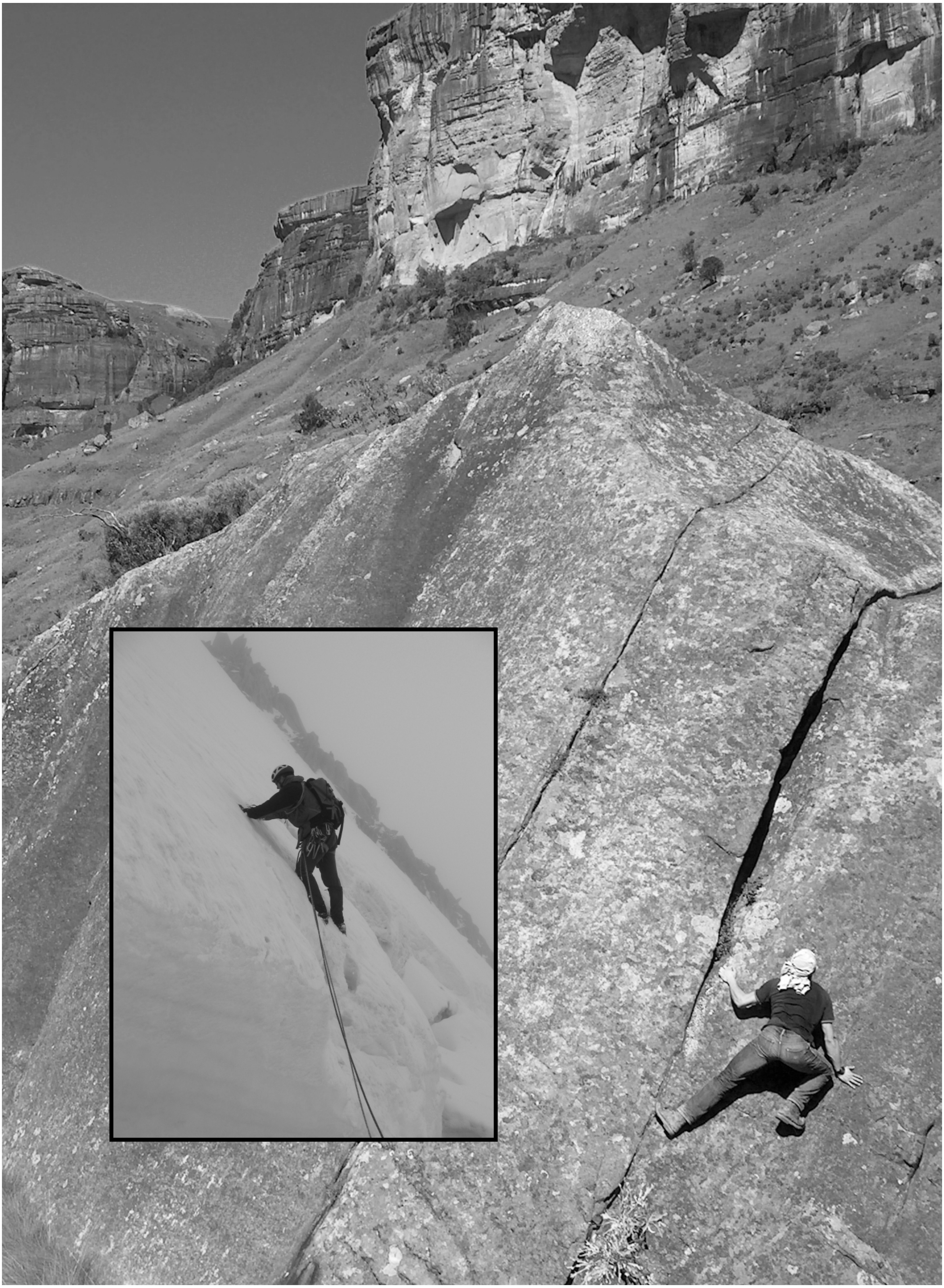
2.7 CONCLUSIONS

Solifluction has been identified as the first process that supplied sediment to the upstream parts of the research area after 50 ka. The sedimentary sequence in Okhombe valley is the result of the interplay in space and time between solifluction and fluvial redistribution of deposits. The expression of this interaction in the landscape is structurally controlled by the presence of resistant barriers, formed by dolerite and sandstone, and otherwise controlled by meandering fluvial action.

Both temperature and precipitation appear to be important in determining the type and balance of landscape processes in this area. Cold, wet periods give rise to solifluction processes, though there is no reason to believe that solifluction occurred over a frozen surface. Increases in precipitation lead to fluvial redistribution of sediments.

In the second half of OIS 3, when temperature was between 6 and 7°C colder than present and precipitation was over 900mm, solifluction was active. In the LGM, with the lowest temperatures and precipitation of the last 100ka, solifuction stopped but deposits were not redistributed, probably because fluvial redistribution was limited by precipitation. In the Holocene, much higher temperatures and a 100 mm increase in precipitation seem to have redistributed deposits from upstream landscape elements over the research area. Recently, redistribution has stopped, probably as a result of a lack of supply of parent material. Since then, strong gully erosion of the Masotcheni Formation deposits themselves has begun.

The same climatic controls may have led to different types of Masotcheni Formation sediments elsewhere in the province, given their drier and warmer position lower in the landscape.



CHAPTER 3

DEALING WITH DEPRESSIONS IN DYNAMIC LANDSCAPE EVOLUTION MODELS

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Notes

CHAPTER 3

DEALING WITH DEPRESSIONS IN DYNAMIC LANDSCAPE EVOLUTION MODELS

Depressions in landscapes function as buffers for water and sediment. A landscape with depressions has less runoff, less erosion and more sedimentation than a landscape without depressions. Sinks in Digital Elevation Models can be existing features that correctly represent depressions in actual landscapes or spurious features that result from errors in DEM creation. In many erosion, landscape and hydrological models, all sinks are considered spurious features and as a result these models do not deal with sinks that do represent real depressions. Consequently, erosion is overestimated and sedimentation is underestimated. Dynamic geomorphological models that simulate soil redistribution in modelled landscapes in multiple timesteps replicate this problem in every timestep. A method that allows these models to deal with depressions in a realistic way is needed. This chapter presents an algorithm that allows models in general and dynamic geomorphological model LAPSUS in particular to deal with sinks in a DEM and thus with depressions in a landscape. An application is presented where LAPSUS runs with the new algorithm are compared to the conventional runs. Results indicate that the new algorithm can realistically model the sediment buffer function of depressions. The inclusion of the new depression algorithm allows modelling landscape processes that can result in depressions, like landsliding, glacial processes and tectonics. It is also demonstrated that static models, running only once with a DEM without sinks, display effects from the filling of the sinks before running.

3.1 INTRODUCTION

Natural depressions, defined as areas with internal drainage, exist in landscapes. They are either filled with water like puddles, ponds and lakes, or dry like karstic features, glacial hollows and landslide-dammed valleys. Their size can range from centimetres, e.g. depressions behind plants and rocks, to kilometres, e.g. lakes and glacial hollows. Depressions store water and sediment in the landscape, decreasing surface runoff and increasing sedimentation as a result. Without depressions, surface runoff would increase, increasing erosion and decreasing deposition.

Analogous to natural depressions, sinks exist in Digital Elevation Models. They are defined as cells or groups of cells with internal drainage. Sinks can be interpreted in two ways: as existing features that correctly represent existing natural depressions in the modelled landscapes, or as spurious features that result from errors in the creation of DEMs.

In many present day erosion, landscape evolution and hydrological models, sinks are considered spurious features (Freeman, 1991; Martz and Garbrecht, 1998). This assumption is valid for most sinks in low resolution or low accuracy DEMs and DEMs that are interpolated from point data (Freeman, 1991).

As a result, most hydrological and geomorphological models have been designed to deal with continuous draining surfaces, from which all sinks have been removed before running the model (De Roo and Jetten, 1999; Moharana and Kar, 2002; Hessel and van Asch, 2003; Huang *et al.*, 2003; Martinez-Casasnovas, 2003; Stolte *et al.*, 2003; Lane *et al.*, 2004). Exceptions are CHILD (Tucker *et al.*, 2001), CAESAR (Coulthard *et al.*, 1998) and Rillgrow (Favis-Mortlock *et al.*, 2000). These models can dynamically deal with sinks in the landscape.

The removal of sinks results in flat surfaces in DEMs. Flow direction methods used in raster based models are unable to route flow through such flats. Consequently, research is focussed on methods to remove both sinks and flats efficiently. Generally, sinks are first filled to the level of their outlet to form flat areas (Martz and Garbrecht, 1999; Jones, 2002). Subsequently, these flat areas and other flat areas in the DEM are attributed a flow direction. In most applications, flow direction is iteratively assigned to grid cells of the flat areas, starting with cells on the edge and working to the interior of the flat surface. In these applications, DEM values of cells in the flat surface remain unchanged (Jenson and Dominique, 1988). In some other applications, flow direction is assigned by adding small values to grid cells of the flat surface to produce a draining surface (Garbrecht and Martz, 1997; Martz and Garbrecht, 1998). Martz and Garbrecht (1999) later changed this method because they realized that sinks can be the result of both underestimation of the sink and overestimation of cells on the rim.

Unfortunately, the removal of all sinks includes the removal of sinks representing natural depressions. Models that are unable to deal with sinks, will be unable to deal with depressions, and thus will fail to account for their storage of water and sediment in the landscape. This is especially true for dynamic geomorphological models that apply actual soil redistribution to the modelled landscape in multiple timesteps to simulate landscape evolution (Coulthard *et al.*, 1998; Schoorl and Veldkamp, 2001; Tucker *et al.*, 2001). If unable to deal with depressions in this type of models, the overestimation of runoff and erosion and the underestimation of sedimentation will be made in every timestep. More importantly, dynamic geomorphological models that model landslides (Claessens *et al.*, 2005; Claessens *et al.*, 2007), glacial processes or tectonics can create depressions by damming valleys or raising and filling parts of the landscape. Without considering and modelling depressions, investigating the role of these processes in the dynamic landscape is impossible.

Recently, DEMs of smaller resolution and higher accuracy are becoming available through digital photogrammetry (*cf.* Baily *et al.*, 2003) and airborne laser altimetry (LiDAR, Lane and Chandler, 2003). It is to be expected that the relative number of sinks correctly representing existing natural depressions will correspondingly increase in these DEMs. Thus, the problem of not realistically dealing with these depressions as existing features in the landscape will also increase. A method to identify existing depressions as opposed to spurious sinks, as well as a method to deal with depressions – and therefore sinks – will be more needed than before. This chapter is concerned with the latter.

The objective of this study was to create a method that enables models in general and dynamic landscape evolution model LAPSUS (Schoorl *et al.*, 2000; Schoorl *et al.*, 2002) in particular to realistically deal with depressions in landscapes, represented by sinks in DEMs. Our study resulted in an algorithm that treats depressions as parts of dynamic landscapes within LAPSUS. It is therefore an adaptation of the model instead of an adaptation of the DEM.

The algorithm does not remove sinks but deals with them in a realistic process way. It is not intended as a replacement of current methods that remove spurious sinks. Its use is envisaged in dynamic geomorphological models, to avoid the necessity of removing depressions that are modelled as parts of the landscape or that, in input DEMs, were considered true representations of natural depressions. Processes that create depressions can then be modelled. Methods for removing spurious sinks, *i.e.* those due to errors in DEM creation, are still needed for input DEMs.

3.2 LANDSCAPE EVOLUTION MODELLING IN LAPSUS

Dynamic landscape evolution model LAPSUS applies soil redistribution through erosion and sedimentation to the DEM in multiple annual timesteps. LAPSUS was developed by Schoorl *et al.* (2000), who give a more comprehensive introduction to the model than below.

The main assumption of LAPSUS is that the energy content of water flowing over the landscape is the driving force for sediment transport (Kirkby, 1971; Foster and Meyer, 1972). Given net water balance per grid cell, LAPSUS uses the multiple flow direction principle (MFD, Holmgren, 1994) to calculate the fraction of the total discharge out of each cell to each of its lower neighbours.

After calculating net discharge for every grid cell, capacities for sediment transport (C), detachment (D) and settlement (T) are calculated as functions of net discharge and slope (Kirkby, 1971). Detachment capacity D is co-determined by surface erodibility factor Kes, settlement capacity T is co-determined by sedimentation characteristic factor Pes. These two factors allow simulation of detachment-limited systems (low values for Kes and Pes, little sediment in transport, sediment transport capacity not limiting erosion) and transport limited systems (high values for Kes and Pes, more sediment in transport, sediment transport capacity limiting erosion).

The amount of erosion or sedimentation for every grid cell is calculated by comparing sediment transport capacity C to current sediment transport rate S0. Here, continuity of sediment movement is assumed as formulated by Foster and Meyer (1972). If the capacity exceeds the rate, sediment will be eroded, if the rate exceeds the capacity, sediment will be deposited. The actual erosion and deposition rates are then a function of Kes and Pes, respectively.

Technically speaking, the DEM is the primary matrix in LAPSUS (dtm); auxiliary matrices store calculated erosion (dz_ero), sedimentation (dz_sed) and discharge (q_flow) for every cell. These matrices all have data type floating point with double precision.

3.3 DEFINING SINKS

Cells in a DEM that have only higher and equally high neighbours are pits. The lowest cell of every sink is a pit by definition, though a sink can have multiple pits. Our algorithm declares new global matrices called lake (integer), status_map (integer) and dtmfill (double). Lake stores information about membership of sinks, status_map stores information about the type of cells: tops (-1), pits (1), outlets (2) and cells on the border of the grid (3). Dtmfill stores information about the level to which sink-cells must be filled, as mentioned below. Also, new global arrays lakelevel (the level of the outlet of the sink in m), lakevolume (the volume of the sink in m3) and lakesize (the number of cells involved in the sink) are declared to store data about the sinks. To store the position of the outlet of each sink, integer arrays drainingoutlet_row and drainingoutlet_col are defined. All arrays are set to have a size equal to the number of pits in the DEM.

Starting from a given pit i (Fig. 3.1A), our algorithm keeps adding consecutive lowest neighbouring cells to the sink (Fig. 3.1B and 3.1C). The altitude of the last cell added to the sink is always stored in lakelevel[i]. Moreover, lake[row][col], lakevolume[i] and lakesize[i] are updated after every addition of a cell.

The first lowest neighbouring cell that is lower than current lakelevel[i] indicates that the outlet of the sink has been passed (Fig. 3.1D). Lakelevel[i] and the other matrices and arrays are no longer updated. The location of the neighbouring lakecell is stored as the outlet of the sink in drainingoutlet_row[i] and drainingoutlet_col[i], as well as in the matrix status_map, where a value of 2 is assigned to the outlet. The sink would then be fully defined (Fig. 3.1E).

If a cell of another sink j is encountered while adding cells to current sink i (Fig. 3.1F and 3.1G), which can be the case for sinks with multiple lowest points, all cells of sink j are added to sink i by changing their values in the matrix lake from j to i. The values of lakelevel[i], lakesize[i] and lakevolume[i] are accordingly updated, while lakelevel[j], lakesize[j] and lakevolume[j] are reset to their sentinel value. In addition, status_map[row][col], drainingoutlet_row[j] and drainingoutlet_col[j] are reset to their sentinel values.

After updating the various matrices and arrays to reflect the joining of sink j with sink i, the algorithm checks if their connecting outlet has another lower neighbour that would make this outlet the true outlet for the new, larger sink. If so, status_map[row][col], drainingoutlet_row[i] and drainingoutlet_col[i] are set and the definition of this sink is finished.

Failing that, we continue adding the lowest neighbour cell to the sink until that cell is lower than lakelevel[i] (Fig. 3.1H). In that case, a new outlet of the sink has been found and the procedure explained above is followed.

If enough sediment is available, sinks will be completely filled in a later stage of the algorithm. Completely flat areas could result. Since no flow direction can be calculated for flat areas, sinks will instead be filled to a level that is higher than lakelevel by a margin that equals the distance – via sinkcells – to the outlet multiplied with 0.000001. Over a distance of 1 km, this margin would amount to a negligible 1mm. Thus it is ensured that a filled sink has a drainable, but as flat as possible surface. To calculate this margin in the matrix dtmfill, a method is used analogous to the method used by Garbrecht and Martz (1997), who use it to define flow direction in a sink. Our version of the method looks for sink-neighbours that already have a dtmfill value, to calculate dtmfill for the current cell. Note that sinks are defined and dtmfill is calculated in every run of the model, which ensures possible interplay with other processes.

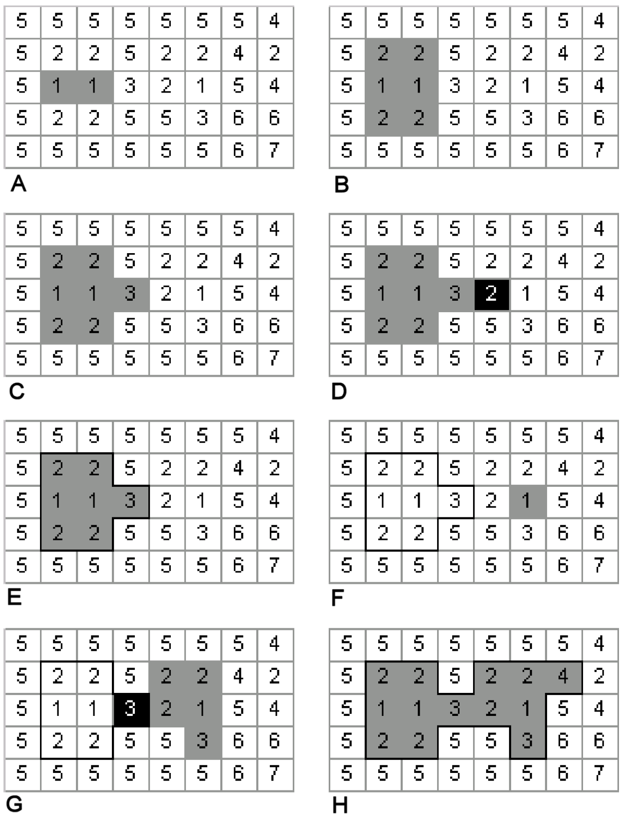


Fig. 3.1: Defining a sink. (A) Start at pit. (B, C) Add consecutive lowest higher neighbours. (D) Found lower neighbour. (E) Sink defined. (F) Start at second pit. (G) Found member of other sink while defining. (H) Defined second sink.

The very small differences between dtmfill and dtm ensure that we do not change patterns of erosion and sedimentation, but merely create a draining surface. Moreover, we maintain continuity of sediment transport by filling the sink using sediment that has eroded upstream.

3.4 Deposition in Sinks

After defining all sinks in the DEM by starting from all pits using the new algorithm, the original LAPSUS core calculates overland flow of water and sediment. Calculation starts at summit-cells and follows the flow of water downstream until a sink is reached. A flowchart of the method to calculate deposition in sinks is given in Fig. 3.2.

When flow is calculated from a cell bordering a sink towards a cell in the sink, i.e. where the matrix lake has a non-sentinel value, the amount of water and the amount of sediment involved are recorded in sink-wide counters for water (q_flow of the outlet) and sediment (double lakesum_sediment). After all higher cells bordering the sink have been considered, these counters equal the total amounts of water and sediment entering the sink.

In the current setup of the algorithm, it is assumed that sinks are initially fully filled with water. Thus, all water entering the depression during a model run will leave the depression via its outlet. Another conceivable setup, better suited for drier climates, could assume initially empty or partially empty sinks, and use the amount of water entering the sinks to calculate a waterlevel within them. This level can either fail to meet lakelevel or exceed it. If the waterlevel exceeds lakelevel, conditions would be similar to the algorithm presented below, though less water would flow out of the sink. If the waterlevel fails to meet lakelevel, overland flow conditions would apply for part of the area of the sink, before underwater deposition conditions would apply. Then, no water would flow out of the sink.

In the current setup, where sinks are initially filled with water, it first checks if the total amount of sediment entering the sink suffices to fill the sink and make it drainable towards its outlet.

If there is enough sediment, dtm-values of the members of the sink are increased to the corresponding dtmfill-values. The amount of water leaving the sink at its draining outlet now equals the amount of water flowing in plus the volume of the sink. The amount of sediment in transport leaving the outlet now equals the total amount of sediment entering the sink minus the volume needed to fill the sink.

If the amount of sediment does not suffice to fill the sink to dtmfill, sedimentation inside the sink will be calculated for every member cell that received water and sediment from non-member cells. For sinks with sizes 2 or 3, a simple rule-based procedure applies. For larger sinks, the situation is more complicated.

We define a constant called delta-angle as the enforced steepness (dz/dx) of sediment that is deposited underwater. Considering small depressions on landscape level, this simplification of the complex delta-formation process seems justified. Even though LAPSUS does not distinguish between different grain sizes in the overland erosion – sedimentation process, varying delta-angle can create flatter deltas for sediments that are finer on average and steeper deltas for sediments that are coarser on average. However, this can only apply to sediments supplied by bedload. The deposition of finer sediment, supplied in suspended state, should be modelled differently.

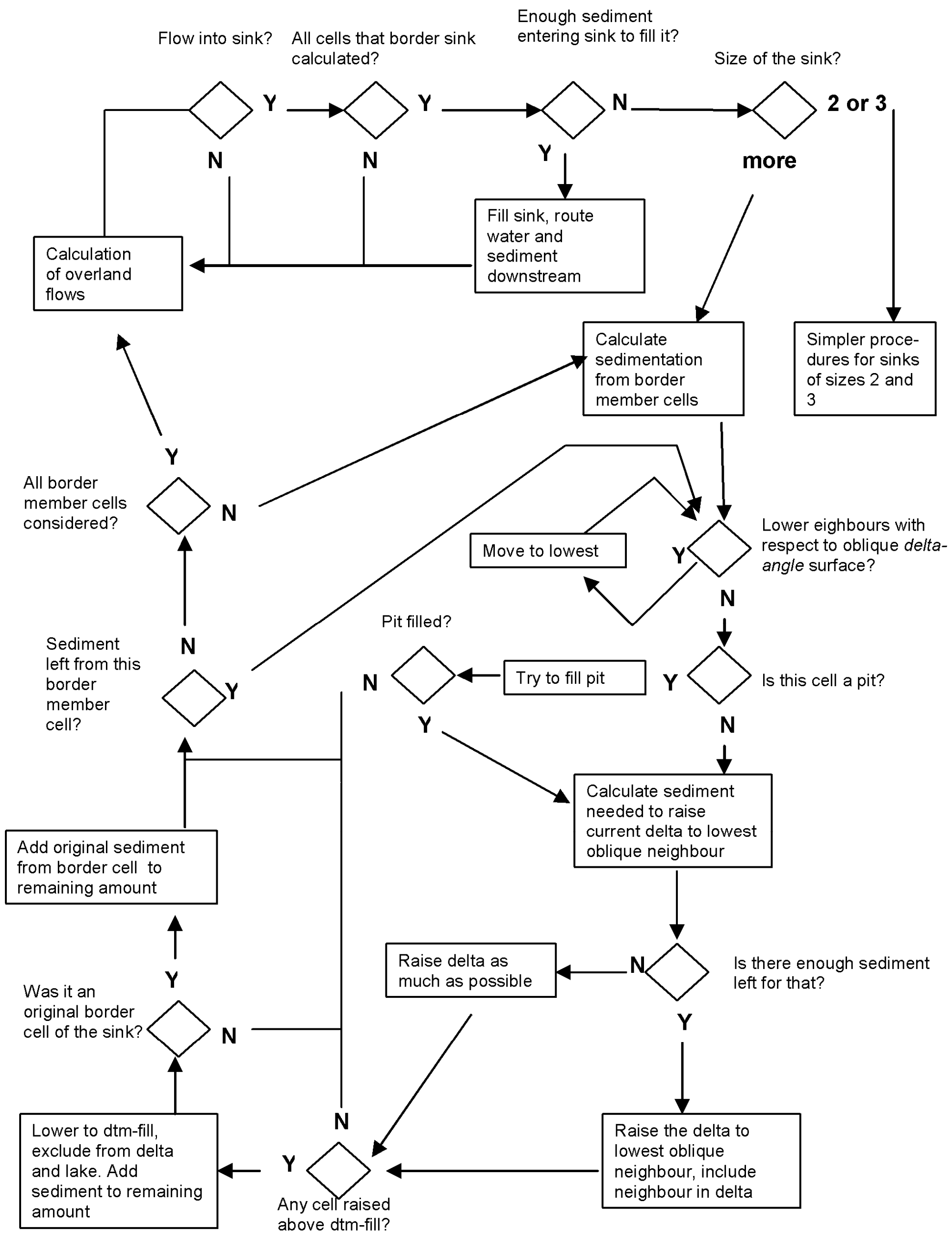


Fig. 3.2: Flowchart of the deposition method.

Starting from a border member cell that received sediment, we find the steepest (dz/dx) member cell of lower height. If the slope tangent to this member cell is steeper than delta-angle, we move all sediment from the first, border member cell to this member cell. This procedure is repeated until the sediment reaches a member cell that has no lower neighbours with a slope steeper than delta-angle. Note that this cell is not necessarily a pit. This cell is then filled to a level that corresponds to its lowest (but higher) neighbour, taking into account delta-angle by means of an oblique plane rather than using a horizontal plane. The sediment in transport of the initial border member cell is reduced with the amount we used to raise the lowest cell. These two cells, now equal with respect to the oblique plane, are given a negative lake value, to reflect that they are part of the current area of sedimentation. We call this area the delta.

Analogous to defining a sink but still taking into account delta-angle, we proceed by adding sediment to cells already member of the delta and including consecutive lowest (higher) neighbour cells to the delta (Figs. 3.2, 3.3A and 3.3B) .

When the amount of sediment in transport of the border member cell no longer suffices to raise all cells of the delta to the altitude that corresponds to the next lowest (higher) neighbour, the delta cells are raised to the maximum altitude possible, given the remaining amount of sediment in transport of the border member cell and the size of the delta. Sedimentation from this border member cell would then be finished and the next border member cell would be considered. Cells that were part of the delta, again receive a positive lake value.

When a lower neighbour is found while raising a delta, still taking into account delta-angle, the remaining sediment in transport of the initial border member cell is transported to this lower neighbour. From that neighbour, we start as we did from the initial border member cell, by looking for even lower neighbours, taking delta-angle into account (Figs. 3.2, 3.3C, 3.3D and 3.3E).

When trying to raise cells of a delta above the level that is needed to make a filled sink drainable, so above dtmfill, we only raise them to dtmfill. These cells are no longer members of a sink or of a delta, so we change their lake values to zero (Figs. 3.2, 3.3F).

We follow the procedure explained above for all border member cells of a sink before calculating the amount of water that will leave the sink from its outlet. This amount of water equals the amount of water that entered the sink through its border member cells, plus the lakevolume that was replaced by sediment.

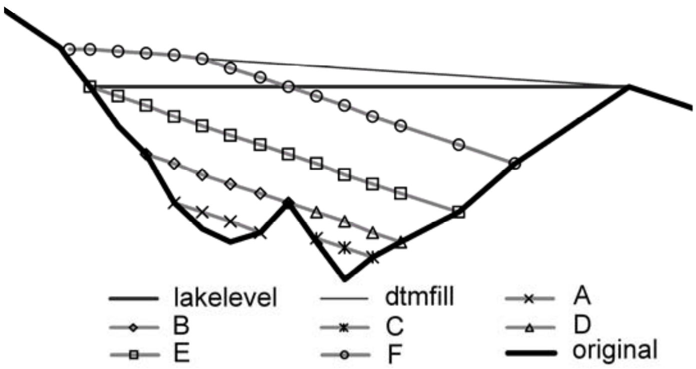


Fig. 3.3: Deposition method. Deposition begins in the left pit, which is the lowest neighbour when starting from the left border of the sink, taking delta-angle into account. A through F represent consecutive deposition stages, depositing sediment to a maximum of dtmfill.

To illustrate the deposition method of the algorithm, a synthetic DEM with a large depression was made (1834 cells). The depression contains two pits. Fig. 3.4 shows the evolution of a delta in this depression. Evidently, most sediment is supplied to the depression by the valley-like feature to the left of the depression. After one run of LAPSUS with the new algorithm, it is visible that deposition is most active in the first pit that this sediment encounters. Only after this pit is filled to some extent, deposition in deeper parts of the depression starts. The fact that the depression is not symmetric, results in stronger infill in the part that is lower in the picture.

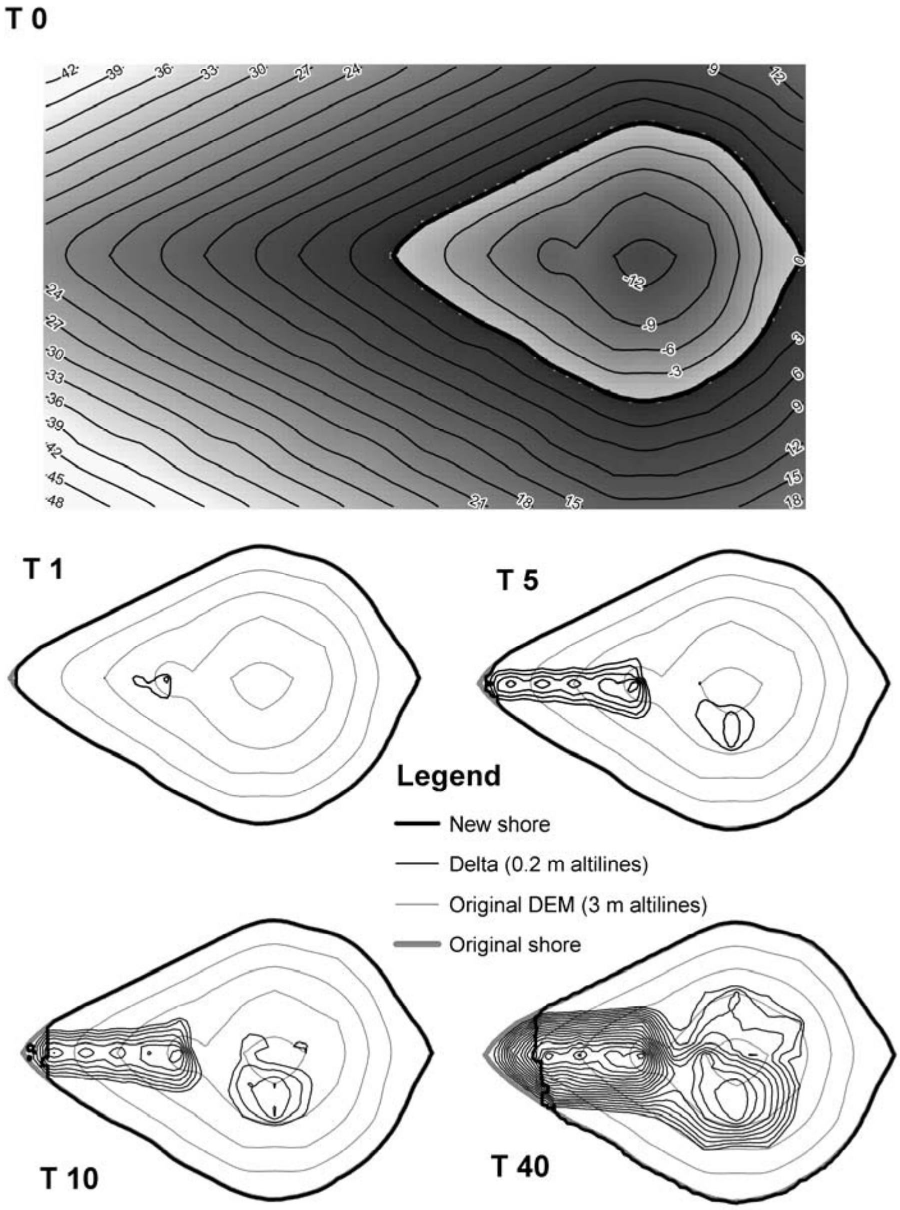


Fig. 3.4: Illustration of the deposition method in a synthetic depression. In the upper part of the picture, the original landscape is shown. In the lower half, development of a delta in the depression is shown.

3.5 EXAMPLE APPLICATION

An example application of LAPSUS with and without the new algorithm is discussed. In this application, LAPSUS is compared with the new algorithm, using a raw DEM with sinks (model version L+), to LAPSUS without the new algorithm, using a pre-processed DEM without sinks (model version L0).

For this application, a DEM of Okhombe valley in the foothills of the Drakensberg in KwaZulu-Natal, South Africa (Fig 1.5) is used. The DEM has a cellsize of 21.30 m, 204120 cells (92.6 km²) and was made by South African workers who interpolated between contour lines and additional point data using the method of Hutchinson (1989) without enforcing drainage.

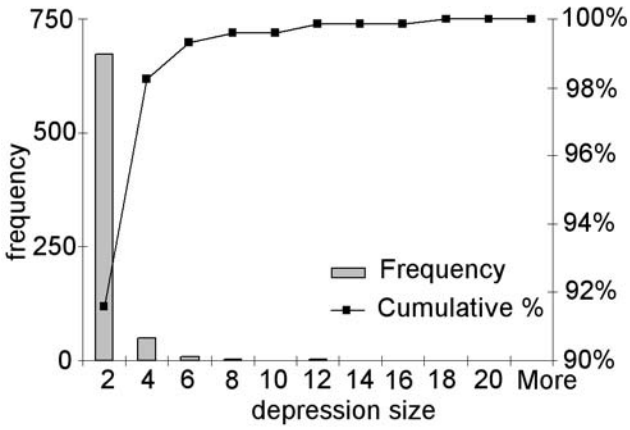


Fig. 3.5: Size distribution of sinks present in the original DEM.

In the original DEM, 762 pits are present (0.37 percent of all cells), forming 735 sinks with 1607 cells. The size distribution of the sinks (Fig. 3.5) shows that almost all sinks consist of only two cells: a pit and an outlet. The largest sink contains 18 cells. Though a certain, possibly large proportion of sinks is bound to be spurious, for this study of the behaviour of our algorithm it is assumed that all sinks exist as real depressions in the landscape. This original DEM was used in model version L+.

Sinks in the original DEM were filled (ArcInfo) and resulting and original flats were removed using the procedure of Jenson and Dominique (1988). The processed DEM that resulted from this procedure was used in model version L0.

Sediment Delivery Ratios (SDRs), defined as the total amount of sediment that leaves the DEM divided by the total amount of sediment that is detached within the DEM, were measured in the different scenarios, using L0 and L+. The portion of detached sediment that does not leave the DEM, has evidently been 'lost' to resedimentation. For L+, using the original DEM, this resedimentation has two components: overland resedimentation and resedimentation due to the partial or complete filling of sinks. For L0, using the processed DEM, resedimentation is only overland resedimentation.

Both model versions were run using a multiple flow parameter p of 3, transport capacity parameters m and n of 1.5 (indicating wash conditions, *cf.* Kirkby, 1987) and annual water balance of 0.555 m. For this explorative study where I focus on catchment-scale functioning of the algorithm, delta-angle was set to 0.05. Unlike slopes imposed on filled sinks in L0 and L+, delta-angle has no direct influence on SDRs. Through the slope imposed on sediments that are raised above lakelevel (*cf.* Figs. 3.2 and 3.3F), delta-angle can influence SDR results when considering multiple timesteps. However, orders of magnitude changes in delta-angle produce only non-systematic promillage changes in SDRs over the period I consider here. Changes in delta-angle thus primarily change the way depressions are infilled, and hardly the amount of sediment deposited in them.

Values for Kes and Pes, indicating lumped surface characteristics, were varied to create different scenarios. Three scenarios were defined: a detachment-limited scenario (Kes and P_{es} set to 0.00002), a transport-limited scenario (K_{es} and P_{es} set to 0.001), and an intermediate scenario (K_{es} and P_{es} set to 0.0001). It was expected that the different scenarios would display distinct system behaviour, resulting in more complete knowledge about the difference between L0 and L+. Both model versions were run with the three scenarios.

Results for the different scenarios and model versions for the first 10 timesteps are presented in Fig. 3.6.

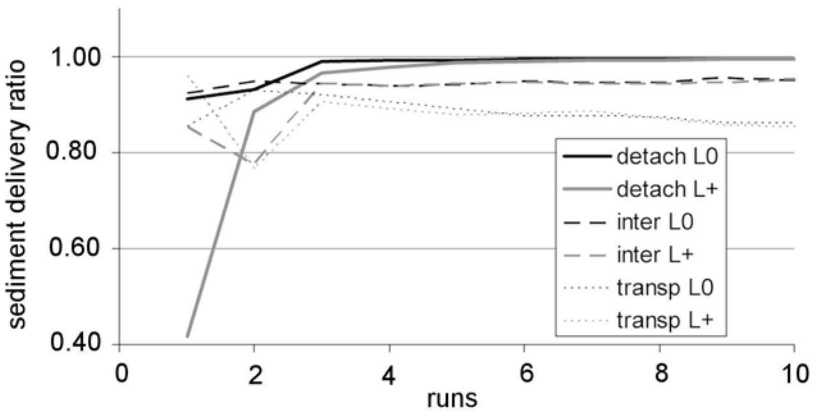


Fig 3.6: Sediment delivery ratios for different runs and setups.

Detachment limited scenario

In the detachment limited scenario, initially lower sediment delivery ratios increase over time to a common maximum close to 100% delivery. SDRs for L+ start at lower values (42% at run 1) and take longer to reach this maximum (99% after 6 runs), than SDRs for L0 (91% at run 1, 99% after 3 runs). The extra resedimentation and the longer period it takes to reach a maximum in the L+ setup can be attributed to resedimentation in sinks. After 8 runs, differences in sediment delivery ratio between L0 and L+ are minimal (<0.0015), because all sinks have been filled.

Intermediate scenario

In the intermediate scenario, again SDRs are initially lower for L+ than for L0, which is attributable to resedimentation in sinks.

For L+, SDR decreases (from 85% to 78%) from run 1 to run 2. This decrease indicates the overland sedimentation on the surface resulting from the filling of sinks in the first run. Apparently, more sediment is deposited on these flat surfaces in the second run than was needed to fill the depressions in the first run.

For L0, this overland sedimentation on the almost flat surfaces of filled sinks occurs in run 1. However, resedimentation in this case is less strong, because the gradient imposed on filled sinks is steeper for the input DEM of L0 (gradient of 0.0001) than for the sinks filled in the DEM after run 1 of L+ (gradient of 0.000001). This steeper slope results in a higher transport capacity and thus in less deposition. Apparently, SDRs are sensitive to this difference in imposed slopes.

After 10 runs, SDRs reach a maximum of about 95%, 4% lower than the maximum for the detachment limited scenario. Because the amount of sediment available for transport is less limiting in this scenario, the amount of sediment in transport will more often exceed transport capacity. Thus, resedimentation will occur more often, as indicated by a lower SDR.

Transport limited scenario

Initial SDR for L0 is lower in this scenario than it is for L+, unlike in the other scenarios. This indicates that the amount of sediment needed to fill sinks in L+ in the initial run is now less than the amount of sediment deposited on flat areas of previously filled sinks in L0 in the initial run. Given the almost flat surface of these pre-filled sinks, virtually all sediment that arrives, is deposited on them in L0, whereas a relatively small amount of sediment is used to fill sinks in L+.

Still, SDR for L+ in the second run is lower than for L0 in the first run. Again, the difference in imposed slope has a strong effect on the amount of sediment deposited on the filled surface of sinks. The fact that this difference between runs is larger than it was in the intermediate scenario, illustrates that the system is now more transport limited. The increased amount of sediment in transport enables more deposition on the filled surfaces.

SDRs for L+ thus display a marked decrease in the second run (from 96% to 77%) due to overland sedimentation on almost flat areas that were filled in the first run. This effect was also observed in the intermediate scenario. This counterintuitive behaviour results from the inability of the algorithm in its current form to fill sinks and deposit sediment on the resulting surface in the same timestep. For this study, where only sinks in the input DEM are considered and no sinks are produced in the model runs, this effect is larger than it would be in reality, where the filling of some sinks and deposition on the surfaces of others would occur in the same timestep.

SDRs in the transport-limited scenario continue to decrease until they reach a relatively stable value of about 60% after more than 150 runs. This decrease is attributed to the continuously decreasing potential energy in the landscape. This is visible in a decreasing gradient of slopes in the landscape, which decreases transport capacity and increases resedimentation. At this temporal extent, this effect is not observed in the intermediate and especially the detachment limited scenario, because total amounts of sediment in transport are much smaller for these scenarios.

The difference between the L+ SDRs of the intermediate and transport limited scenarios is very limited in the second run. This indicates that the transport capacity over the flat surfaces of sinks that were filled in the first run is so low that, regardless the amount, almost all arriving sediment is deposited at these areas.

3.6 CONCLUSIONS

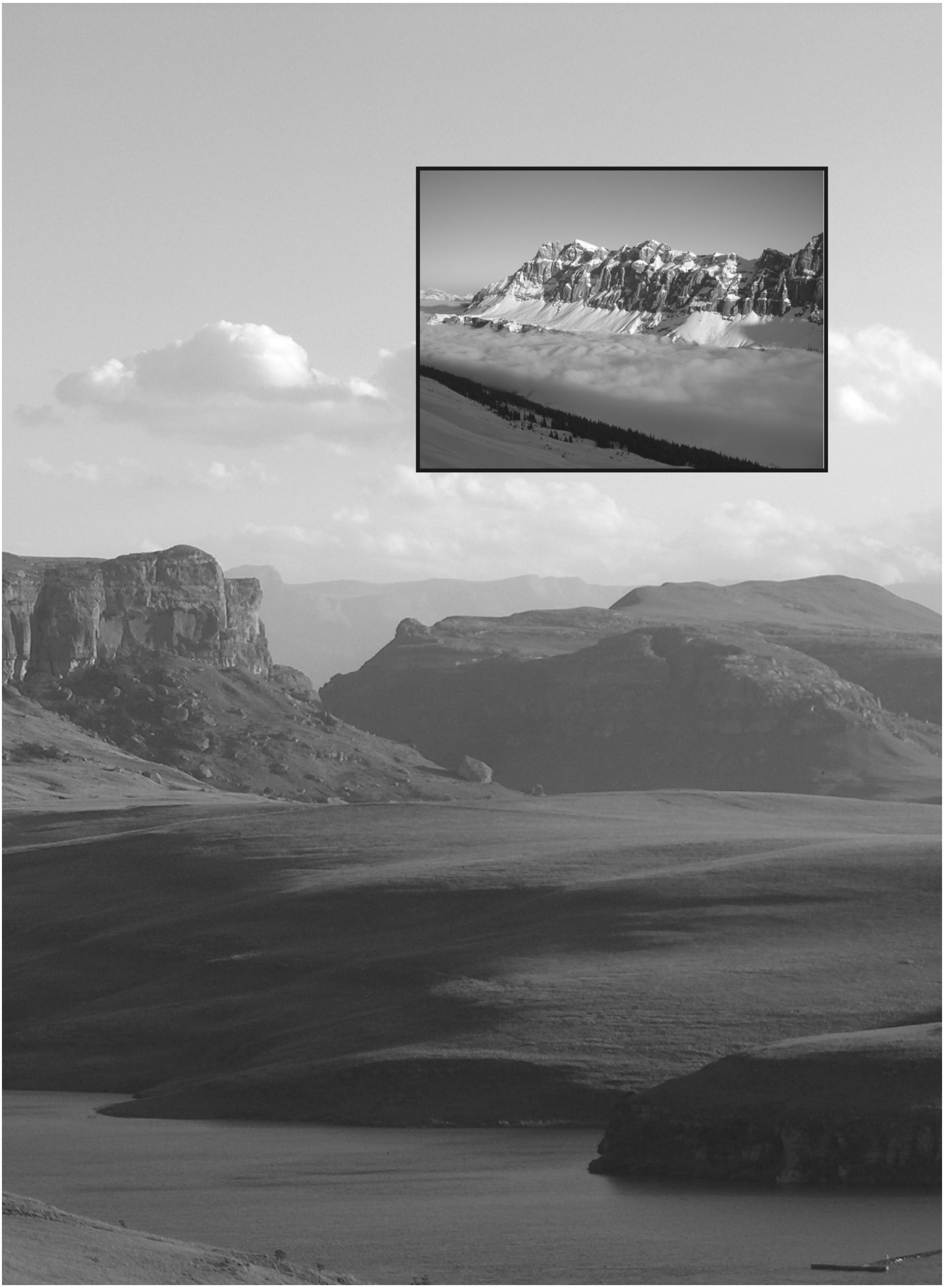
The results from the application of the new algorithm show that the algorithm can simulate flow through and sedimentation in sinks. Thus, it enables dynamic landscape evolution models to include processes into the dynamic landscape framework that model depressions in the landscape, *i.e.* sinks in the DEM. These processes may include landsliding, glacial processes and tectonics.

Moreover, summed over 10 runs, the model with the new algorithm results in an increase of resedimentation within the landscape for transport limited, detachment limited and intermediate scenarios when compared to the model without the new algorithm. This increase results from differences in the input DEM only. Therefore, differences in sediment delivery ratios between LAPSUS with the new algorithm and LAPSUS without the new algorithm decrease over time. If processes that produce depressions in the landscape are included in dynamic landscape evolution models, stronger resedimentation in the landscape using the new algorithm will be visible continuously. I expect that this larger resedimentation in the landscape is a property of all models that feature a dynamic sink-filling algorithm, regardless of the way that deposition within depressions is modelled.

The slow decrease in sediment delivery ratios for over 150 runs in the transport limited scenario indicates the ability of both the conventional LAPSUS and LAPSUS with the new algorithm to model the attenuation of potential energy in the landscape. If boundary conditions do not change, decreasing slopes will eventually change any landscape into a plain.

From the first two runs of the intermediate and transport limited scenarios, it has become apparent that the slope imposed on the surfaces of filled sinks, either before or during model runs, has a strong effect on resedimentation on them. This sensitivity indicates the importance of calibrating and validating the value of these imposed slopes, rather than using pre-defined values in a method to remove sinks.

The counterintuitive behaviour that is visible in the intermediate and transport limited scenarios for L+, with SDRs decreasing strongly from the first to the second run before increasing, is not something new. It is an essential, though hidden result of models that fill sinks before running, which has merely become visible in our results. While being a cause of technical concern for our algorithm, it is a conceptual problem for models that fill sinks before running. Results of these models in their first, and only, timestep partly reflect the reaction of the landscape to the artificial filling of the sinks before running. Recording this reaction in the results is undesirable because the reaction of the landscape to this artificial filling of apparently spurious sinks must be as spurious as the filled sinks themselves.



CHAPTER 4

SETTING UP CASE-SPECIFIC MULTI-PROCESS LANDSCAPE EVOLUTION MODELS

Based on: Temme, A.J.A.M., Claessens, L, Veldkamp, A.. Setting up case-specific multi-process landscape evolution models. Submitted to Earth Surface Processes and Landforms

Notes

CHAPTER 4

SETTING UP CASE-SPECIFIC MULTI-PROCESS LANDSCAPE EVOLUTION MODELS

The interest in landscape evolution models that simulate multiple landscape forming processes is growing. Modelling multiple processes constitutes a new starting point for which the set-up of landscape evolution models must be re-evaluated. Such re-evaluation is the objective of this chapter.

I discuss why an ideal landscape evolution model does not exist, and which choices must be made to set up a case-specific landscape evolution model. A model setup scheme is presented that structures these choices. Case studies from South-Africa, New Zealand, Belgium and Croatia present tests that can help in making these choices. These tests can indicate the sensitivity of models for different simplifications as a function of case study properties. Taken together, the scheme and the tests help to set up multi-process landscape evolution models for different case-studies.

4.1 INTRODUCTION

Changes in landscapes have many causes. In the words of Press and Siever (1994),

"Landscape is controlled by the interaction of Earth's internal and external heat engines. The internal engine drives tectonics, elevates mountains and volcanoes and lowers tectonic valleys and basins. The external heat engine, powered by the Sun, wears away the mountains and fills in the basins with sediment. Sunlight causes the motions of the atmosphere that produce climate, the different temperature regimes of the globe, and the rainwater that runs off the contintents as rivers (p.410)"

The internal and external heat engines power a wide range of landscape forming processes, including, when taken figuratively, those involving vegetation and human activity. How exactly these landscape forming processes act and interact, is a topic of continuing interest for geomorphology.

It stands to reason that Landscape Evolution Models (LEMs) can play an important role in pursuing this interest, given their potential to make hypotheses about landscape evolution and interactions between processes explicit in space and time (e.g. Coulthard, 2001). Both the development of LEMs themselves and the interpretation of simulation results may lead to improved understanding of the complex dynamics of landscape evolution.

Currently, landscape evolution studies that model a single landscape forming process still outnumber those that model multiple processes. Work has been done on for example water erosion and deposition (Takken *et al.*, 1999; Schoorl and Veldkamp, 2001; Collins *et al.*, 2004), tillage erosion (Heuvelink *et al.*, 2006), landsliding (Claessens *et al.*, 2005; Claessens *et al.*, 2007), weathering (Heimsath *et al.*, 1997; Minasny and McBratney, 2001), soil creep (Minasny and McBratney, 1999; Minasny and McBratney, 2001; Minasny and McBratney, 2006) fluvial action (Coulthard *et al.*, 1998; Coulthard *et al.*, 2000; Coulthard *et al.*, 2002) and dune formation (Baas, 2007; Baas and Nield, 2007).

To a large degree these studies aimed at development and validation of process descriptions. For other landscape forming processes, empirical identification of controls is ongoing and landscape-scale process descriptions are still premature. Examples are wind erosion (Okin *et al.*, 2006), gelifluction (Harris *et al.*, 2003), solifluction (Matsuoka *et al.*, 2005) and frost weathering (Williams and Robinson, 2001).

However, the interest in studying multiple processes and their interactions in the landscape is growing, particularly in combination with the increased focus on reduced complexity modelling in fluvial geomorphology (Brasington and Richards, 2007), which stresses the simplification of process knowledge required for landscape-scale landscape evolution models:

"A key benefit of reduced complexity modelling is that it provides a framework within which multiple processes can be represented in models of landscape evolution (p. 176)"

Recent LEM studies have started to focus on multiple processes and their interactions. The combination of water and tillage erosion received attention in agricultural landscapes in Belgium (Govers *et al.*, 1996; Peeters *et al.*, 2006) and Spain (Schoorl *et al.*, 2004). Follain *et al* (2006) simulated the combined effect of soil creep and water erosion in an agricultural landscape in France, Coulthard and Van de Wiel (2006) and Van de Wiel *et al.* (2007) combined several processes in the fluvial domain in Wales and Temme and

Veldkamp (in press) combined water erosion, biological and frost weathering, creep and solifluction in a study of a valley in South Africa. Coulthard and Baas (2008) combined aeolian dune activity and fluvial activity using an example from Mongolia.

Attention is also being given to the interactions between landscape forming processes and land use and cover change processes (Veldkamp *et al.*, 2001). Claessens *et al.* (2008) modeled interactions and feedback mechanisms between landscape forming processes water erosion and deposition, and tillage on the one hand and land use change on the other hand.

Frameworks for LEMs increasingly include multiple processes in a modular setup. Frameworks that combine processes include CHILD (Tucker *et al.*, 2001), CAESAR (Coulthard *et al.*, 1998), LAPSUS (Schoorl *et al.*, 2000; Schoorl *et al.*, 2002), SIBERIA (Willgoose *et al.*, 1990), CASCADE (Braun and Sambridge, 1997) and WATEM (Van Oost *et al.*, 2000).

A major difficulty of multi-process studies is calibration (Temme and Veldkamp, in press), especially calibration of the individual processes, since their contributions to overall landscape change are often hard to establish. If no information is available to constrain activity of individual processes and model results are calibrated using information on overall landscape evolution, the inclusion of extra landscape processes with associated calibration parameters may merely result in a reduction of degrees of freedom. However, for studies where results from different model versions are compared with each other and assessed in terms of their differences, that is less important.

The modelling of multiple processes in the dynamic landscape constitutes a new starting point from which the way in which we build landscape evolution models has to be re-evaluated. The objective of this chapter is to perform such re-evaluation. Firstly, the reasons why an ideal landscape evolution model does not exist are explored, before discussing the concessions, discretization and simplifications, in short: choices, that are necessary in setting up case-specific optimal landscape evolution models. A model setup scheme is then presented that can guide workers in structuring and reporting these choices. Finally, case studies illustrate some of the steps in the scheme and may help to operationalize the process of choosing in other studies.

The focus of this chapter is on choices in overall model setup, not on the descriptions of individual processes. Therefore, the discussion of the process descriptions used in the case studies is kept as brief as possible. Furthermore, for reasons of practicality the focus is on LEMs that use Digital Elevation Models (DEMs), though some results may be applicable wider afield.

An ideal landscape evolution model?

An ideal LEM would calculate correct quantities of landscape change in the correct position at the correct moment. This ideal cannot be achieved because, like in all models, in LEMs simplifications and discretizations of processes and boundary conditions are necessary. These simplifications and discretizations encompass all steps needed to get from our real-world understanding of a changing landscape to a landscape evolution model. They include the reduction in complexity of process descriptions meant by Brasington and Richards (2007).

It is a shared paradigm throughout geomorphology that multiple processes are distinguished. Changes in the landscape are thought of as the result of discrete processes and are described in mono-genetic terms. These single-process changes may interact and accumulate as they do in multi-process landscape evolution models.

It might be argued that what are seen as processes, are actually arbitrary sets of landscape activity defined in a multi-dimensional space of material properties and affecting forces. These sets may, problematically, intersect (Fig. 4.1, A) or leave space in between (Fig. 4.1, B), which could cause multi-process LEMs using these process definitions to calculate intended activity twice (A) or not at all (B). For instance, a process description that calculates water erosion and deposition (for every gridcell, e.g. Schoorl *et al.*, 2002) could overlap a process description of fluvial action that calculates fluvial erosion and deposition (for every gridcell having more than a treshold value of overland flow, e.g. Coulthard *et al.*, 2002). Process definitions may also cause conceptual problems when two sets are adjacent but have different driving factors (Fig. 4.1, C).

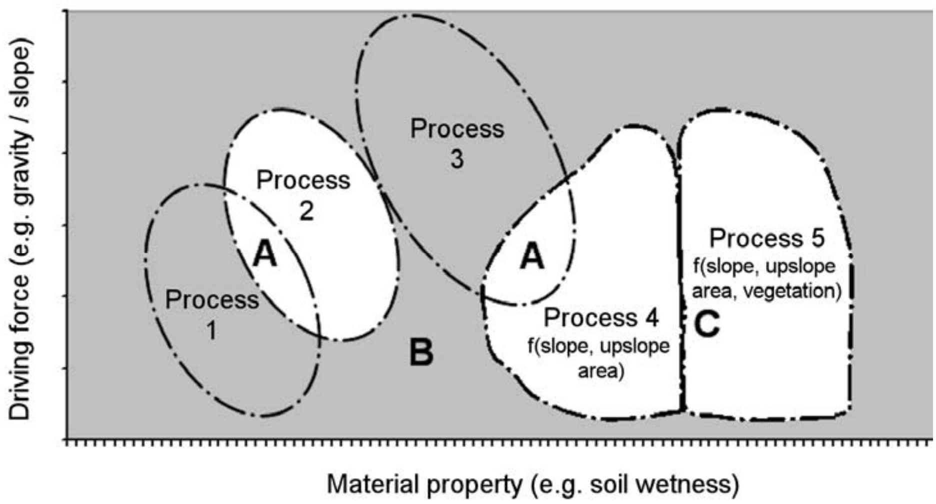


Fig. 4.1: Hypothetical process definitions in a space of material properties and affecting forces. Definitions may overlap (A), leave space in between (B) or be adjacent but have different driving factors (C).

It is not the objective of this chapter to criticize or discuss the process-paradigm in detail because it concerns the description of individual processes. However, its existence merits mention because setting up a multi-process landscape evolution model requires being specific about what the included processes descriptions do and do not model and making sure that they do not overlap.

Accepting that processes are distinguished, an ideal LEM is rephrased as calculating correct quantities of change in the correct location and moment for all landscape forming processes. In other words, there are four requirements: all processes, correct location, correct moment and correct quantity. Meeting these requirements and starting with correct boundary conditions entails that every process acts on a correctly modelled landscape in every timestep. If it is also assumed that processes only influence other processes through changes in the landscape, and not also through changes in e.g. climate or vegetation, then interactions between processes would be modelled correctly. In that case, landscape evolution is modelled correctly.

Below, the simplifications and discretizations affecting the four requirements of the rephrased ideal model are explained in more detail.

The first requirement is that all landscape forming processes are included. A first simplification in landscape evolution models is to only include case-relevant processes. In many LEM studies, this simplification is implicitly made when only one landscape forming process is assessed.

Relevance is defined here as the role of a process in landscape evolution, which is not necessarily the same as the importance in quantitative terms. For instance, landslides can dam valleys and have large off-site consequences for up- and downstream erosion and deposition (e.g. Korup, 2002) and could thus be included in a landscape evolution model study even if much less material is involved in landsliding than in water erosion and deposition.

Determining which processes are relevant and should be included may not be easy, particularly when literature and fieldwork are mostly focussed on one single landscape forming process. In addition, adding descriptions of landscape forming processes should not cause overlap, as discussed above.

Second, implementations of processes must model process activity in the correct location. The typical discretization of space into finite elements, and one that this chapter is limited to, is to subdivide the spatial extent into rows and columns of square surfaces with uniform altitude (cells) in DEMs. Alternatively, space can be divided into Delaunay triangles. That results in Triangulated Irregular Networks (TINs) which enjoy the advantages that the triangular surfaces need not have uniform altitude and that data density can be varied within the spatial extent. The primary disadvantage of this method is the difficulty in developing process descriptions. Landscape evolution model frameworks CASCADE (Braun and Sambridge, 1997) and CHILD (e.g. Tucker *et al.*, 2001) use TINs.

Model results are sensitive to the discretization of space, essentially because of schemes routing flow between cells that become necessary in DEM based approaches (Nicholas, 2005). This leads to resolution dependency of parameters in process descriptions and of final model results (e.g. Schoorl *et al.*, 2000; Thompson *et al.*, 2001; Claessens *et al.*, 2005).

Given the discretization into grid cells, the second requirement translates into a requirement to model process activity in the correct cells. In achieving this, implementations should be generic in the sense that a process can in theory occur in every cell of a grid; the spatial uniformity of law and process *sensu* Gould (1965). Whether the process is active, and how active, depends on local conditions that are dynamic in time. Because of these local rules, LEMs are sometimes called cellular automata (e.g. Crave and Davy, 2001; Frauenfelder *et al.*, 2008).

Third, implementations of processes must model process activity at the right time. In LEMs, discretization of time is necessary, and temporal resolution is typically a year or more. Processes should be modelled for every timestep throughout the temporal extent of study; the temporal uniformity of law and process *sensu* Gould (1965), but their activity should be dynamic in time and temporal resolution need not be uniform between processes (Coulthard, 2001).

The discretization of time makes it difficult to model multiple processes simultaneously. Determining the right time typically translates into a requirement to determine the right order of processes within a timestep. This is interesting when the temporal behaviour of processes differs. For instance, landsliding, water erosion and creep have profoundly different temporal behaviour which can lead to discrepancies between process and model timesteps and hence are of interest in model setup.

Fourth, implementations of processes must calculate the correct quantitities. Given the simplifications in process descriptions and boundary conditions, this translates into finding the right balance between details in process description and the amount of error and uncertainty introduced. Instead of highly accurate descriptions that reflect the state of the art in process understanding, it can be better to use less elaborate but more precise descriptions in LEMs (Fig. 4.2, Passioura, 1996). In fluvial geomorphology for instance, Computational Fluid Dynamics are typically replaced with spatial and cellular algorithms (Brasington and Richards, 2007).

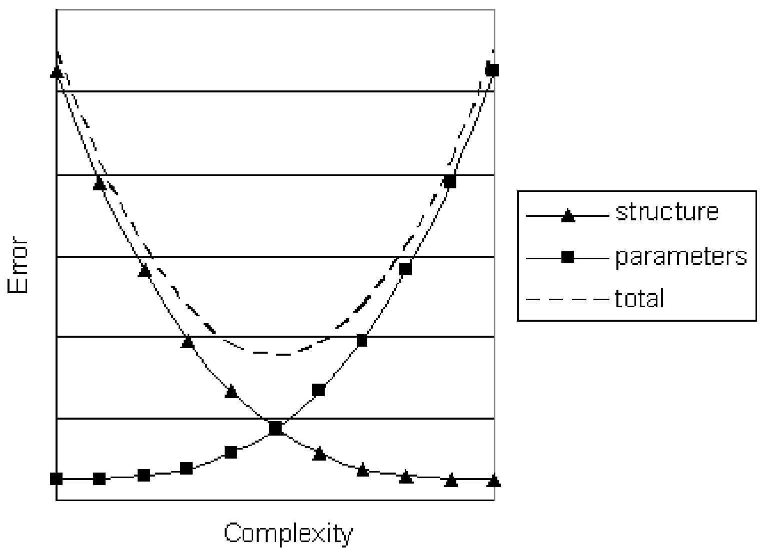


Fig. 4.2: Error due to model structure decreases as accuracy increases with increasing model complexity. Error due to parameter uncertainty increases as precision decreases with increasing model complexity. The minimum cumulative error occurs at an intermediate level of complexity (Passioura, 1996).

Given that the landscape is the only medium for interaction between processes, as assumed above, it stands to reason that quantities calculated with the process descriptions should be trusted and that the resulting simulated landscape should be considered a correct input for the next consideration of a process. For this reason, removal of model-simulated sinks (as opposed to supposedly spurious sinks in input DEMs) is problematic in three ways: 1) it adds sediment to the system with associated problems for the mass balance, 2) it hampers consideration of the functioning of sinks in a dynamic landscape, and 3) it implies that earlier results are not trusted (Temme *et al.*, 2006). To counter these problems, process descriptions and model algorithms that can deal with sinks are required.

Following the discussion above, I argue that no ideal landscape evolution model exists, but that there are case-specific optimal LEMs. This suggests that LEM frameworks should facilitate different case-specific optimal LEMs and, ideally, the choices that lead to them. This objective is arguably best achieved with LEM frameworks that have a modular or loosely coupled setup, where processes or sub-models can be activated when the case study requires. Advantages and drawbacks of loosely coupled models are discussed in Antle and Stoorvogel (2006).

4.2 METHODS

In this section, a model setup scheme is presented that structures the choices that must be made when setting up a multi-process LEM, as discussed above. Then, the setup of case studies is discussed.

Model setup scheme

The discretizations and simplifications of space, time and process should be consciously made and reported on. I propose a simple model setup scheme that may help in this purpose (Fig. 4.3). The scheme has two levels: extent and resolution, at which choices must be made in terms of space, time and process. Choices are reported in model setup reports (e.g. Table 4.2).

	Space	Time	Process
Level 1 Extent	**Spatial extent** **Constraints**: input data (esp DEM) and computing **Choice**: depending on objective, but should include water divide plus buffer to prevent problems with edge effects. Reporting on results after masking	**Temporal extent** **Constraints**: input data (esp. climate, vegetation) and computing **Choice**: depending on objective	**Process extent** **Constraints:** fieldwork-informed **Choice**: In terms of relevance for landscape evolution or other process **Validation**: Including in or excluding from final model **Requirement**: No overlap
Level 2 Resolution	**Spatial resolution** **Constraints**: input data (esp DEM) and computing **Choice**: usually minimum allowable within constraints **Validation**: study resolution effects **Requirement**: process description designed for chosen resolution or spatial resolution a parameter in process descriptions **Interaction**: landscape only medium of interaction, changed only by results of landscape forming processes.	**Temporal resolution** **Constraints**: input data (esp. climate, veg.) and computing **Choice**: usually minimum allowable within constraints **Validation**: study resolution effects **Requirement**: Temporal resolution should be a parameter in process descriptions or process description should be designed for chosen resolution **Interaction:** order and frequency should be user-specified. Both regular and random occurences should be possible.	**Process resolution: level of detail in description** **Constraints**: available process descriptions **Choice**: maximum precision and accuracy **Validation**: uncertainty analysis

Fig. 4.3 : Model setup scheme for a multi-process landscape evolution model.

On the first level of the scheme, decisions are made concerning the extent of study: spatial extent, temporal extent and process extent.

When setting up a LEM, spatial and temporal extent are usually determined by the study objectives and constrained by data availability and boundary conditions like DEM, climatic records and computing power. Hence, room for choice is limited. Still, given the importance of gravity and water in many landscape forming processes, it is advisable to choose a spatial extent including at least one complete catchment. Results should be masked to exclude incomplete catchments.

Note that catchments are defined differently for different flow routing schemes. Catchments are mutually exclusive when using steepest-descent flow routing schemes (Moore *et al.*, 1991). Their borders are the steepest-descent water divides. Catchments overlap when multiple flow routing schemes are used (e.g. Holmgren, 1994). This should be reflected in the choice of spatial extent for LEM studies. Moreover, computational edge effects become progressively more important if less cells beyond the water divide are included in the spatial extent (Wood, 1996). It is therefore advisable to include a buffer of cells beyond the waterdivide. Case study 1 presents an ex-post test to determine the minimum size of such a buffer.

When spatial and temporal extent have been chosen, the next step in model setup is determining which landscape forming processes will be modelled; the process extent. In studies where the focus is on landscape evolution *per se*, it is advisable to start with a case-complete set of processes, possibly narrowing that set down in an ex-post evaluation of relevance for each process, as in case studies 1a and 1b. In studies where the focus is on the activity of a specific landscape forming process (e.g. under changing climatic conditions), it may be less necessary to include other processes. Also in those cases, it would be advisable to verify the validity of that decision after model construction, as e.g. climate-dependency of one process may be influenced by interaction with other processes.

On the second level of the scheme, decisions are made about resolutions for each of the processes included in the model: spatial resolution, temporal resolution and the level of detail in the process description. The way in which interactions between processes are included, must be defined in both space and time at this level.

In many LEMs, spatial and temporal resolution are constant for every landscape forming process and constant in space resp. time (e.g. LAPSUS, SIBERIA and WATEM). Temporal resolution is also constant in TIN-based LEMs CASCADE and CHILD. A notable exception is CAESAR, where temporal resolution is small and variable for fluvial redistribution, and large and constant for hillslope processes (Coulthard *et al.*, 2000).

Typically, minimum possible spatial and temporal resolution are chosen within input data and computing constraints. In most cases, that means that the resolution of the available input DEM determines the spatial resolution. It is important to use process descriptions that are designed for use at the chosen spatial and temporal resolution, or where spatial and temporal resolution are parameters (Coulthard *et al.*, 1998; Schoorl *et al.*, 2000; Jetten *et al.*, 2003; Claessens *et al.*, 2005).

Interaction in space requires, as discussed above, that the modelled landscape is used directly as input for a next process or timestep, without removing sinks. In that case, interaction is modelled correctly if spatial resolution is uniform for the different processes. If spatial resolution is not uniform for the different processes, inevitable errors in aggregation and desaggregation of results between processes will lead to errors in the interaction (*cf.* Wu and Li, 2006).

The implementation of interaction in time is dependent on the choices made for temporal resolution of process descriptions. If temporal resolution is uniform for the different processes, the order of process consideration in the model must be chosen. For models with temporal resolution that is large relative to the temporal extent, i.e. with few timesteps, this can be a non-trivial choice. If temporal resolution is not uniform, validity of interaction between processes may decrease, similarly as with varying spatial resolution.

When spatial and temporal resolution have been chosen, process resolution is the last step in the model setup scheme. The resolution of process descriptions, in other words the level of detail used in the description of landscape forming processes, influences the expected precision and accuracy of model outputs. Given a certain level of process knowledge, it can be argued that there is a tradeoff between precision and accuracy, as in Fig. 4.2. However, it is difficult to obtain information on this trade-off, especially because a scarcity of spatially distributed field-truth data makes it difficult to assess errors (Jetten *et al.*, 2003). This means that the choice for a certain process description is often based on other considerations, including data needs, familiarity and ease of use. This last step in the model setup scheme is outside the focus of this chapter.

Case studies

Below, case studies are presented where different steps in the model setup scheme are illustrated with data from New Zealand, Croatia, Belgium and South Africa (Fig. 4.4, Fig. 4.5). The focus is on methodological, model-building aspects of the case studies.

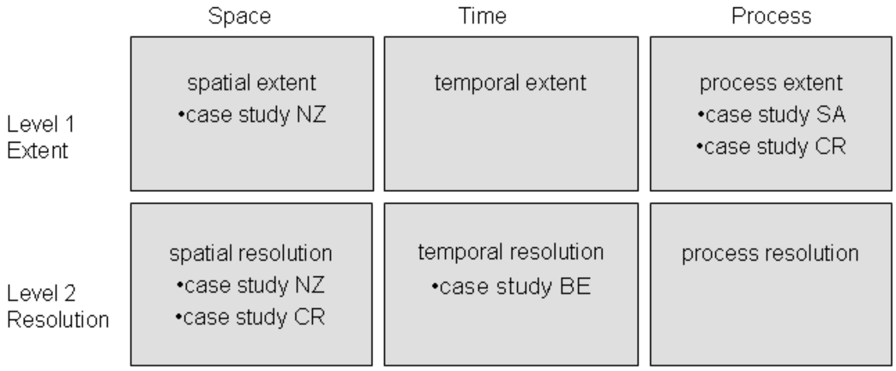


Fig. 4.4: Position of case studies in the model setup scheme (Fig. 4.3).

In the spatial extent case study in New Zealand, the importance of increasing the spatial extent beyond the water divide of catchments is examined. In the process extent case studies in South Africa and Croatia, the relevance of different landscape forming processes on landscape evolution model results is explored.

Spatial resolution case studies in New Zealand and Croatia consider the gains associated with considering the landscape the only medium of interaction and allowing it to change only as a result of process descriptions. The effect of retaining sinks as legitimate, modelled landscape elements is shown. The temporal resolution case study in Belgium illustrates the importance of temporal resolution for the interaction of two landscape forming processes.

Parameter values for the landscape forming processes used in the different case studies were kept at default values from literature, except in case study 4 where calibration was performed.

Areas

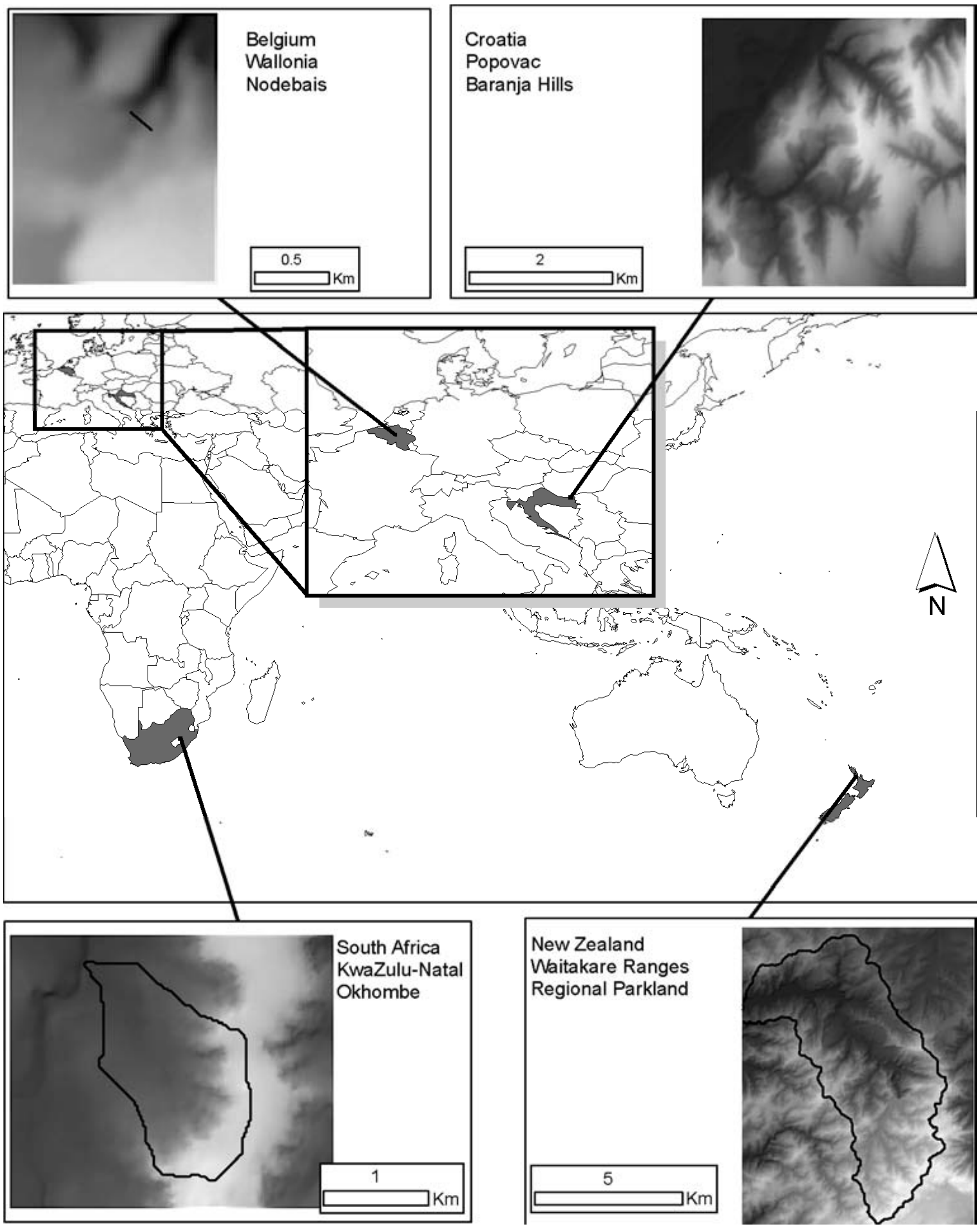


Fig. 4.5: Overview of the locations of the case study areas. For Belgium, the position of the study transect is indicated, for South Africa and New Zealand, the steepest-descent water divides are indicated. For Croatia, no catchment mask was used.

For New Zealand, data are used from studies by Claessens *et al* (2005; 2006; 2007) in the Waitakere Ranges Regional Parkland. The area is mostly covered in thick forest. Altitude ranges from sea level to 474 m. The area has a subtropical climate with mean annual rainfall ranging from about 1400 mm near the Tasman coast to 2030 mm at higher altitudes (ARC, 2002). The landscape is mantled by deep volcanic soils but locally bedrock crops out. Main landscape forming processes in the area are rainfall triggered shallow landsliding and water erosion by runoff. A 25m cellsize DEM is available.

For Croatia, data are used from a book on geomorphometry from the Baranja Hills (Hengl and Reuter, 2008). The area is mainly used as arable land, pasture and forest. Altitude ranges from 85 to 250 m. Climate is temperate continental, soil depth varies with landscape position and ranges from deep alluvial soils in the flat areas in the northwest to very shallow on the steep slopes next to incising rivers. A 20m cellsize DEM is available.

For South Africa, data are used from the Okhombe valley in KwaZulu-Natal (Fig 1.5). The area is under grassland, with patches of forest. Altitude ranges from 1200 to 1500 m. The area has a temperate Mediterranean climate with annual rainfall of about 1100 mm concentrated in the summer months (Nel and Sumner, 2006). Soils are shallow except for depositional areas where Luvisols are found. Landscape forming processes for the last 50 ka have been water erosion and deposition, creep, solifluction, frost weathering and biological weathering. A 10m cellsize DEM is available (see Chapter 5).

For Belgium, data are used from studies in the Nodebais catchment in the Belgian Loess belt, where detailed data on landscape evolution of a 120m transect are available (Rommens *et al.*, 2005, 2007; Peeters *et al.*, 2006). The area is in use as arable land and altitude ranges from 150 to 200 m. Climate is temperate oceanic with mean annual rainfall of around 750 mm. Soils are mainly Luvisols. Slopes range from 0% to 30% and form gently rolling topography. Landscape forming processes observed for the last 2500 years are water erosion and deposition and tillage erosion and deposition.

Process descriptions

LEMs for the case studies are built using the LAPSUS LEM framework. Initial work with LAPSUS focussed on water erosion and deposition (Schoorl *et al.*, 2000; 2002; 2004; Schoorl and Veldkamp, 2001), but the framework has expanded to include landsliding erosion and deposition (Claessens *et al.*, 2005; 2006; 2007), tillage redistribution (Schoorl *et al.*, 2004; Heuvelink *et al.*, 2006), creep, solifluction (Temme and Veldkamp, in press) and biological and frost weathering (Temme and Veldkamp, in press). Except for tillage, these process descriptions are used in the case studies in different combinations.

Table 4.1 summarizes the main driving factors of the landscape forming process descriptions in LAPSUS and mentions where elaborate discussions and formulas can be found.

Table 4.1: Summary of landscape forming process descriptions used in the case studies.

Process	Driving factors				Source of description
	Tangent of slope	**Overland flow**	**Vegetation**	**Temperature**	
Creep	yes	no	yes	no	(Temme and Veldkamp, in press), using (Follain *et al.*, 2006)
Solifluction	yes	yes	yes	no	(Temme and Veldkamp, in press)
Landsliding	yes	yes	yes	no	(Claessens *et al.*, 2007)
Water erosion and deposition	yes	yes	yes	no	(Schoorl *et al.*, 2002)
Biological weathering	no	no	yes	no	(Temme and Veldkamp, in press), using (Minasny and McBratney, 2006)
Frost weathering	yes	no	yes	yes	(Temme and Veldkamp, in press)

Three measures are used to quantify model outputs in the case studies. The Root Mean Square Error (RMSE) of a result, when compared to another result, is calculated as:

$$RMSE = \sqrt{\frac{\sum_{i=1,j=1}^{i=nr,j=nc}\left(model_{i,j} - observation_{i,j}\right)^2}{nr * nc}} \tag{4.1}$$

Where the square of the error per gridcell is summed over the number of rows (nr) and the number of columns (nc). The RMSE is a measure of the average absolute difference between outputs.

The Model Efficiency Factor (MEF) is a measure of the difference in variance between the model error and the observations:

$$MEF = 1 - \left(\frac{\mathrm{var}(model - observation)}{\mathrm{var}(observation)}\right) \tag{4.2}$$

A MEF value of 1 indicates a zero variance of the model error, i.e. the only possible error in model results is a uniform bias. Lower MEF values indicate a relatively larger variance of model errors.

For the process of water erosion and deposition, a common characteristic is the Sediment Delivery Ratio (SDR, e.g. Peeters *et al.*, 2008; Takken *et al.*, 1999):

$$SDR = \frac{\sum sediment\_exported}{\sum_{i=1,j=1}^{i=nr,j=nc} sediment\_eroded_{i,j}} \tag{4.3}$$

A SDR value of 1 indicates complete export (delivery) of sediment from a system. Lower SDR values indicate a relatively larger role of redeposition within the system.

4.3 RESULTS

Spatial extent, New Zealand

This case study illustrates the importance of choosing a spatial extent that exceeds catchment size, in order to prevent edge effects. An ex-post evaluation is made, where results from different model versions are compared. Table 4.2 is the model setup report for these model versions.

Table 4.2: Model setup report about the preparation of LAPSUS for the spatial extent case study in New Zealand.

Step	Choice
Spatial Extent	- for standard model version equal to the steepest-descent catchment in Fig. 4.5 - decreased as well as increased with 1, 2, 3, 5, 10 and 15 cells from the edges, resulting in 12 extra model versions
Temporal Extent	100 a
Process Extent	1 (water erosion and deposition)
Spatial resolution	25 m. Sinks not removed, landscape only medium of interaction
Temporal resolution	1 a
Process resolution	See Schoorl *et al.* (2002)

For every model version, exports of water and sediment were measured for the area upstream of the lowest point included in the smallest spatial extent (Fig. 4.6).

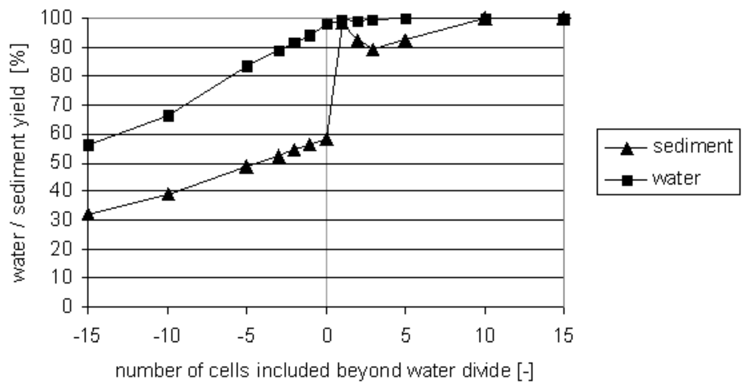


Fig. 4.6 : Amounts of water and sediment leaving the catchment while varying the number of cells included beyond the water divide.

The outflow of water is at a constant maximum when the spatial extent includes at least ten cells beyond the steepest-descent water divide. Small decreases in water outflow (<2%) are visible for spatial extents between the steepest-descent water divide and ten cells larger, larger decreases are visible when the spatial extent decreases to less than the steepest-descent water divide.

The outflow of sediment is also at a constant maximum when spatial extent is ten cells larger than the steepest-descent water divide and decreases strongly when spatial extent is smaller than one cell beyond the steepest-descent catchment size. Also, sediment outflow varies strongly with intermediate spatial extents, when the small changes in water availability in the steepest, most upstream cells lead to large changes in transport capacity. Fig. 4.7 illustrates this for spatial extents equal to and three cells larger than the steepest-descent catchment. Changes between model versions are visible on the highest, steepest slopes (more erosion with larger extent) and in a few sinks in the valley bottom (more deposition with larger extent).

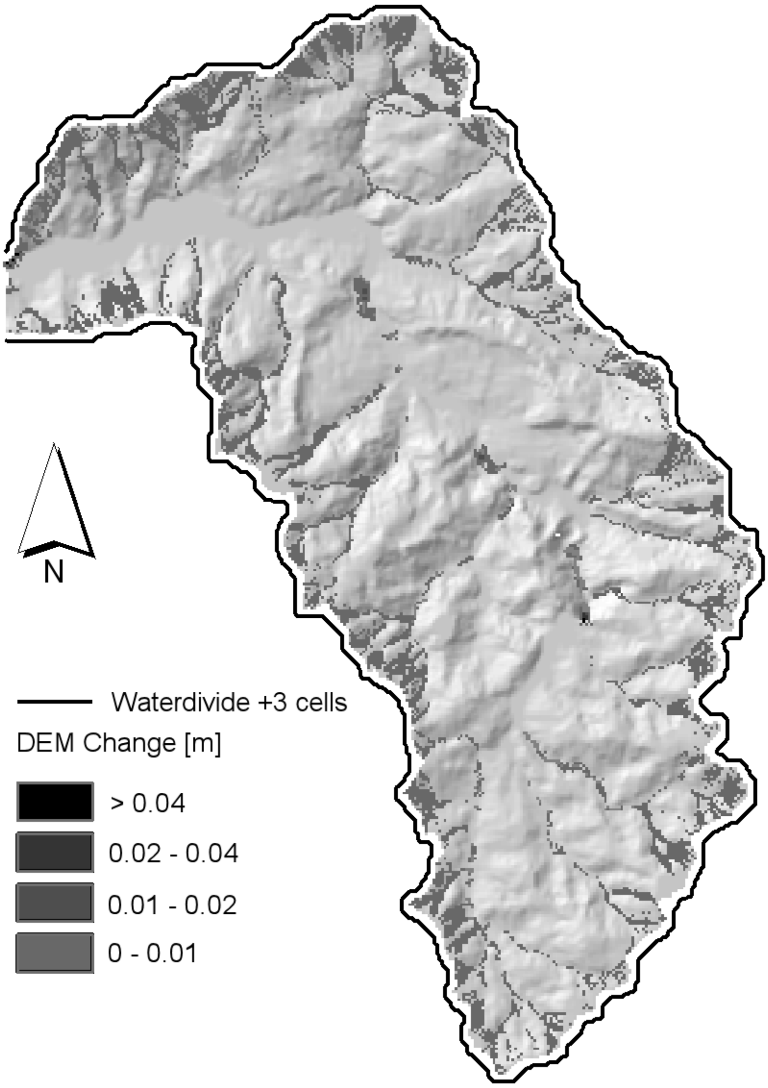


Fig. 4.7: Change in output DEM for the steepest-descent defined catchment when varying spatial extent between the steepest-descent defined catchment and three cells larger. The latter extent is indicated. Zero-differences are transparent, the underlay is a shaded image of the DEM. Positive differences indicate more erosion with larger extent.

Judging from Fig. 4.6, a spatial extent of at least five cells larger than the steepest-descent water divide effectively prevents edge-effects for the model used in this case study. Results of this test will vary when varying choices are made in the model setup scheme, possibly leading to even larger edge-effects especially when topography is more rolling and divergence and convergence of flow play a larger role.

Process extent, South Africa

An ex-post evaluation of the relevance of the processes included in a landscape model requires completion of all steps of the model setup scheme. Table 4.3 presents the choices made in the different steps to set up LEM LAPSUS for this case study.

Table 4.3: Model setup report for the process extent case study in South Africa.

Step	Choice
Spatial Extent	1.82 * 2.27 km = 4.13 km^2, water divide included, catchment mask applied
Temporal Extent	50.000 a
Process Extent	5 (water erosion and deposition, creep, solifluction, frost weathering, biological weathering) in the standard model version and 4 in each of the other versions after removing one of the above processes.
Spatial resolution	10 m for all processes. Sinks not removed, landscape only medium of interaction, processes at same spatial resolution
Temporal resolution	10 a for all processes. All processes at same temporal resolution, in the order mentioned above
Process resolution	See (Temme and Veldkamp, in press) for details about the five processes.

The resulting LEM was run, and the output DEM of the standard version was compared with DEMs of the other versions. Fig. 4.8 shows the changes in output in terms of MEF and RMSE.

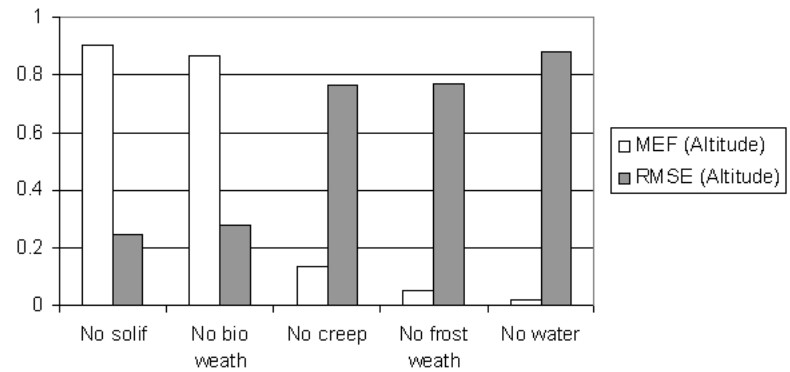


Fig. 4.8: Change in model results of altitude change (MEF and RMSE) when excluding single landscape forming processes from the full model.

The results suggest that solifluction is the least relevant landscape forming process (after removal: MEF = 0.9 and RMSE = 0.25 m) and water erosion and deposition is the most relevant landscape forming process (after removal: MEF = 0.02 and RMSE = 0.88 m). In order of increasing importance to simulated altitude change after 50 ka the processes are solifluction, biological weathering, creep, frost weathering and water erosion and deposition.

Alternative analyses are possible to get more information on the relevance of landscape forming processes, for instance by using soildepth instead of altitude, by subdividing results over meaningful zones, by incorporating uncertainty in inputs (as in the process extent case study in Croatia) or by using other measures than MEF and RMSE. Combining information from these different analyses, workers can decide whether or not to remove a landscape forming process from their model. In this case study, solifluction would be the first candidate for removal from the model, but whether or not this is desirable depends on the study objectives.

An alternative setup of this type of ex-post evaluation is conceivable in which different landscape forming processes are added to a model with a minimal number of processes, rather than removed from a model with a more complete set of processes. This setup seems particularly suited when the focus of study is on a particular landscape forming process rather than on the evolution of the landscape as a whole. In that case, the alternative setup can test whether or not other processes have been justifiably ignored in a one-process model.

Process extent, Croatia

An ex-post evaluation of the relevance of processes comparable to the previous case study is made for the case study area in Croatia. For this area, information about the errors in the input DEM is available (Temme *et al.*, 2008a), allowing for an estimate of the influence of uncertainty in the DEM on uncertainty about the relevance of processes included in the model. Comparable tests could assess this influence for other uncertain model inputs.

For studies where uncertainty or sensitivity analysis are deemed important, it is advisable that these are first performed on the parameters and inputs of the individual process descriptions, before performing them as presented here.

Because soildepth is not limiting on the 20 a temporal extent of study in this area, landscape forming processes biological and frost weathering (of bedrock material) were excluded from the model. The ex-post evaluation of relevance focussed on water erosion and deposition, creep and solifluction. Table 4.4 summarizes the other choices made in model preparation.

Table 4.4: Model setup report for the process extent case study in Croatia.

Step	Choice
Spatial Extent	3.675 * 3.725 km = 13.68 km^2, water divide included, catchment mask not applied
Temporal Extent	20 a
Process Extent	3 (water erosion and deposition, creep, solifluction)
Spatial resolution	25 m for all processes. Sinks not removed, landscape only medium of interaction, processes at same spatial resolution
Temporal resolution	1 a for all processes. All processes at same temporal resolution, in the order as mentioned above
Process resolution	See Temme and Veldkamp (in press)

A Monte Carlo setup was chosen, where the analysis was repeated 63 times with equiprobable DEMs created by adding stochastically simulated DEM error maps to the original DEM. Fig. 4.9 summarizes that method. Subtracting the original DEM values (2) from control points (1) yields a list of errors with their location (3). From the list, mean, standard deviation and spatial autocorrelation of the error are calculated (4). Using sequential Gaussian simulation (Goovaerts, 1997), 63 simulations of the possible error are generated (5) and added to the original DEM to yield 63 equiprobable DEMs (6). Each of the equiprobable DEMs simulated by this procedure may be the true DEM, unlike the original DEM which contained errors. However, since an infinite number of equiprobable DEMs exists, the chance that the correct DEM is included, is very small. The procedure is explained in more detail in Temme *et al.* (2008a).

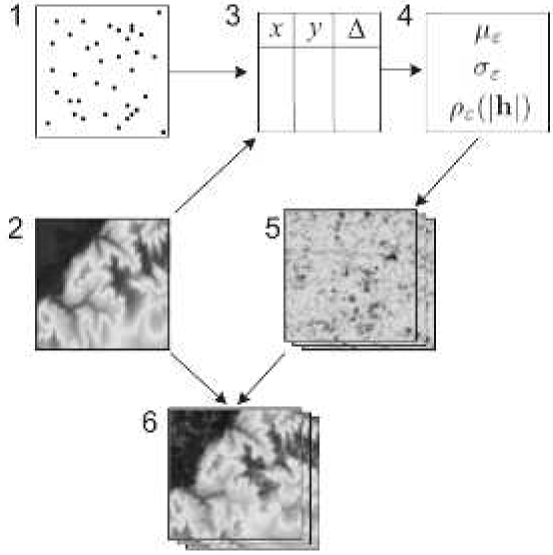


Fig. 4.9: The procedure to create equiprobable DEMs.

RMSE and MEF relative to the model with all processes were recorded when removing each of the processes for every DEM (63 * 3 runs). Fig. 4.10 presents the aggregated results of this analysis.

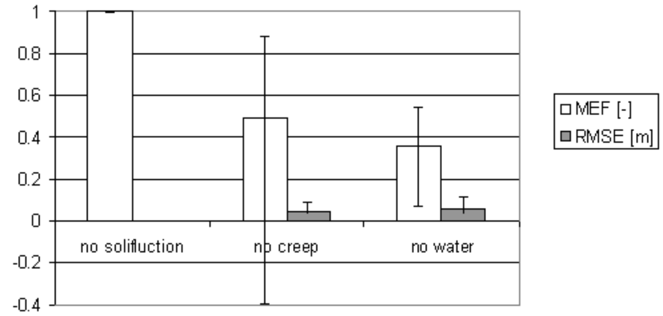


Fig. 4.10: Change in model results in terms of MEF and RMSE for altitude when removing different landscape forming processes from the full model. The error bars indicate 0.05 and 0.95 quantiles of MEF and RMSE.

MEF is almost 1 and RMSE is almost zero when removing solifluction, regardless of the uncertainty in the DEM, suggesting that this landscape forming process is irrelevant in this landscape at this temporal extent. The removal of creep or water erosion and deposition results in significant changes in model output, with the latter process more important than creep when looking at the average results.

However, a closer look at the outputs shows that the MEF when removing creep varies considerably more over the 63 equiprobable DEMs than the MEF when removing water erosion and deposition. On the other hand, the RMSE when removing either process varies more or less the same. This can be explained with basic information about the process descriptions that were used: water erosion and deposition is co-determined by flow accumulation, which is a variable that is strongly influenced by upslope area. Creep is not (Table 4.1). The influence of small changes in DEMs on upslope area is very small, helping to decrease the influence of uncertainty on water erosion and deposition. However, the increases and decreases in creep resulting from changes in the DEM average out over the spatial extent, similar to the increases and decreases in water erosion and deposition, hence the comparable RMSE values.

The additional information obtained from this ex-post evaluation of included processes can help estimate the uncertainty associated with adding or removing different landscape forming processes. In this case study, workers could for instance decide to remove solifluction but not creep from their model because, given the known uncertainty in their input DEM, the uncertainty about the effect of removing creep on model outputs is too large.

Comparing these results with the previous case study, the order of importance of the three shared processes is the same for both models. However, the importance of removing creep or water erosion and deposition is smaller than in the previous case study. Reasons for this can include all steps in the model setup reports (Tables 4.3 and 4.4) where different choices were made, particularly the characteristics of the studied landscapes (DEMs) and the temporal extent of study.

Monte Carlo-type analyses are not limited to DEMs, but may be used for every input to a process description for which uncertainty estimates can be made. If information on the uncertainty of an input is lacking, the Monte-Carlo setup may be replaced with a sensitivity analysis, where the variation of values of input parameters is chosen instead of drawn from a probability distribution. In that case the result of such analysis would be conditional on the actual uncertainty.

Spatial resolution, Croatia

This case study presents a way to quantify the importance of dealing with, instead of removing sinks, by comparing model results of two model versions with one landscape forming process for the case study area in Croatia.

In both model versions, water erosion and deposition is simulated annually. The input DEM contains 72 spurious and non-spurious sinks and the method of dealing with these sinks differs between the model versions.

Model version A deals with all sinks as non-spurious flooded parts of a dynamic landscape that can be created, fragmented, combined and completely or partially filled with sediment (Temme *et al.*, 2006). Model version B deals with all sinks as spurious by filling them before the first run, hence leaving no opportunity for interaction with water erosion and deposition. Techniques to remove sinks from DEMs prior to use differ in computational efficiency and in geomorphological finesse (see Wang, 2006; Hancock, 2008). Arguably one of the simplest and most efficient is the method of Planchon and Darboux (2002), which is used in model version B.

At this point in model building, most of the model setup scheme (Fig. 4.3) has been completed. Table 4.5 presents the choices that were made. Note that no catchment mask has been applied.

Table 4.5: Model setup report for the two model versions used in the spatial resolution case study in Croatia.

Step	Choice for model version A	Choice for model version B
Spatial Extent	3.675 * 3.725 km = 13.68 km^2, water divide included, catchment mask not applied	
Temporal Extent	100 a	
Number of processes	1 (water erosion and deposition)	
Spatial resolution	25 m	
Temporal resolution	1 a	
Level of detail in description	Water erosion and deposition: (Schoorl *et al.*, 2002) with ability to deal with sinks dynamically (Temme *et al.*, 2006)	Water erosion and deposition: (Schoorl *et al.*, 2002) with ability to fill sinks as errors (Planchon and Darboux, 2002).

The number of sinks present in the landscape varies strongly between the two model versions (Fig. 4.11), with water erosion and deposition filling about 40 sinks in 50 years before maintaining the number of sinks around 30 in model version A, and model version B removing all sinks in the first run. The sinks remaining in model version A at this point are predominantly in the flat area bordering the hills in the northwest and non-spurious (Fig. 4.12).

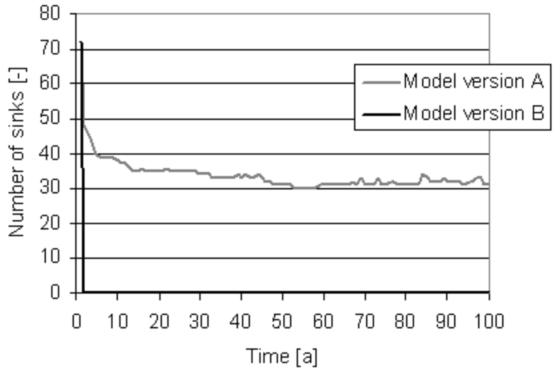


Fig. 4.11: The number of sinks under model versions A and B.

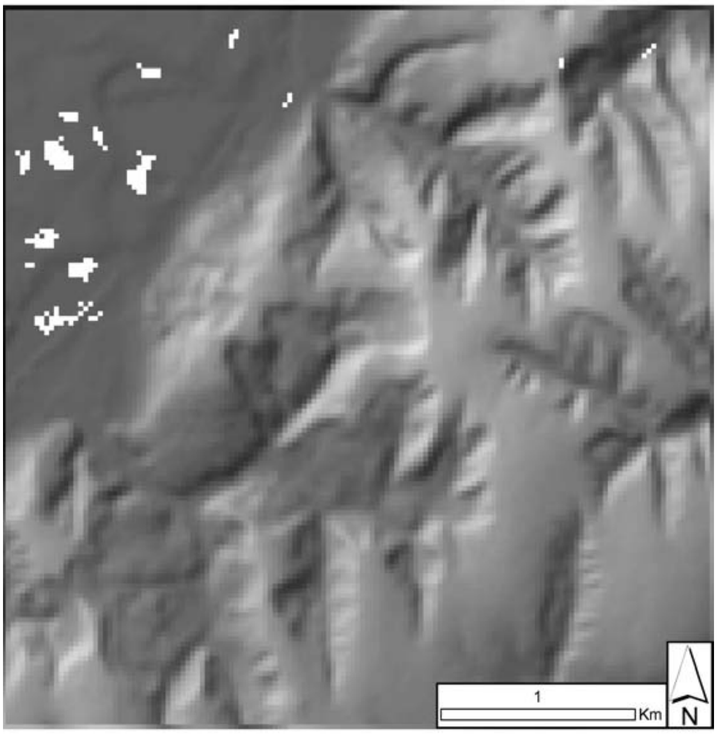


Fig. 4.12: Sinks remaining after 100 years of water erosion and sedimentation, in white.

This difference is reflected in the delivery of sediment from the landscape (Fig. 4.13). After stabilisation, about 30 percent of eroded sediment is removed from the landscape in model version A, and about 80 percent in model version B. The difference is used to fill sinks in model version A.

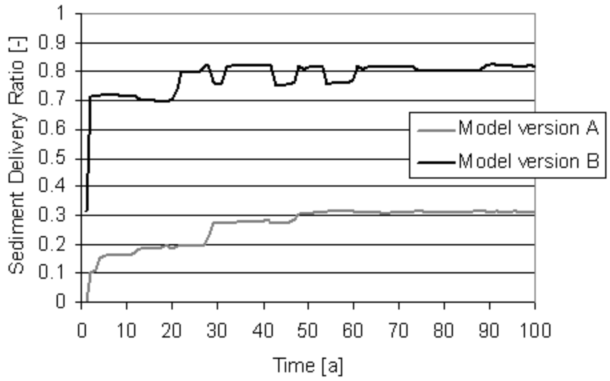


Fig. 4.13: Sediment Delivery Ratio over time for the two model versions.

Figs. 4.11 and 4.13 indicate that the difference between removing and dealing with sinks is large and persists over the temporal extent of this case study. This is in agreement with results of Hancock (2008) for two catchments in Australia, who however found a decrease of the difference to zero for periods of thousands of years. That is not the case in our case study (as visible from Fig. 4.14) and in general is likely a function of the studied landscape and climate characteristics.

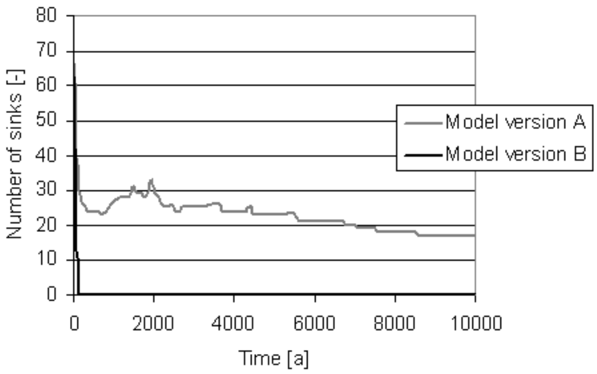


Fig. 4.14: Development of the number of sinks under model versions A and B when increasing temporal extent to 10 ka.

Taken together, tests like Hancock's (2008) and ours suggest that it depends on the case study, especially the temporal extent, whether or not it is important to deal with sinks present in the initial DEM in landscape evolution models. Obtaining and using this information for particular LEM studies is possible with this test.

Whether or not it is important to deal with sinks that result from the interaction of landscape forming processes during model runs is a totally different matter. Whereas sinks in input DEMs may be spurious, these model-created sinks must be considered non-spurious. In fact, they are often intended results.

Spatial resolution, New Zealand

This case study evaluates the importance of assuming the landscape the only medium of interaction, but in this case for a model with two interacting landscape forming processes. The case study area in New Zealand is used.

Two model versions are used, like in the previous case study. In both model versions, landscape forming process water erosion and deposition was activated in every year, and the process of landslide erosion and deposition was activated once every ten years, with increasing intensity. This leads to an increase in the number of sinks every ten years, as landslide deposits dam valleys. The method of dealing with these sinks differs between the model versions like in the previous case study.

Table 4.6 presents the choices that were made in the model setup scheme to prepare the two model versions for this case study.

Table 4.6: Model setup report for the two model versions used in the spatial resolution case study in New Zealand.

Step	Choice for model version A	Choice for model version B
Spatial Extent	7.85 * 10.5 km = 82.4 km^2, water divide included, catchment mask applied	
Temporal Extent	100 a	
Number of processes	2 (water erosion and deposition, landslide erosion and deposition)	
Spatial resolution	25 m for all processes	
Temporal resolution	1 a for water erosion and deposition 10 a for landslide erosion and deposition	
Level of detail in description	Water erosion and deposition: (Schoorl *et al.*, 2002) with ability to deal with sinks dynamically (Temme *et al.*, 2006) Landslide erosion and deposition: (Claessens *et al.*, 2007)	Water erosion and deposition: (Schoorl *et al.*, 2002) with ability to fill sinks as errors (Planchon and Darboux, 2002). Landslide erosion and deposition: (Claessens *et al.*, 2007)

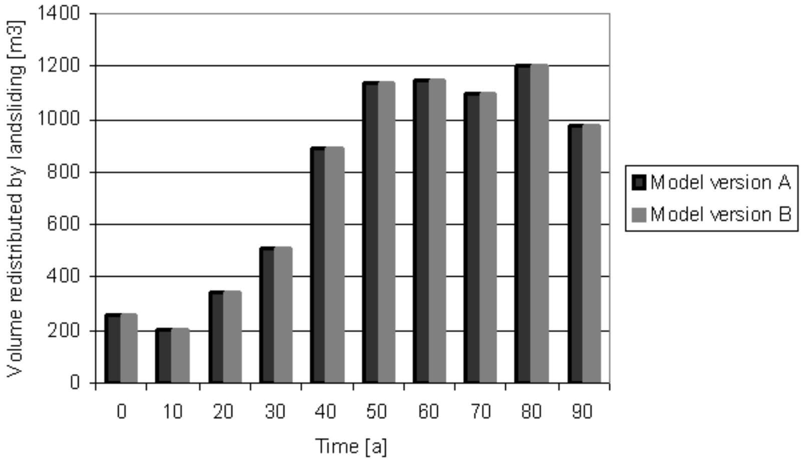


Fig. 4.15: The volume of landslide deposition over time for model versions A and B.

The increasing intensity of landsliding resulted in a generally increasing volume of soil redistribution by means of landsliding (Fig. 4.15) even though a legacy effect is evident at high levels of intensity (*cf.* Claessens et al, 2007). Differences between the two model versions in terms of the soil redistribution by means of landsliding are minimal, indicating that sinks created by landsliding do not influence landsliding in later timesteps. Apparently, for this case study, the importance of considering the landscape the only medium of interaction is minimal when only interested in the process of landslide erosion and deposition

However, when interested in landscape evolution as a whole, or in water erosion and deposition, interaction may be important. The number of sinks in every model run is compared between model versions in Fig. 4.16.

The number of sinks present in the landscape varies strongly between the two model versions, with depression-removal by the process of water erosion and deposition taking multiple runs, and the presence of sinks leading to a different reaction to landslides in terms of sink formation. For instance, at 60 a, the same landslide activity (Fig. 4.15) leads to the creation of 17 (23-6) new sinks in model version A, and 20 (20-0) new sinks in model version B. Model version A predicts fragmentation and combination of sinks between 30 and 40 a, leading to fluctuations in their number instead of a consistent decrease.

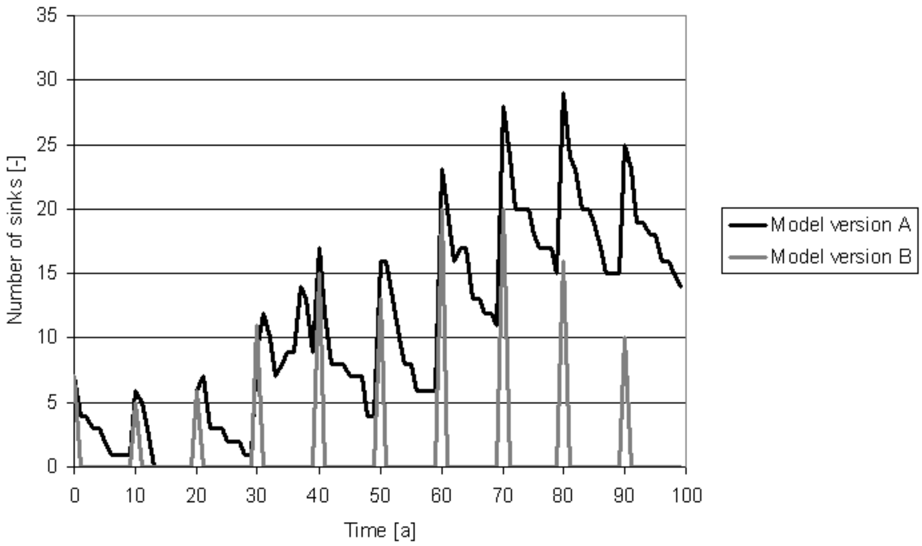


Fig. 4.16: The number of sinks over time in model versions A and B. In model version B, the volume of sinks is non-zero immediately after landslide deposition and zero in other timesteps.

The next step is examining the response of water erosion and deposition to these differences. Fig. 4.17 presents the development of SDR over time for the two model versions.

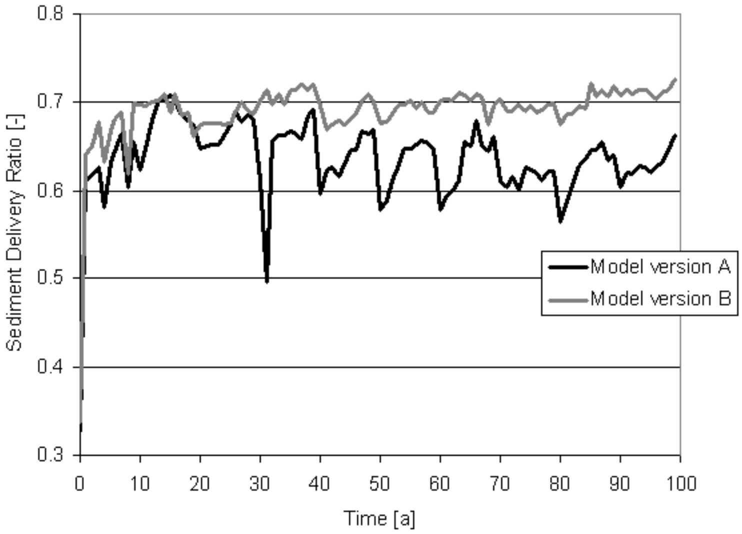


Fig. 4.17: Sediment Delivery Ratio over time for the two model versions.

The difference in Sediment Delivery Ratio is mostly caused by a difference in redeposition in the narrow valleys of the area and is larger when there are more sinks in model version A. Over the 100 years of this case study, the average increase in soildepth along the longitudinal river profile of the largest completely included catchment is 40 cm in model version B, and 86 cm in model version A.

It is possible to use alternative and more elaborate measures for the importance of interaction on both the individual processes and landscape evolution as a whole, particularly measures that look at spatial differences within the extent. Regardless of the measure used, tests like this help to make clear what the importance of including or removing sinks is. Depending on study objectives, workers can then decide how to build their model and whether or not to remove sinks between runs.

The tests in the spatial resolution case studies can only be performed when process descriptions are available that can deal with sinks. That is sometimes problematic for processes that involve the movement of water through the landscape. However, the increasing availability of process descriptions that can deal with sinks (Temme *et al.*, 2006; Hancock, 2008) is reducing that problem.

Temporal resolution, Belgium

In evaluating the importance of temporal resolution, a useful test is to study its effect with different model versions. For the case study area in Belgium (Fig. 4.18), temporal resolution was increased from 1 to 2500 years in 11 steps, resulting in a decrease of interaction in time. Temporal resolution was changed for tillage and water erosion and deposition simultaneously as well as for each process individually while the other process was kept at annual resolution.

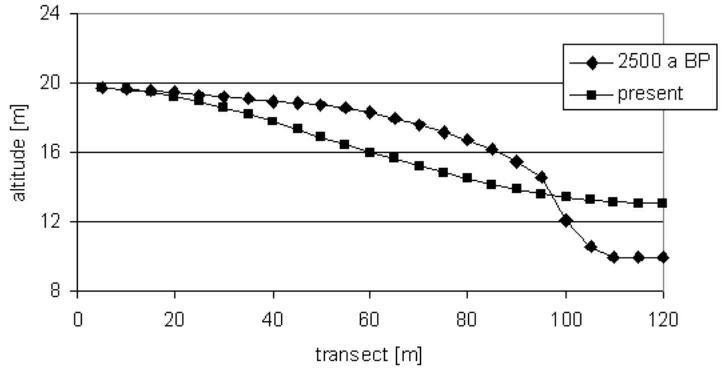


Fig. 4.18: The transect at 2500 a BP and present (Rommens et al., 2007).

Table 4.7 presents the choices that were made in the model setup scheme to prepare the model versions for this case study.

Table 4.7: Model setup report for the model versions used in the temporal resolution case study in Belgium.

Step	Choice
Spatial Extent	0.12 * 0.005 km = 0.0006 km², water divide included, catchment mask not applied (transect – 24 * 1 cells)
Temporal Extent	2500 a
Number of processes	2 (water erosion and deposition, tillage)
Spatial resolution	5 m for the two processes. Sinks not removed, landscape only medium of interaction, processes at same spatial resolution
Temporal resolution	Varying between 1, 2, 5, 10, 25, 50, 125, 250, 500, 1250 and 2500 years for both processes and the two processes independently (33 model versions).
Level of detail in description	Water erosion and deposition: (Schoorl *et al.*, 2002) with ability to deal with sinks dynamically (Temme *et al.*, 2006) Tillage: (Schoorl *et al.*, 2004)

Each model version was calibrated individually and MEFs were calculated (Fig. 4.19). Results show that model performance is not stable when changing the number of years per timestep, i.e. the amount of interaction in time is important. Performance stays close to its maximum until the number of years per timestep for both processes exceeds 50 and MEF is below zero for the model version with interaction only once in 2500 years.

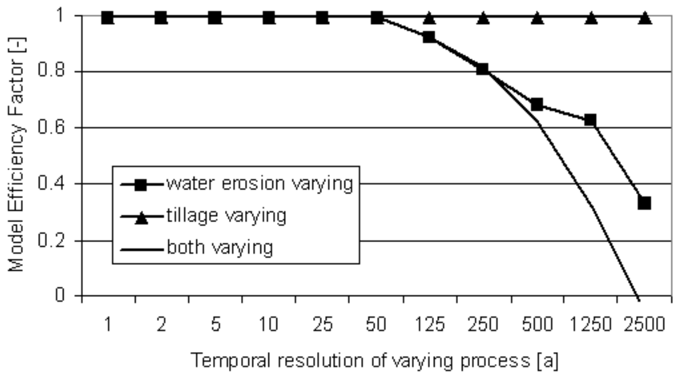


Fig. 4.19: Change in Model Efficiency Factor when increasing the number of years per timestep for both processes (both varying), for water erosion only (water erosion varying) and for tillage redistribution (tillage varying).

This suggests that for this case study, interaction between landscape forming processes is important, but that it is not necessary to take interaction into account on an annual basis. Using MEFs as a measure of performance, uniform temporal resolution of 50 years would still result in good performance while saving computing time.

The small number of cells (24) and the fact that the area is a transect instead of an area, make it possible to achieve near perfect matches between model results and reality when enough interaction in time is allowed. Model performance would likely be lower in case studies that use larger areas and the negative effect of decreasing interaction in time on model performance may be visible at a lower temporal resolution relative to the temporal extent.

MEFs increase when one of the processes is allowed a constant minimal temporal resolution of one year. Improvement is dramatic when water erosion has a constant minimal temporal resolution, such that MEFs stay close to unity regardless of the temporal resolution of tillage redistribution.

Tests like these may suggest models that have a non-uniform temporal resolution for the different landscape forming processes, like CAESAR (Coulthard, 2001). For this case study, a model that has reduced temporal resolution of 50 years for water erosion and 2500 years for tillage redistribution seems justified (though this combination is not presented in Fig. 4.19 and would require a further test).

The almost constant model performance when varying the temporal resolution of tillage, suggests that the relevance of tillage itself, and not only of its temporal resolution, for landscape evolution in this case study is low. However, that relevance should be tested differently, like presented before. On the other hand, keeping tillage at annual timesteps explaines the difference between the model versions where temporal resolution of both processes, resp. water erosion and deposition varies. This points to a non-zero relevance.

4.4 CONCLUSIONS

Landscape evolution models are always case-specific. In setting up these models, a number of choices must be consciously made and reported on. The model setup scheme presented in this chapter helps workers in structuring and reporting these choices. The tests in the different case studies illustrate methods to make the choices, typically by comparing the results of different model versions. Taken together, the scheme and the tests help to set up landscape evolution models for various settings, or to assess the validity of existing models. They can indicate the sensitivity of models for different simplifications as a function of case study properties.

The case studies presented in this chapter are meant as examples of tests and their actual results must be interpreted with caution. However, a number of points is worthy of consideration:

- The spatial extent case study indicates that for the multiple flow routing scheme used and over a period of 100 years, edge effects are observed for spatial extents less than ten cells larger than the steepest descent water divide. Effects are especially important for sediment export.
- The process extent case studies indicate that the relevance of different landscape forming processes for model results varies and hence that single-process landscape evolution models may miss important contributions to landscape evolution.
- The spatial resolution and interaction case studies indicate that the importance of sinks on landscape evolution may be both large and long-term. Hence, it is important for multi-process landscape evolution models to deal with, instead of remove, model-simulated sinks. This contrasts with the findings of Hancock (2008).
- The temporal resolution and interaction case studies indicate that the effect of temporal resolution on model results varies and may be large. Reasonable decreases in temporal resolution may be justified and save computing time.

Landscape evolution model frameworks can facilitate the different choices that can be made using the model setup scheme. This entails that they are modular or loosely-coupled, that the landscape is the only medium of interaction between landscape forming processes, that they can deal with non-spurious sinks and that they allow spatial and temporal resolution to vary between processes. Whether or not all of these features are actually required in a landscape evolution model study, follows from workers' choices.

CHAPTER 5

MULTI-PROCESS LATE QUATERNARY LANDSCAPE EVOLUTION MODELLING OF OKHOMBE VALLEY

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Notes

CHAPTER 5

MULTI-PROCESS LATE QUATERNARY LANDSCAPE EVOLUTION MODELLING OF OKHOMBE VALLEY

Landscapes evolve in complex, non-linear ways over Quaternary timespans. Integrated geomorphological field studies usually yield plausible hypotheses about timing and impact of process activity. Landscape Evolution Models (LEMs) have the potential to test and falsify these landscape evolution hypotheses. Despite this potential, LEMs have mainly been used with hypothetical data and rarely to simulate the evolution of an actual landscape.

In this chapter, I use a LEM (LAPSUS) to explore if it is possible to test and falsify conclusions of an earlier field study on 50 ka landscape evolution in Okhombe valley, KwaZulu-Natal, South Africa. In this LEM, five landscape processes interact without supervision: water driven erosion and deposition, creep, solifluction, biological weathering and frost weathering. Calibration matched model results to three types of qualitative fieldwork observations: individual process activity over time, relative process activity over time and net landscape changes over time. Results demonstrate that landscape evolution of Okhombe valley can be plausibly simulated.

A particularly interesting and persistent feature of model results are erosional and depositional phases that lag climatic drivers both by decades, and by several ka within a few hundred meters. The longer lag has not been reported for this spatial extent before and may be an effect of slow landscape-soil-vegetation feedbacks. The combined modelling and fieldwork results allow a more complete understanding of these responses to climate change and can fill in hiatuses in the stratigraphical record. Suggestions are made for methodological adaptations for future LEM studies.

5.1 INTRODUCTION

Landscapes are known to evolve in complex, non-linear ways over thousands of years. This is because both type and intensity of landscape forming processes change over this period (Thomas, 2004), due to changes in climate, topography, vegetation and tectonics. Integrated geomorphological studies, where in-depth analyses of landscapes and deposits are complemented by dating, are indispensable to unravel this complex behaviour. Such studies often result in simple qualitative hypotheses on how the interaction of landscape processes in space and time has led to the present regional landscape and deposits (Veldkamp *et al.*, 2001).

Landscape Evolution Models (LEMs) predict or simulate the 3D development of landscapes over time (Kirkby, 1971; Ahnert, 1976). Consequently, they have the potential to test and falsify landscape evolution hypotheses.

LEMs have hardly been used for this purpose for five reasons: 1. there is a lack of robust process descriptions for many processes; 2. most existing process descriptions can not be scaled up to millenial timescales; 3. there is a general shortage of quantitative input data with the required spatial or temporal extent; 4. boundary conditions are unknown; 5. there are insufficient data for quantitative calibration. The latter is even a problem on decadal timescales for erosion models (Jetten *et al.*, 2003).

Instead, studies with LEMs have commonly been focussed on testing process descriptions (Minasny and McBratney, 2001; Heimsath *et al.*, 2002; Schoorl *et al.*, 2002; Collins *et al.*, 2004; Heimsath *et al.*, 2005; Hancock, 2006), resolution effects (Coulthard *et al.*, 1998; Schoorl *et al.*, 2000; Thompson *et al.*, 2001; Claessens *et al.*, 2005), or sensitivity analyses (Collins *et al.*, 2004; Tucker, 2004; Claessens *et al.*, 2005).

LEMs have had some success in simulating ka-scale landscape evolution (e.g. De Alba, 2003; Garcia-Castellanos *et al.*, 2003; Van Oost *et al.*, 2003; Minasny and McBratney, 2006) but have rarely been used to examine evolution of an actual landscape (Coulthard, 2001). Only recently, landscape evolution of real-world catchments has been modelled over multiple ka: Coulthard *et al.*, (2002, 9.2 ka), Peeters *et al.*, (2006, 2.5 ka), Follain *et al.*, (2006, 1.2 ka). Applications that cover the major climatic and geomorphic changes from the Last Glacial Maximum (LGM) to present are still lacking.

This chapter presents a first attempt to cover the last 50 ka including the Glacial-Interglacial transition. This was possible because the modelling setup was based on close interactions with field- and laboratory work that supplied landscape evolution hypotheses. The close collaboration allowed us to tackle the last three LEM limitations mentioned above: fieldwork yielded input-data, boundary conditions and qualitative calibration data.

For this approach to be succesful, simple and robust descriptions of the processes involved were designed from basic geomorphological theory, preferably using existing descriptions of similar processes as starting points. Whereas further experimentation and calibration of these descriptions is probably needed, the simple, initial versions presented here can be suitable for a long-term study (*cf* Brasington and Richards, 2007).

If different processes are allowed to interact without supervision, results may provide a semi-independent validation of landscape evolution hypotheses. Moreover, LEM results can give new perspectives by filling in fragmented stratigraphical records and exposing inconsistencies and misinterpretations in landscape evolution hypotheses.

This chapter starts with an existing robust landscape evolution model (LAPSUS, Schoorl *et al.*, 2002) which has only been tested and validated for decadal applications. It is attempted to model 50 ka landscape evolution of the Okhombe valley, KwaZulu Natal, South Africa (Chapter 1, Figs 1.2, 1.4 and 1.5). The objectives are:

- To combine and, where needed, develop generic descriptions of relevant landscape forming processes in Okhombe valley for the Late Pleistocene to present in LAPSUS.
- To derive model input data, boundary conditions and calibration data from fieldwork results.
- To run and calibrate LAPSUS for the spatial and temporal extent of the fieldwork.
- Using this calibrated model, to explore the implications of the conclusions of (Temme *et al.*, 2008b) for Okhombe valley.
- To explore if the combination of fieldwork and modelling results leads to new perspectives and methods for landscape evolution modelling studies in general.

5.2 METHODS

Modelling setup

Long-term palaeo-landscape evolution can be studied in two ways. One can either start with the current landscape and model backward in time, or start in the past with a palaeo-landscape and model forward in time. Both methods face fundamental difficulties (Peeters *et al.*, 2006).

Two main issues that cause difficulties for backward modelling are equifinality; the notion that different palaeo-landscapes can evolve into one present landscape, and polygenesis; the notion that different processes may have acted to produce the present landscape. The main difficulty with forward modelling is the definition of the initial palaeo-landscape. For our study that focuses on the type, intensity and interaction of different landscape forming processes in space and time, and where some information on the palaeo-landscape is available (Temme *et al.*, 2008b), forward modelling is the logical choice.

Landscape evolution modelling requires being specific about temporal and spatial extents and resolutions (Chapter 4, Schoorl *et al.*, 2000; Veldkamp *et al.*, 2001). It was decided to let the field study determine these parameters. Consequently, temporal extent was 50 ka B.P. to present, the period that was reconstructed by Temme *et al.*, (2008b). To limit the number of time steps, temporal resolution was set at 10 a.

Based on the field study area, the spatial extent was a subcatchment of Okhombe valley, with a buffer zone to avoid edge effects. Spatial resolution (cellsize) was 10 m. Seven zones were defined in the subcatchment (Fig. 1.5). Total decadal volumes of the activity of landscape forming processes for the zones and the subcatchment as a whole were recorded as model results.

Model runs took a few hours each, and fieldwork conclusions were not sufficiently quantitative to calibrate the model automatically by checking hundreds of parameter combinations. Instead, first sensitivity analysis was performed on a 1 ka extent (Table 5.1) to find out which parameters had the largest influence on modelled volumes. Sensitivity was expressed in percentage change of the total sediment volume transported or weathered per percentage change in parameter. Note that sensitivity analysis did not focus on the sensitivity for change in patterns, but for change in volumes. Only parameters available for calibration were included in the analysis, input data were excluded.

Table 5.1: Modelling setup

	Sensitivity analysis processes	Calibration
Temporal extent	1 ka	50 ka
Temporal resolution	10 a	10 a
Number of timesteps	1.10^2	5.10^3
Spatial extent	4.1 km^2	4.1 km^2
Spatial resolution	10 m	10 m
Number of cells in grid	41.10^3	41.10^3

Second, model calibration was performed, with initial parameter values based on literature where available. Calibration was trial and error and tried to simultaneously match model outputs to three types of qualitative fieldwork results. First, model outputs for individual landscape processes must match fieldwork conclusions about process activity in time and space. Second, relative activities of landscape forming processes in model outputs must conform to fieldwork conclusions. Third, modelled soil thickness development, i.e. the net sum of the activities of the landscape forming processes over time, must match fieldwork conclusions. The term soil thickness is used to refer to the net sums of the volumes weathered or transported by the landscape forming processes, indicating their multi-process origin (*cf* Follain *et al.*, 2006; Minasny and McBratney, 2006).

After calibration, quantitative validation results were demonstrated using the Model Efficiency Factor (MEF, Nash and Sutcliff, 1970):

$$MEF = 1 - \frac{\sigma^2}{\sigma_{obs}{}^2} \tag{5.1}$$

Where σ^2 is the variance of the difference between modelled and true current elevations, and $\sigma_{obs}{}^2$ is the variance of the difference between palaeo and true current elevations. MEF was calculated based on individual cells, and on several higher aggregation levels. Note that an *assumed* palaeo DEM was used as the starting point to model current elevations and therefore MEF is no objective measure of model fitness in this study. No maximisation of MEF was attempted.

Model

Landscape evolution model LAPSUS (LandscApe ProcesS modelling at mUlti dimensions and scaleS, Schoorl *et al.*, 2002) was used, working with sinks as non-spurious features in landscapes using the algorithm of Temme *et al.* (2006). Based on the process reconstruction, the following processes had to be incorporated in the LEM: water erosion or deposition, biological and frost weathering, soil creep and solifluction. LAPSUS simulates these processes in every timestep and in every gridcell, which is arguably more generic but also more time-consuming than the alternative: distinguishing between processes in terms of spatial and temporal resolution, like e.g. in CAESAR (Coulthard *et al.*, 1998). Processes operate on a volume-balance basis.

Process descriptions in LAPSUS are designed for use at annual resolution. To use the model at decadal resolution in this study, two methods were combined. First, process parameter values were changed to reflect activity for longer than one year, and second, results of processes were multiplied with a uniform factor before adding them to the DEM. This factor is called *timefactor* and is used as an overall calibration parameter (ref Table 5.4, Eqs. 5.6 and 5.7).

In the model equations below, suffix s is used to indicate variability of an input or parameter in space, and suffix t to indicate variability in time.

Hydrology

LAPSUS's continuity equation for water for every cell is given below:

$$outflow_{s,t} = \sum_{j=0}^{\max 7} inflow_{j,s,t} + precipitation_t - (infiltration_{s,t} + evapotranspiration_{s,t}) \tag{5.2}$$

With all variables in [$m^3\ m^{-2}$]. The terms in this equation are annual sums of the amounts involved in individual rain events. It is assumed that between rain events, evapotranspiration uses up water that infiltrated during rain events and therefore, that infiltration during rain events is limited only by total storage capacity (assuming saturation excess overland flow).

The implementation of the hydrological model is a variation of the precipiton approach (Crave and Davy, 2001). In every timestep, 'precipitons' (simulating total precipitation within a timestep) are dropped on every cell of the grid. Cells are then considered in order of relative altitude. Outflow is calculated for cells that have no higher neighbour, or whose higher neighbours have been considered before, and that are not sinks. Sinks and the cells of their surrounding depressions follow a set of additional rules (Temme *et al.*, 2006). Note that the processing order of the grids may change every timestep, as the landscape evolves.

This variation of the precipiton approach requires many scans of the grid in every timestep until all cells have been considered. The time required may be reduced by scanning the grid from different directions (Planchon and Darboux, 2002), but the amount of reduction is strongly dependent on the type of flow routing. In this study, the grid was always scanned from the same direction.

Outflow from every cell to its maximum 8 lower neighbours is calculated with multiple flow routing (Holmgren, 1994):

$$f_i = \frac{(\Lambda)_i^p}{\sum_{j=1}^{\max 8} (\Lambda)_j^p} \tag{5.3}$$

Where f_i [-] is the fraction of the outflow from a cell to its neighbour *i*. Diffusivity of flow is determined by *p* [-], with p=1 dividing flow proportional to the tangent of slope Λ [-] and $p=\infty$ resulting in steepest descent behaviour (*sensu* Moore *et al.*, 1991).

Infiltration (Buis and Veldkamp, 2008) and evapotranspiration are calculated:

$$infiltration_{s,t} = soilthickness_{s,t} * porosity \tag{5.4}$$

$$evapotranspiration_{s,t} = evap_{\max} . V_{s,t} \tag{5.5}$$

With *soilthickness* and $evap_{\max}$ in [m] and *porosity* and V, the relative vegetation cover, in [-].

Vegetation

Vegetation is a key factor in landscape processes (Weltz *et al.*, 1998; Shugart, 2000; Okin and Gillette, 2001; Dirnbock *et al.*, 2002; Collins *et al.*, 2004) and may even leave a discernible signature on landscapes themselves on ka scales (Dietrich and Perron, 2006). On the other hand, landscapes determine the location of different types of vegetation through microclimate and soil properties (e.g. MacMillan, 2007). The inclusion of soil-vegetation-landscape interactions in LEMs is therefore desirable.

An explicit consideration of these interactions in a LEM requires the inclusion of vegetation, or a proxy of it, as a state variable. This state variable should be defined such that it can be a) calculated with or related to (input and modelled) data that are available over the temporal and spatial extent of study and b) meaningfully used in the various landscape process descriptions active in the model. In a study of vegetation influence on landscape evolution, Collins *et al* (2004) defined and used V [-]: the relative vegetation cover at or near ground level. V, also used in this study, satisfies both conditions mentioned above: it can be related to either pollen records or temperature and precipitation records and model-supplied soil thickness, and it can be used as a proxy for the different vegetation properties that play a role in landscape processes.

Landscape forming processes

Landscape forming processes previously included in LAPSUS are water erosion and deposition (Schoorl *et al.*, 2002), tillage (Schoorl *et al.*, 2004; Heuvelink *et al.*, 2006) and landslide activity (Claessens *et al.*, 2007, not used in this study). Reduced-complexity implementations of biological and frost weathering, creep and solifluction were added for this study (Table 5.2). Given the focus on landscape-scale interactions between processes over thousands of years, instead of on exact single-process predictions, reduced-complexity versions of these implementations were assumed sufficient.

Table 5.2: Landscape forming processes used in LEM LAPSUS for this study.

Landscape forming process	**Source of implementation starting point**
Water erosion and deposition	Schoorl *et al.*, 2002
Creep	Follain *et al.*, 2006
Solifluction	Follain *et al.*, 2006, Matsuoka *et al.*, 2005
Biological weathering	Minasny and McBratney, 2006
Frost weathering	Bloom, 1998

Thus, ignoring differences in density between soil and bedrock, the continuity equation of soil thickness (using the notation used by Minasny and McBratney, 1999) is formulated:

$$\frac{\partial h}{\partial t} + \left(\frac{\partial e_p}{\partial t} + \frac{\partial e_f}{\partial t} \right) = \left(q_D + q_E + q_S \right) \tag{5.6}$$

Where h is soil thickness [m], e_p is biological weathering of bedrock [m] and e_f is frost weathering of bedrock [m]. Soil transport terms are q_D [m t^{-1}] for water erosion and deposition, q_E [m t^{-1}] for creep (diffuse transport) and q_S [m t^{-1}] for solifluction. Timefactor [-] is used to increase temporal resolution (ref section 2.2).

Similarly, the continuity equation of the surface is formulated:

$$\frac{\partial dtm}{\partial t} = \left(q_D + q_E + q_S \right) \tag{5.7}$$

Water erosion and deposition. The process description for water erosion and deposition is based on early work of Kirkby (1971) and is detailed in Schoorl *et al.* (2002). A capacity for transport of sediments between cells C [m²] is calculated using overland flow q [m] and tangent of slope Λ [-]:

$$C_{s,t} = \alpha \cdot Q_{s,t}{}^{m} \cdot \Lambda_{s,t}{}^{n} \tag{5.8}$$

With a to correct the units. Transport capacity is compared to the incoming amount of sediment in transport S_0 [m²] to calculate the amount of sediment S [m²] that will be transported:

$$S_{s,t} = C_{s,t} + (S_{0\,s,t} - C_{s,t}) \cdot e^{-cellsize/h} \tag{5.9}$$

Eq. 5.9 shows that portions instead of totals of the surplus or deficit in capacity are satisfied in every cell, depending on *cellsize* [m] and erodibility or sedimentation charateristics captured in h [m]. For larger cells, a larger portion of surplus or deficit is satisfied. Erodibility or sedimentation characteristic h [m] is a function of

$$h_{s,t} = \frac{C_{s,t}}{P_{s,t} \cdot Q_{s,t} \cdot \Lambda_{s,t}}$$ in case of deposition (5.10) and

$$h_{s,t} = \frac{C_{s,t}}{K_{s,t} \cdot Q_{s,t} \cdot \Lambda_{s,t}}$$ in case of erosion (5.11)

Where Schoorl *et al*'s (2002) K [m^{-1}] and P [m^{-1}] factors were adapted for this study to include the effect of vegetation, assuming a linear effect:

$$K_{s,t} = K_{normal} - K_{veg} V_{s,t} \quad (5.12)$$

$$P_{s,t} = P_{normal} + P_{veg} V_{s,t} \quad (5.13)$$

Where K_{normal} [m^{-1}] and P_{normal} [m^{-1}] are erodibility and sedimentation characteristics in non-vegetated conditions, and K_{veg} [m^{-1}] and P_{veg} [m^{-1}] the changes in these characteristics under complete vegetation cover V [-]. In this implementation, it is more difficult to erode, and easier to deposit, with increasing vegetation cover. More elaborate implementations of the effect of vegetation on water erosion and deposition are possible, but for the purposes of this long-term case study the linear effect presented above was deemed appropriate.

Creep. Studies of diffuse transport processes in soil-mantled landscapes assumed at equilibrium have shown that creep is best described as a soildepth- and slope dependent process (Heimsath *et al.*, 1999; Braun *et al.*, 2001; Heimsath *et al.*, 2005), instead of a slope dependent process (e.g. Follain *et al.*, 2006). However, the implementation in this study is based on the latter, more commonly used description because of its simplicity:

$$q_{E\,s,t} = \frac{D_E}{cellsize}.(\tan\alpha)_{s,t} \quad (5.14)$$

Where q_E is the volume of creep [m t^{-1}], D_E is the diffusivity for creep [m^2 t^{-1}], *cellsize* is the DEM cellsize [m], and tan α is the tangent of slope [-]. In this implementation, creep is distributed proportionally over downslope neighbours, based on slope between donor and receptor cells.

Vegetation influence is implicit in diffusivity D_E. This influence is made explicit by redefining D_E as the diffusivity under complete vegetation cover and assuming that creep is linearly controlled by vegetation:

$$q_{E_{s,t}} = \frac{D_E}{cellsize}.(\tan\alpha)_{s,t}.V_{s,t} \quad (5.15)$$

Solifluction. Knowledge of the controlling factors of solifluction is incomplete, though the positive influence of slope and seasonal saturation and the negative influence of vegetation are known (e.g.

Matsuoka, 2001). Realizing moreover that solifluction is accelerated creep (Matsuoka *et al.*, 2005) that behaves in a less diffusive way, Follain *et al*'s (2006) implementation was adapted to describe solifluction.

In this implementation, the sum of outflow and infiltration is used as a proxy for saturation. Moreover, the stabilizing role of vegetation is included:

$$q_{S\,s,t} = \frac{D_s}{cellsize}.(\tan\alpha)_{s,t}.solifactor_{s,t}.(1-V_{s,t}) \tag{5.16}$$

Where q_S is the volume of creep [m t^{-1}], D_s is the diffusivity for solifluction [m^2 t^{-1}], *cellsize* is in [m], tan α is the tangent of slope [-], *V* is relative vegetation cover [-] and with *solifactor* [-]:

$$solifactor_{s,t} = 1 + \log(outflow_{s,t} + infiltration_{s,t}) \tag{5.17}$$

Where *outflow* and *infiltration* are in [m^3]. Minimum and maximum values for *solifactor* are 1 and 5. The difference in diffusive behaviour is captured with a variation of Holmgren's multiple flow direction algorithm (1994):

$$f_i = \frac{(\tan\alpha)_i^{solifactor_{s,t}}}{\sum_{j=1}^{\max 8}(\tan\alpha)_j^{solifactor_{s,t}}} \tag{5.18}$$

Solifactor here determines the diffusivity of the flow of sediment, with *solifactor*=1 dividing flow proportional to the tangent of slope (as implemented for creep by Follain *et al.*, 2006) and *solifactor*=5 resulting in practically all flow directed to the steepest neighbour. This implementation leads to less diffusive behaviour of solifluction with increasing saturation of the soil.

Seasonality of rainfall is ignored in the implementation above, because no quantitative data are available. Yet, the distribution of rainfall over a year is crucial for solifluction because it determines seasonal saturation of the soil (Matsuoka, 2001). Therefore, solifluction was only activated in periods when seasonal saturation was likely (ref Chapter 5.3.1).

The implementations of creep and solifluction are similar and a combination seems possible. However, development and validation at ka scale are first needed for the solifluction process description. Since that is not the objective of this study, creep and solifluction were considered separate processes.

Biological weathering. For biological weathering, our implementation was based on Minasny and McBratney (2006), who used the 'humped' model proposed by Dietrich *et al.* (1995). This model is mostly used to describe physical, biological and chemical weathering (a soil production model *cf* Heimsath *et al.*, 1997; Minasny and McBratney, 1999), but is seen as biological weathering in this chapter, because of our focus on vegetation interactions and to clarify the difference with (physical) frost weathering.

In the humped model, weathering increases with soil thickness until optima for biotic activity are reached, but decreases when soils get thicker and biotic activity has less influence on weathering:

$$\frac{\partial e_p}{\partial t}_{s,t} = -(P_0(e^{-k_1 soilthickness_{s,t}} - e^{-k_2 soilthickness_{s,t}}) + P_a) \tag{5.19}$$

Where e_p [m] is the volume of biological weathering, P_0 [m t^{-1}] is the maximum weathering rate of bedrock, k_1 [t^{-1}] is the weathering rate constant when soil thickness > h_c, and k_2 [t^{-1}] is the rate when soil thickness ≤ h_c. P_a [m t^{-1}] is the biological weathering rate at steady state. Soil thickness h_c [m] where maximum biological weathering occurs is given by:

$$\mathrm{h_c} = \frac{\ln(k_2 / k_1)}{k_2 - k_1} \tag{5.20}$$

The main criticism of this implementation is that it is not a function of topographic position, and hence that water is always assumed present in optimal amounts given current soil thickness (Minasny and McBratney, 2006). In reality, equally thick soils on crests, slopes, and in valleys would hold different amounts of water as a result of their position, and weathering rates would be influenced. For our case study area, where an excess of water was deemed improbable, a simple approach was chosen that assumes that rainfall has a positive linear effect on biological weathering.

Another disadvantage of the implementation of Minasny and McBratney (2006) is the fact that the influence of vegetation on weathering is implicitly dependent on soil thickness only. In reality, under constant soil thickness, changing vegetation would change the values of the four constants mentioned above. Because it is not known how that would occur, a simple approach was chosen that assumes that vegetation cover V [-] has a positive linear effect on weathering, through increased root burrowing.

In the resulting implementation, the four constants of Minasny and McBratney (2006) have been redefined as those occurring under conditions of maximum vegetation cover and rainfall:

$$\frac{\partial e_p}{\partial t}_{s,t} = -(P_0(e^{-k_1 soilthickness_{s,t}} - e^{-k_2 soilthickness_{s,t}}) + P_a).(rain_t / rain_{\max}).(V_{s,t}) \tag{5.21}$$

With $rain_t$ and $rain_{max}$ in [m]. Note that weathering is assumed independent of lithology. Fig. 5.1 shows the resulting rate of weathering under changing soil thickness, when *rain* is $rain_{max}$, V = 1, and the other parameters have the uncalibrated values from Table 5.4.

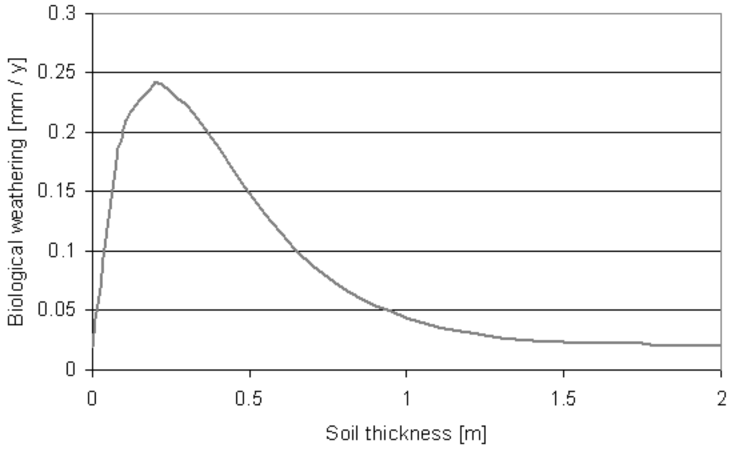


Fig. 5.1: Biological weathering intensity under changing soil thickness.

Frost weathering. For frost-weathering, a simple implementation was designed that takes into account that weathering occurs perpendicular to the surface, that a certain below-zero maximum air temperature is required, that no extra frost-weathering occurs when temperatures are below a certain minimum and that soil buffers temperature changes (Bloom, 1998):

$$\frac{\partial e_f}{\partial t} = F_0 . \frac{(T_t + (a.soilthickness_{s,t})) - T_{\max}}{(T_{\min} - T_{\max}).\cos\alpha} \tag{5.22}$$

Where e_f is the volume of frost weathering [m], F_0 is the maximum frost weathering on a flat surface [m t^{-1}], T is the Mean Annual Average Temperature (MAAT) [°C], T_{max} is the maximum MAAT [°C], T_{min} is the minimum MAAT [°C], a is the buffering parameter for soil thickness [°C m^{-1}], and cos α is the cosine of slope [-].

This implementation assumes a linear decrease of frost weathering with increasing soil thickness. In reality, amplitudes of temperature change decrease exponentially with increasing soil thickness (e.g. Minasny and McBratney, 1999) and frost weathering rates likely would too. Differences in lithology are not taken into account.

5.3 CASE STUDY

Case study area

The case study area is the bounding rectangle of a subcatchment of Okhombe valley in the Drakensberg foothills, KwaZulu-Natal, South Africa (Figs. 1.2, 1.4 and 1.5).

Late Pleistocene to present landscape evolution of Okhombe valley was studied by means of macro- and micromorphology, stable carbon isotope analysis and Optically Stimulated Luminescence dating (Temme *et al.*, 2008b). Conclusions from that work, which mainly focussed on the colluvial record in Landscape Element (LE) C, have been used for qualitative calibration of the LEM. Below, these conclusions are summarized.

After erosion removed almost all deposits from LE C, solifluction occurred from LE B to the upper parts of LE C in three phases, buried between 42 and 30 ka. A period of limited activity followed. During the LGM, limited erosion of deposits occurred in the upstream part of LE C. Between 11 and 7 ka, fluvial deposition occurred in the lower parts of LE C, before the system started to erode colluvia in LE C in the last few ka, apparently because of a shortage of transportable material in LE A and B. Fig. 5.2 further simplifies these conclusions by showing when and in which landscape elements fluvial erosion, fluvial deposition and solifluction were observed.

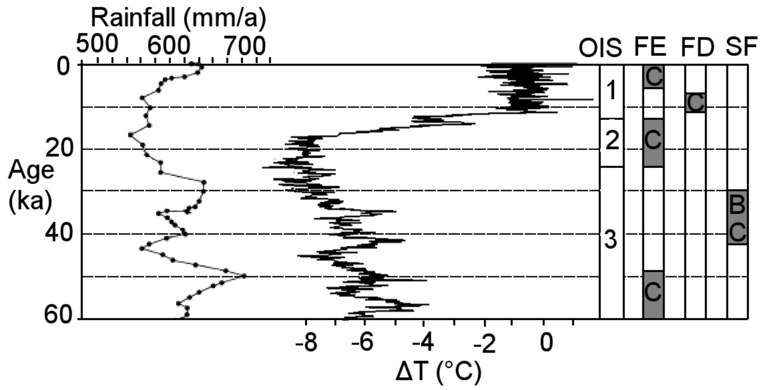


Fig. 5.2: The last 60 ka of the Pretoria Saltpan precipitation (Partridge et al, 1997) and Vostok temperature change (Petit et al, 1999) records, with a simplification of the conclusions of (Temme et al., 2008b). OIS = Oxygen Isotope Stage, FE = Fluvial Erosion, FD = Fluvial Deposition, SF = Solifluction. Dates for solifluction indicate burial, not deposition.

In addition to biological weathering, also frost weathering played a role, particularly in the LGM (Temme *et al.*, 2008b). Creep has been active on the slopes in the area.

Sumner and Nel (2006) predict mean annual rainfall in Okhombe around 1000 mm at 1300 m.a.s.l., which compares with values used by Sonneveld *et al* (2005). A late Pleistocene 200 ka rainfall record is available from the Pretoria Saltpan (Fig. 5.2). Rainfall has been strongly determined by orbital forcing during OIS 4 and 5, but other factors must have played a role during OIS 3 through 1 (Partridge *et al.*, 1997). The maximum amount of rain within the temporal extent, $rain_{max}$, occurred at 50 ka. After correcting for the difference in current annual rainfall between the Saltpan and Okhombe valley, $rain_{max}$ = 1175 mm.

Current rainfall is strongly seasonal, with most rain falling in the summer months October through March (Schulze *et al*, 1997). Palaeo-seasonality under glacial conditions has probably been less, as summer transport of moisture from the tropics decreased (Scott, 2002; Chase and Meadows, 2007). This led to winter saturation of the soil and solifluction, at least between 43 and 30 ka (Temme *et al.*, 2008b). To account for seasonality and rainfall changes, solifluction was switched off during the Holocene (due to summer rainfall) and during the LGM (due to general drought).

Present MAAT in Okhombe is about 15 °C. The warmest ten-day period of the year has average maxima around 29 °C, the coldest ten-day period of the year has average minima around 0 °C (AGIS, 2007). Frost and snow occur in most years, but typically last less than 10 days. A suitable continuous late Pleistocene record of temperature changes for this study is the 420ka Vostok ice-core record (Fig. 5.2, Petit *et al.*, 1999). Records from the Southern African subcontinent itself are qualitative (Johnson *et al.*, 1997), contain hiatuses (Holmgren *et al.*, 2003) and/or have insufficient temporal extent for this study (Tyson *et al.*, 2000; Holmgren *et al.*, 2001).

Current vegetation is predominantly grassland with some patches of *Protea*; the montane vegetation (*cf* Killick, 1978) or Southern Tall Grassveld (*cf* Acocks, 1988). Vegetation cover is strongly determined by grazing (Sonneveld *et al.*, 2005) and in places limited by shallow soils. Current spatial patterns of vegetation growth and presumably vegetation cover in the Southern African grasslands are more dependent on rainfall than on temperature (Rikie Suzuki, 2006).

Looking at temporal changes of vegetation using stable carbon isotopes from palaeosol organic matter, Botha *et al* (1992), in a comparable site in northern KwaZulu Natal, found an increase of shrub species within grassland from 35 ka to the Last Glacial Maximum (LGM), followed by a decrease in shrub species when temperature increased. The stable carbon isotope record from our case study area (Temme *et al.*, 2008b) corresponds with these results, though it is an incomplete record.

Around 20 ka, lowest temperatures led to an increase in shrubby vegetation consistent with a 1000 m lowering of vegetation belts compared to present (Botha *et al.*, 1992). This indicates that vegetation in the case study area at the LGM must have been grassland with significant contributions of *Erica, Chrysocoma* and *Helichrysum;* the sub-alpine vegetation *cf* Killick (1978). Wider afield in (sub)tropical Southern Africa, similar temperature-controlled changes have been reported in Scott's review of grassland development (2002). Apparently, temperature and rainfall have both been driving factors of vegetation changes, with rainfall playing a larger role when temperatures are less limiting (e.g. Rikie Suzuki, 2006).

Input data preparation

A 20m cellsize current Digital Elevation Model (DEM) of the case study area (Fig. 5.3A) was used as starting point. The palaeo-DEM was created by changing contours of this input DEM, as more advanced methods required more data than available to accurately interpolate a palaeo-surface (e.g. Rommens *et al*, 2005).

After resampling to 10m cellsize and smoothing, 10m contour lines were created from the current DEM. Then, a set of landscape-change rules derived from the work of Temme *et al.* (2008b, Table 5.3) was used to manually alter these contour lines to describe the palaeo landscape (Fig 5.3A). Changing contour lines was judged a better way to accommodate the rules in Table 5.3 than changing cell-by-cell altitude values. Subsequently, the method of Hutchinson (1989), as implemented in ArcGIS, was used to generate a 10m cellsize DEM from the palaeo-contour lines. After smoothing and sink-filling, this DEM was used as the palaeolandscape in LAPSUS (Fig. 5.3C).

Table 5.3: Conclusions from the work of Temme et al. (2008b) and derived criteria for 50ka palaeo-landscape definition.

Palaeo-landscape at 50ka	Criteria for palaeo-DEM	Criteria for palaeo-soil thickness
Cutbacks in LE B must have been smaller than today	Cutbacks less prominent in LE B, and all positions in LE B must advance at least one meter relative to current DEM	Soil thickness LE B: 0.2 m
	Overlying slopes in LE A must connect to slopes LE B and have approximately the same steepness as today.	Soil thickness LE A: 0.3 m
Bedrock was partly bared in LE C	Estimated thickness of current deposits must be subtracted from the current DEM in LE C	Soil thickness LE C limited: 0.2 m
Very resistant dolerite present in LE D	No change to DEM in LE D	Soil thickness LE D limited: 0.2 m

Note that manually changing contour lines based on qualitative conclusions is a subjective method and that the resulting palaeoDEM must be seen as an estimate. However, the palaeo-DEM is likely a better estimate of the true palaeo-landscape than the current DEM, and in absence of a present soil-thickness map, the palaeo-soil-thickness map is the only available estimate. A map of palaeo-soil thickness was prepared by assigning the values in Table 5.3 to the different landscape elements and smoothing (Fig. 5.3D).

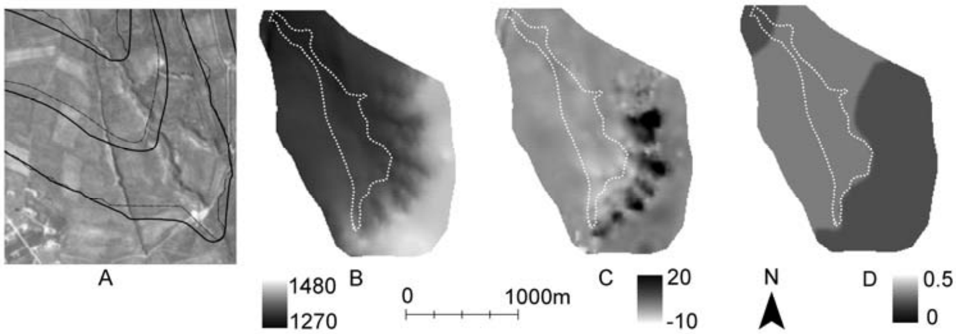


Fig. 5.3: Example of shifting contours upstream in LE C where palaeolandscape was lower (A), with maps of original DEM (B), difference with palaeo DEM (C) and assumed soil thickness at 50ka (D). Borders of actual colluvium (dotted line) and landscape elements (continuous lines) in B-D drawn for orientation.

Soil porosity [-] was assumed constant in space and time, regardless of parent material lithology or process of deposition or weathering. Porosity was set at 0.3 to reflect the high bulk density of the deposits in Okhombe valley (Sonneveld *et al.*, 2005; Temme *et al.*, 2008b).

Linear interpolation was performed on the Vostok and Saltpan records to obtain decadal values for temperature change and rainfall for 50 ka. A linear correction was made for the difference in current annual rainfall between the Saltpan and Okhombe valley. An altitudinal trend in rainfall (Sumner and Nel, 2006) was not taken into account, nor was the effect of cold air drainage (Samways, 1990).

Base erodibility values for water erosion were varied with lithology. Relative to the erodibility of soil (Eq. 5.12), erodibility of mudstone was assumed 50 times smaller, of sandstone 100 times smaller, and resistant dolerite 500 times smaller. These values were estimated using qualitative information from e.g. Tooth *et al* (2004). The occurrence of dolerite was defined by an input map that was prepared during fieldwork. The occurrence of sandstone and mudstone in the remaining area was captured with elevation rules, which was possible given the horizontal stratification in the area.

It was assumed that relative vegetation cover V is determined by climate and soil thickness. Assuming that temperature changes were responsible for gradual shifts between the montane and subalpine vegetation types mentioned above (Botha *et al.*, 1992) and that rainfall determines the cover of this vegetation, V_{pot} was calculated as the potential relative vegetation cover [-]:

$$V_{pot,t} = (V_{montane} + (V_{subalpine} - V_{montane}).\frac{\Delta T_t}{\Delta T_{LGM}}).\frac{\text{rainfall}_t}{\text{rainfall}_{50ka}} \quad (5.23)$$

And V as the actual relative vegetation cover [-]:

$$V_{s,t} = V_{pot,t}.soilthickness_s + \frac{V_{pot,t}}{2} \qquad \text{for } 0.0 < \text{soil thickness} < 0.5\text{m} \quad (5.24)$$

$$V_{s,t} = V_{pot,t} \qquad \text{for soil thickness} > 0.5\text{m} \quad (5.25)$$

In calculating vegetation cover, it was assumed that $V_{montane}$ = 0.5 and $V_{subalpine}$ = 1.0, reflecting the much denser vegetation in the subalpine zone (Killick, 1978; Acocks, 1988). Temperature change at the LGM, ΔT_{LGM}, was set at -8 °C (Petit *et al.*, 1999). For every timestep, average precipitation and temperature change values for the previous 5 decades were taken, to simulate the lag in vegetation adaptation to changing conditions (e.g. Thomas, 2004).

Timeseries of V_{pot}, average V and soil thickness from the calibrated model are given in Fig. 5.4. When mean soil thickness is above 0.5, V practically equals V_{pot}., reflecting the fact that grassland and shrubs need no deeper soils (Killick, 1978; Acocks, 1988).

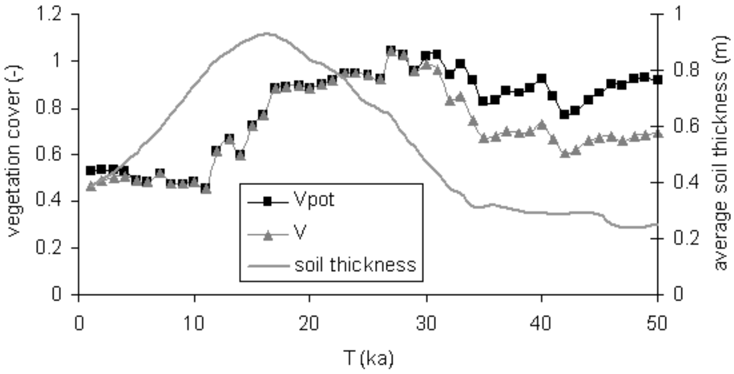


Fig. 5.4: Timeseries of Vpot , average V and average soil thickness from the calibrated model. Measurements taken every ka.

Validation of the timeseries of V_{pot} by comparing with the current spatial variation in vegetation cover is not possible because current climatic conditions in the surroundings of the case study area do not overlap palaeo climatic conditions within the case study area.

5.4 RESULTS

Sensitivity analysis

The initial values and sources of the different parameters are presented in Table 5.4. The results for the individual processes are visible in Fig. 5.5.

Table 5.4: Initial and calibrated values and sources for the parameters used in sensitivity analysis

Process	Calibration parameter	Unit	Source	Initial value	Calibrated value	Equation
Overall	timefactor	[-]	this chapter	1.0	3.0	
Hydrology	p	[-]	(Schoorl *et al.*, 2002)	1.5	1.5	(5.3)
	$evap_{max}$	[m]	this chapter	0.9	1.4	(5.5)
Water erosion and deposition	m	[-]	(Follain *et al.*, 2006)	1.0	0.3	(5.8)
	n	[-]	(Follain *et al.*, 2006)	0.8	0.4	(5.8)
	K_{normal}	$[m^{-1}]$	(Schoorl *et al.*, 2002)	0.00002	0.00003	(5.12)
	P_{normal}	$[m^{-1}]$	(Schoorl *et al.*, 2002)	0.00002	0.00004	(5.13)
	K_{veg}	$[m^{-1}]$	this chapter	0.00001	0.000025	(5.12)
	P_{veg}	$[m^{-1}]$	this chapter	0.00001	0.00004	(5.13)
Creep	D_E	$[m^2\ t^{-1}]$	(Follain *et al.*, 2006)	0.1	0.3	(5.14),(5.15)
Solifluction	D_S	$[m^2\ t^{-1}]$	(Follain *et al.*, 2006)	0.1	0.3	(5.16)
Biological weathering	P_0	$[m\ t^{-1}]$	(Minasny and McBratney, 2006)	1.0	1.5	(5.19),(5.21)
	k_1	[-]	(Minasny and McBratney, 2006)	4.0	4.0	(5.19),(5.21)
	k_2	[-]	(Minasny and McBratney, 2006)	6.0	6.0	(5.19),(5.21)
	P_a	$[m\ t^{-1}]$	(Minasny and McBratney, 2006)	0.02	0.02	(5.19),(5.21)
Frost weathering	a	$[°C\ m^{-1}]$	this chapter	6	6	(5.22)
	Tmax	[°C]	this chapter	11	9	(5.22)
	Tmin	[°C]	this chapter	5	5	(5.22)
	F_0	$[m\ t^{-1}]$	this chapter	- 0.2	-2	(5.22)

In Fig. 5.5, two types of results are common. First, results that approximate the x=y line indicate parameters that are multipliers in the process descriptions. This occurs for creep and frost weathering. Where an increase in process activity inhibits the process in later timesteps, saturation effects occur. This seems to be the case for solifluction and biological weathering.

Second, hyperbolic results indicate parameters that are divisors in the process descriptions. These results occur for parameters of biological and frost weathering.

Sensitivity of water erosion and deposition for its different parameters is lower than sensitivity of the other processes for their respective parameters. The reason is that the most important multiplier in the

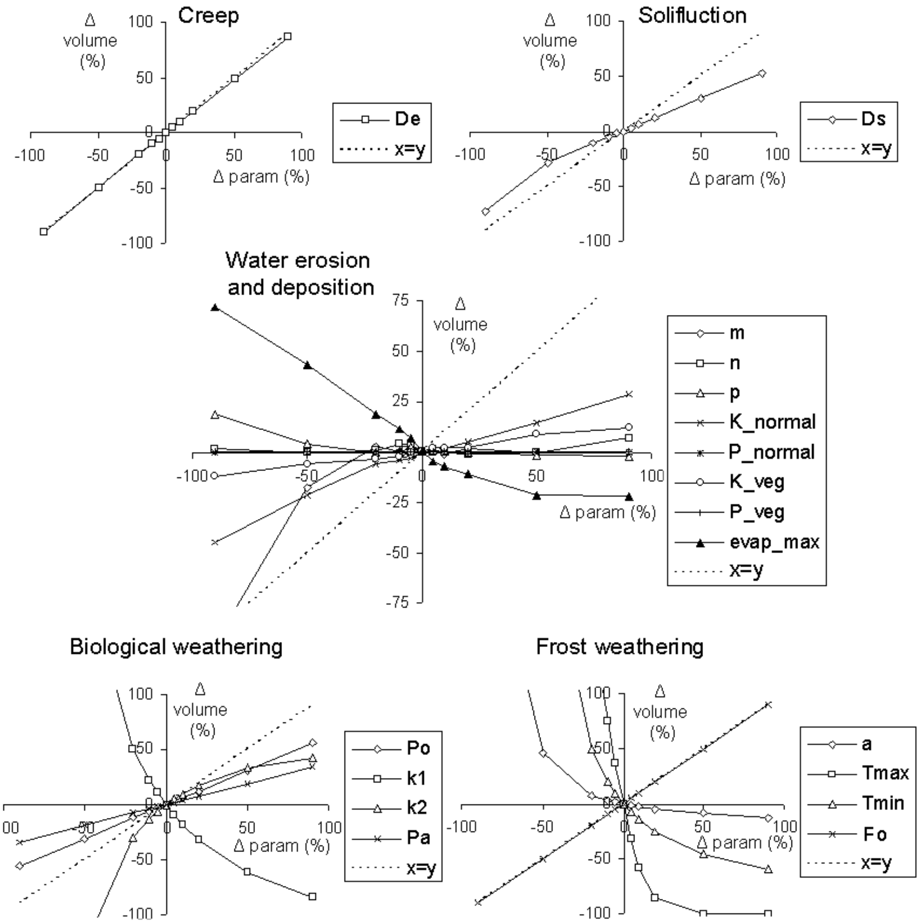


Fig. 5.5 : Percentage change in volumes transported or weathered resulting from percentage change in parameters available for calibration for different landscape forming processes. Note the different scale of the y-axis for water erosion and deposition.

process desciription, the amount of water flowing over the surface, *outflow*, is not a parameter but a resultant of input data and therefore not considered in this sensitivity analysis.

The low sensitivity of water erosion and deposition for both P_{normal} and P_{veg} suggests that transport capacity is not limiting sediment transport with the current parameter settings, i.e. that sediment transport in the landscape is detachment limited. Sensitivity of biological weathering for parameters k_1 and k_2 is almost mirrored, reflecting the role of these parameters in the implementation of the process (Eq. 5.21). Sensitivity of frost weathering for parameters T_{max},T_{min} and a is similar; values closer to zero strongly increase frost weathering.

It is possible to explore the overall sensitivity of landscape changes to changes in volume transported or weathered by the individual landscape forming processes. This is of most interest when using the calibrated model over the full temporal extent. Fig. 5.6 presents results of such aggregated sensitivity analysis, where results for individual processes were manually increased or decreased. MEF values relative to the calibrated model decrease when process volumes are increased or decreased relative to calibrated volumes. This suggests that calibration has at least found a local optimum in parameter combinations and, significantly, that each of the five processes plays an important role in determining model outcome.

Looking closer, the non-linearity of the interaction between processes is visible. For instance, the decrease in MEF relative to the calibrated value is larger with a 10 % decrease in biological weathering volume than with a 20 % decrease. Apparently, a change in process activity leads to complex changes in the activity of other processes over time and space.

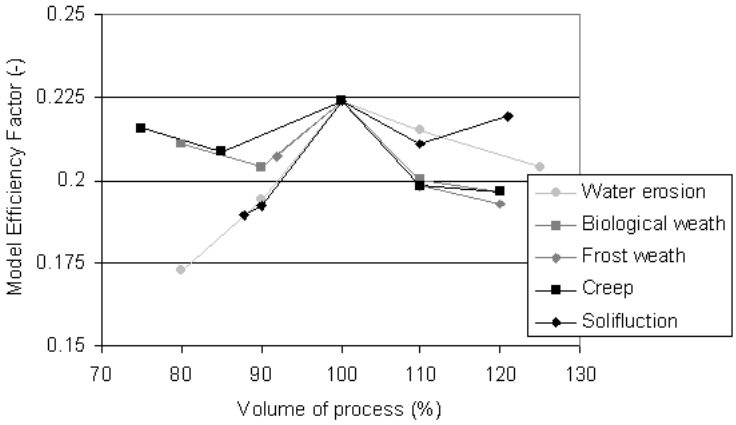


Fig. 5.6: Aggregated sensitivity analysis. Changes in Model Efficiency Factor resulting from changes in volumes transported or weathered by landscape forming processes.

Model calibration

The first objective of calibration was to match model results of individual process activity with fieldwork observations (Fig. 5.2) of process activity in relevant zones for fluvial erosion, fluvial deposition and solifluction (Fig. 5.7).

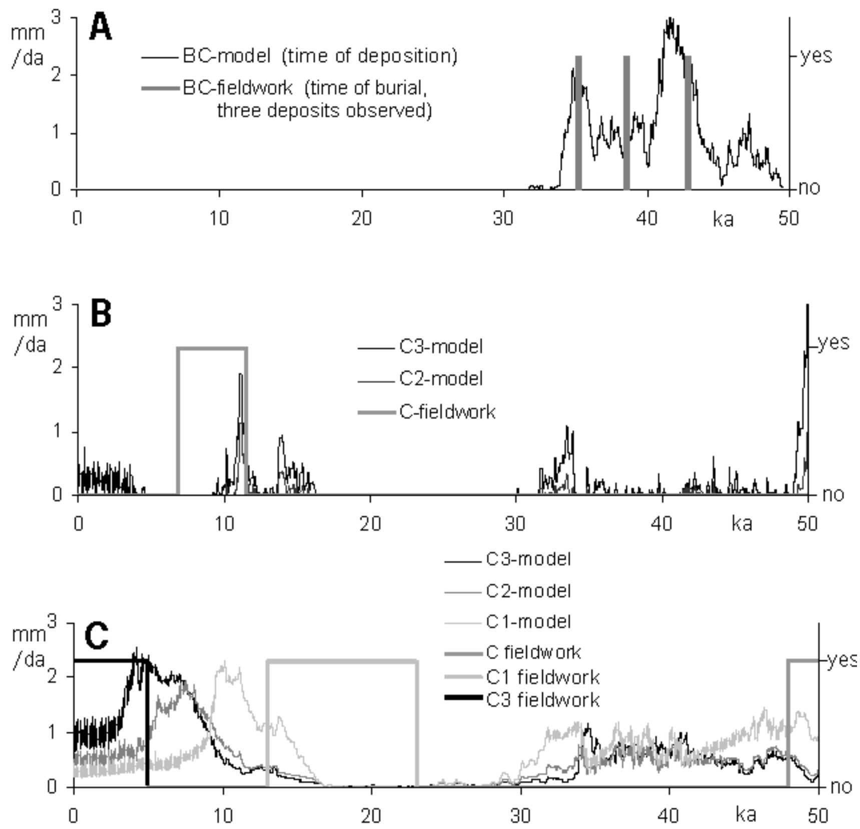


Fig. 5.7: Comparison of model results for individual landscape forming processes with conclusions of Temme et al. (2008b). A = solifluction, B = fluvial deposition, C = fluvial erosion. C3-model to BC-model are model results, BC fieldwork and C fieldwork are fieldwork results (with zones from Fig. 1.5).

In Fig. 5.7A, conclusions based on fieldwork observations indicate time of burial, and model results indicate time of deposition. Realizing that fieldwork conclusions are ± 2.4 – 3.7 ka (chapter 2), the three phases that are apparent in model results may reflect the three phases of solifluction that were observed in the deposits. Note that solifluction was not activated during the LGM and OIS 1, i.e. from 25 ka to present.

After initial deposition during model initialisation, the largest peak of fluvial deposition in the downstream parts of zone C occurs around 11 ka, corresponding with fieldwork results. Peaks in deposition were modelled, but not observed in these zones around 14 ka (related to the Younger Dryas event) and 33 ka as well. In both cases, rapid decreases in temperature caused an increase in vegetation cover, which facilitated deposition.

For fluvial erosion, the uncertainty in fieldwork results is considerable. Erosional activity was inferred from hiatuses in deposition at sites where infilled erosion gullies were visible in the stratigraphy. A peak of erosion in zone C3 was observed during fieldwork and is modelled around 5 ka.

The fieldwork observation of erosion in the LGM is not well reflected in model results at first sight. However, the observation from Temme *et al.* (2008b) was about limited erosion in the upstream parts of LE C, to which the modelled peak in erosion for zone C1 conforms. Model results also reflect the erosion shortly after 50 ka, though this may result from model initialisation.

From this first aspect of calibration, it is apparent that individual processes and climatic and vegetation controls included in LAPSUS for this study can reasonably reproduce the results of Temme *et al.* (2008b) for the mentioned zones.

A second objective of calibration was to reproduce the relative importance of landscape forming processes over time. Fig. 5.8 presents four sets of climatic controls in which different processes were observed during fieldwork. In set 1, from about 50 to about 30 ka, solifluction and creep were the most active landscape forming processes. In set 2, during the LGM, no landscape activity was observed. In set 3, fluvial redistribution was active, giving way to more fluvial erosion in set 4.

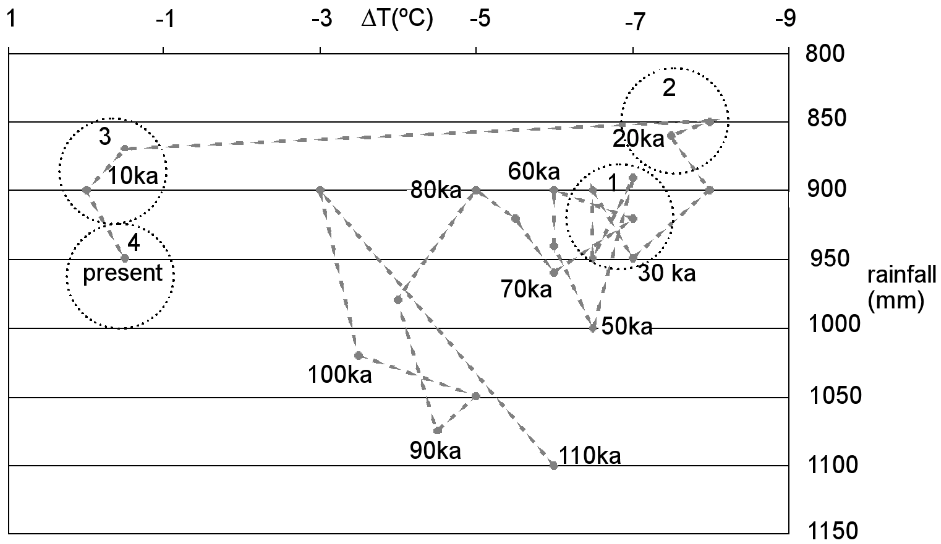


Fig. 5.8: Different sets of climatic controls on landscape evolution in Okhombe Valley (Temme et al., 2008b). Palaeo-precipitation and -temperature values were taken from the records in Fig. 5.2 at every 5 ka. Fields 1 to 4 approximate sets of climatic conditions under which different processes have been observed. Boundaries of fields do not suggest actual boundaries to sets of climatic conditions.

The modelled timeseries of the volumes weathered or transported by the landscape forming processes within the study area are shown in Fig. 5.9.

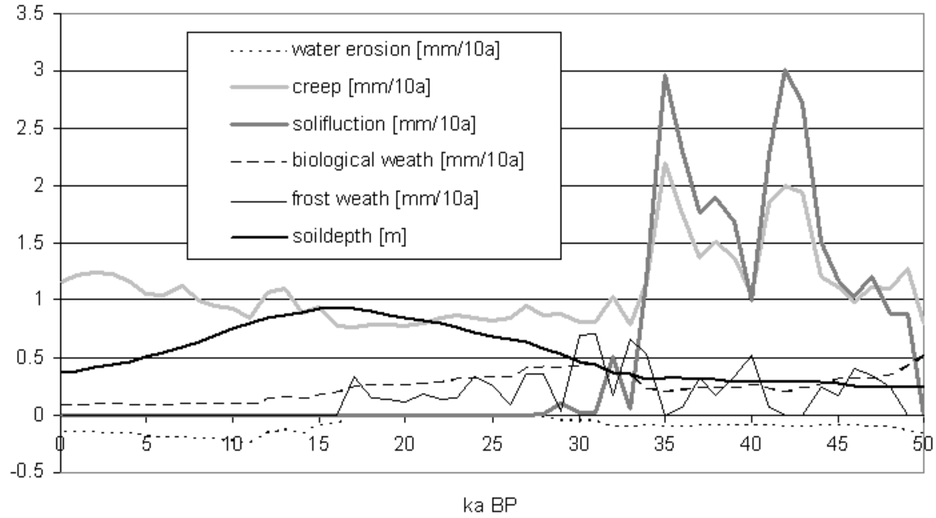


Fig. 5.9: Modelled volumes weathered or transported by landscape forming processes (average over study area) and development of average soil thickness from 50 ka to present. Values were recorded every ka.

In the model results, three different periods can be distinguished. Between 50-33 ka, fluvial erosion removes less sediment than is supplied by biological and frost weathering. Solifluction and creep redistributed material within the area. As a result, soil thickness slowly increases. This balance of processes agrees with fieldwork results in set 1 (Fig. 5.8).

Between 33-16 ka, vegetation is almost completely of the subalpine type. Vegetation cover reaches its maximum but then decreases with precipitation. Due to high vegetation cover and evapotranspiration, little water flows over the surface, inhibiting fluvial erosion. Frost weathering values remain high, leading to a further increase in average soil thickness to its maximum of 0.9 m around 17 ka. The absence of fluvial activity and solifluction agrees with fieldwork results in set 2 (Fig. 5.8). Note that solifluction was manually deactivated after 23 ka.

Between 16-0 ka, when temperatures increase, frost weathering ceases and biological weathering is at a minimum due to the maximum in soil thickness. Vegetation cover and evapotranspiration are low, resulting in more water flowing over the surface, and an increase in fluvial redistribution. Initially, not all sediment is exported from the subcatchment, as evident from lower sediment delivery ratios (not shown in Fig. 5.9), but near 0 ka, redeposition within the subcatchment has stopped. As a result of these changes, average soil thickness decreases. For this third period, results agree broadly with fieldwork results in sets 3 and 4 (Fig. 5.8). However, the timing of the shift from fluvial redistribution (set 3) to fluvial erosion (set 4) can not be reproduced by the model.

The third objective of calibration was to match modelled soil thickness development to fieldwork conclusions for the different zones in the study area (Fig. 1.5). Because no detailed map of current soil thickness is available, model output is qualitatively compared to current zonal soil thickness estimates and to soil thickness development conclusions.

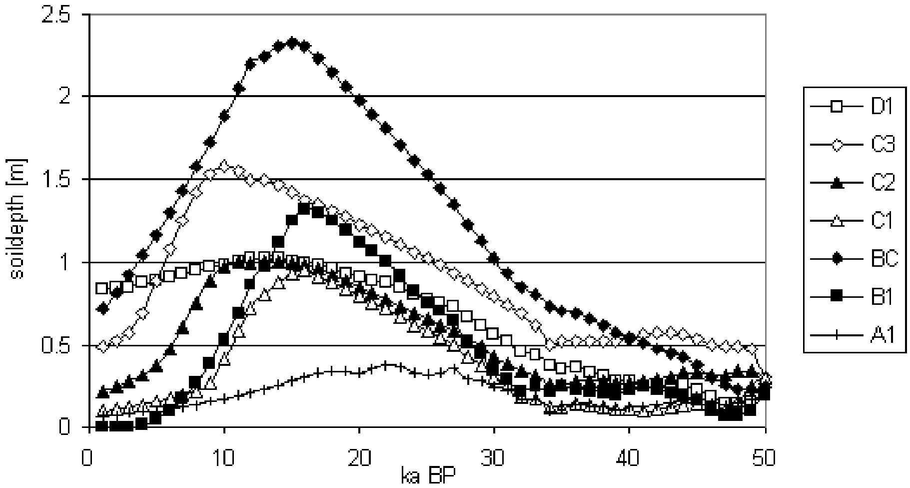


Fig. 5.10: Timeseries of modelled average soil thickness for the different zones of Fig. 1.5. Values were recorded every ka.

For zones A1 and B1, current near-zero average soil thickness is reflected in model results. For zone BC, the current strong gully erosion exposes colluvium between 1 and 10 metres deep. This is reflected in the strong and continuing decrease from a maximum of several metres in model results for zone BC. For zones C1-C3, current soil thickness is between 0.5 and 0.1 metres, which is reflected in model results. However, the decrease in current soil thickness when going downstream through these zones, can not be reproduced by the model. For zone D1, soil thickness is about 0.25 m, while model results predict the highest soil thickness at about 0.85 m. The difference between model results and reality in this last zone may be explained by undercutting from the river Khombe and by extremely slow weathering of the dolerite. These two effects are not included in the model. In the model results, soil thickness in zone A1, where sediment supply by deposition is almost zero, remains lowest on average. In all other zones, soil thickness increases until 16ka or later before decreasing toward present.

The development of soil thickness for the different zones displays similar behaviour as the overall development of soil thickness in terms of long-term controls, and modelled current soil thickness in the different zones corresponds well to actual soil thickness in the research area.

Summarizing, calibration has resulted in a model version that is reasonably successful in reproducing individual process activity, relative process activity and net landscape development, though aspects of the development of soil thickness in the downstream part of zone C in the last 16ka can not be reproduced. Overall, this is promising when realizing that the interaction between processes was not supervised and that process descriptions and parameter values have not been changed over the extent of study (i.e throughout OIS 3 to 1).

Parameter values after calibration are in Table 5.4. Fig. 5.11 shows the overall outputs of the calibrated model. The resulting DEM (Fig. 5.11A) is generally smoother than the true DEM, except for incisions in landscape element B, which are deeper and narrower than in the true DEM. The deepest colluvium is modelled next to channels and in concave positions in LEs C and B, corresponding to reality (Fig. 5.11B).

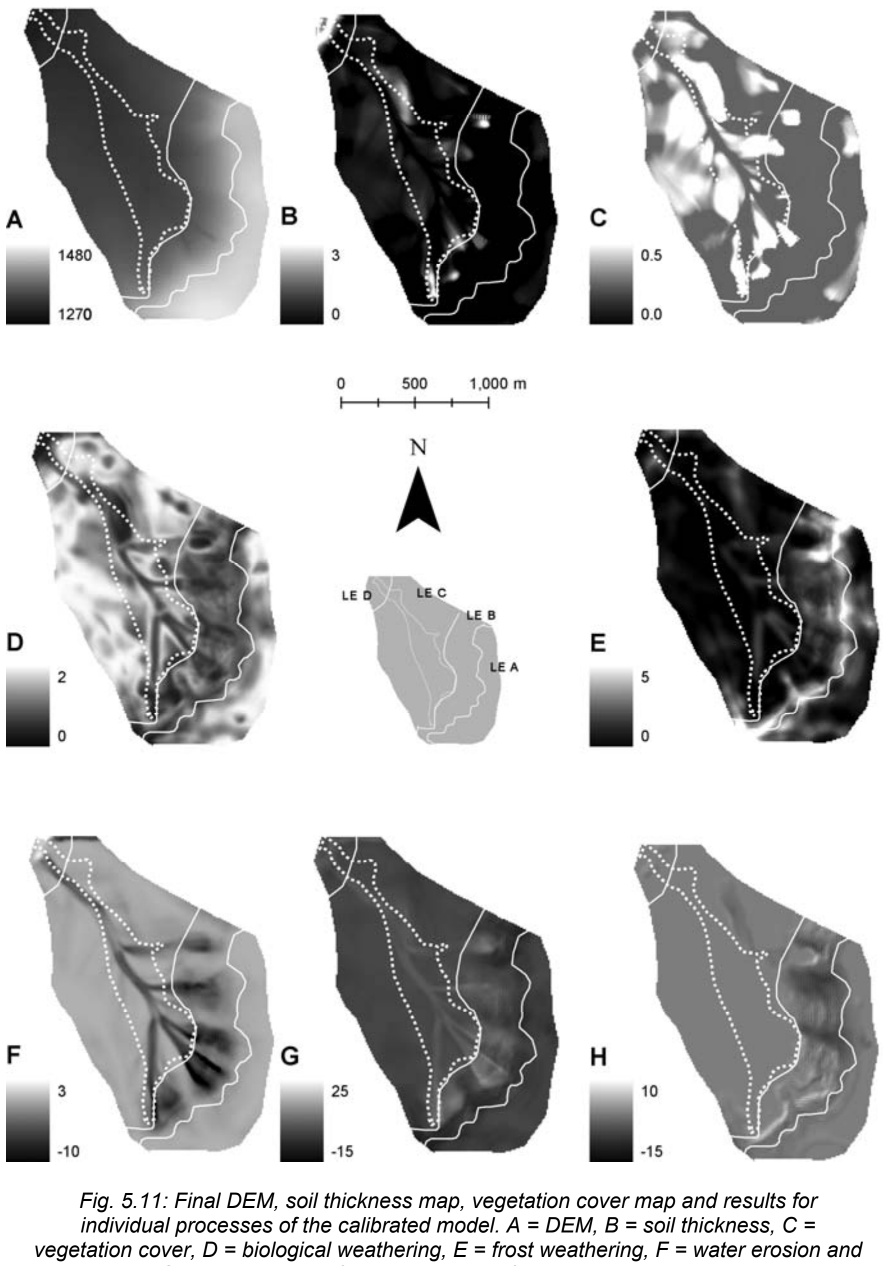


Fig. 5.11: Final DEM, soil thickness map, vegetation cover map and results for individual processes of the calibrated model. A = DEM, B = soil thickness, C = vegetation cover, D = biological weathering, E = frost weathering, F = water erosion and deposition, G = creep, H = solifluction. Borders of colluvium and landscape elements

drawn for orientation. Positive values are deposition or weathering, negative values are erosion.

Highest vegetation cover is found in the colluvium in LE C, lowest vegetation cover in LE B, except for the most concave positions (Fig. 5.11C). Biological weathering is minimal along channels (due to shallow soils) and in positions with deep soils (due to buffering, Fig. 5.11D). Frost weathering is prominent in LE B, especially along the border with LE A, where slopes are steepest and soils are most shallow (Fig. 5.11E). Most water erosion was modelled along the channels, deposition was modelled where the valley connects to Khombe River (Fig. 5.11F). Creep and solifluction have been a net supplier of material from the upper to the lower slopes in LE B, and to some of the highest parts of LE C (Fig. 5.11G, H).

For a quantitative comparison, the output DEM was compared to the actual current DEM. Performance expressed as MEF equalled 0.22 when calculating based on individual cells. Higher values for MEF were achieved when lumping over 3*3 windows (0.23), the 7 zones of Fig. 1.5 (0.48) or the 4 landscape elements of Fig 1.5 (0.85). This effect is not uncommon in spatial landscape pattern validation exercises (Kok *et al.*, 2001).

5.5 DISCUSSION

Model validity

In long-term landscape evolution modelling, cell by cell comparisons of modeled results with reality usually meet with little succes (e.g. MEF = 0.29 for a study with two landscape forming processes over 2500 timesteps, Peeters *et al.*, 2006). When lumping over landscape elements, values typically increase (Peeters *et al*, 2006 : MEF = 0.78 for 9 elements).

In general, reasons for low cell-by-cell values include a lack of detail and confidence in input data and boundary conditions, which decrease when lumping, and the fact that process descriptions used for studies at a ka scale are necessarily strong simplifications of physical processes (Brasington and Richards, 2007). Whereas the success of the qualitative comparisons suggests that climatic controls and landscape position of these processes are reasonably well captured, the unsatisfactory results of the quantitative comparison may reflect imperfections in the model. The following in particular may have caused errors:

- Only few parameter values could be set to values known from work in comparable areas. Other parameter values were set to default values from less-comparable areas. Since calibration efforts were limited, the latter values remain as best-guess in some cases (Table 5.4). Information from new work in comparable areas and more elaborate calibration could decrease this problem.
- Important differences in biological weathering and frost weathering may exist between the different lithologies in the study area. These were not included in the model.
- The process descriptions of solifluction and biological weathering are work in progress and have not been independently validated by other work.

- To a lesser degree, the same may be true for the changes that were made in the existing process descriptions of water erosion and deposition, creep and biological weathering.
- Incision by the river Khombe and its possible effects on the study area have not been included in the model

To more objectively compare reality and model results, studies aimed at combining geomorphological fieldwork with landscape evolution modelling may benefit from adapting alternative sampling strategies. Complementing observations at meaningful and often exceptional sites, where hypotheses are usually developed, such fieldwork should observe landscape charateristics using independent sampling schemes, at sites that are not of immediate interest for development of hypotheses. Observations from these sites would be of value for improvement of hypotheses after modelling, by providing more detailed boundary conditions for LEM studies. Using in-situ produced cosmogenic nuclide concentrations may help to obtain these data.

In this study, the close connection between fieldwork and modelling has made it possible to propose a number of qualitative criteria to which model results have been calibrated. An emphasis on development of such criteria during future fieldwork for studies of this type will also allow stricter calibration.

In the next paragraph, two examples where model-fieldwork combinations can improve landscape evolution hypotheses are presented, instead of an exhaustive review of the consequences of this modelling exercise for landscape evolution hypotheses of the case study area.

Perspectives

Model results can detail and complement stratigraphical records. As an example, Fig. 5.12 presents model results for site 1 (Fig. 1.5). The stratigraphic record contains information on preserved depositional phases (e.g. phases C, D and possibly E in Fig. 5.12) and fieldwork typically results in conclusions about the dominant processes that deposited strata in these phases.

For these strata, model results can detail and complement information, especially where the interaction of several processes, rather than the activity of one process, has led to deposition. This is visible in phase D, for which fieldwork has concluded that slope processes supplied sediment. Model results suggest that fluvial erosion, frost and biological weathering also played non-trivial roles.

However, the main advantage of modelling lies in its ability to fill in gaps in the record. Stratigraphical development can be followed over time and process activity can be recorded at any phase, including erosive phases (e.g. phases A and B in Fig. 5.12). In the example, model results suggest that the decrease in soil thickness from about 15 ka is due to both water driven erosion and slope processes.

Alternatively, model results may contradict fieldwork results and pose new questions. For instance, it was noted above that model results meaningfully contradict fieldwork results in landscape element C between 11 ka and present (Fig. 5.7C). Temme *et al.* (2008b) reported:

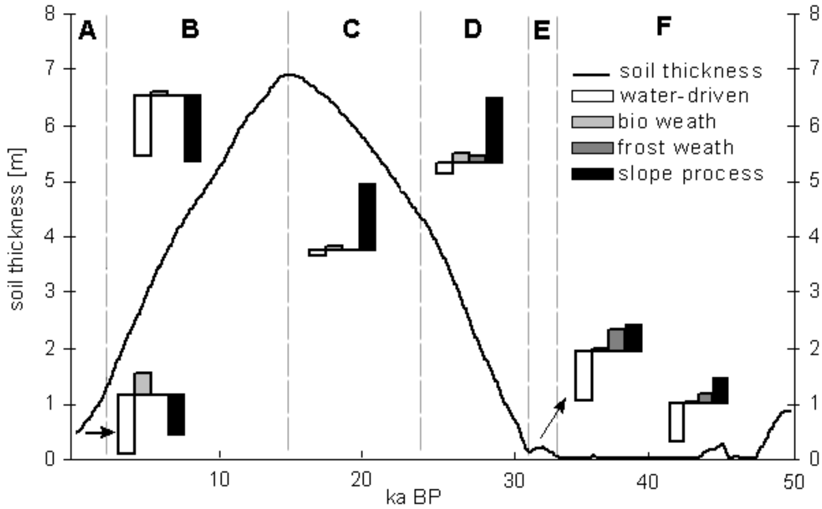


Fig. 5.12 : Model results can fill in blanks in the stratigraphical record. Relative process activities in terms of volumes transported or weathered are presented for every phase. Data recorded at site 1 (Fig. 1.5). Phases A-F have been defined by breaks in the development of soil thickness.

"*In the Holocene, much higher temperatures and a 100 mm increase in precipitation seem to have redistributed deposits from upstream landscape elements over the research area. Recently, redistribution has stopped, probably as a result of a lack of supply of parent material. Since then, strong gully erosion of the deposits themselves has begun*"

In contrast, model results indicate decreasing soil thickness throughout landscape element C after 11 ka, with the exception of zone C3, where results suggest that soil thickness began decreasing around 10 ka (Fig. 5.10). However, the mechanism that Temme *et al* propose is visible: model results suggest that the effect merely occurred earlier, starting around 16 ka. The zone of net erosion then moved downstream, visible by the lag between decrease in soil thickness in zones A1, B1 and C1 on the one hand (16 ka) and zones C2 (13 ka) and C3 (10 ka) on the other hand.

This lag is an order of magnitude larger than lags reported for upper reaches of fluvial systems (e.g. Veldkamp and Tebbens, 2001), especially considering the proximity of the zones within small upstream catchments. Apparently, the cause of the lag in Okhombe valley is not in the fluvial, but in the geomorphological domain. Slow landscape-soil-vegetation feedbacks are likely causes for the observed lag.

This does not mean that results contradict Veldkamp and Tebbens' (2001) conclusion that rapid (<1 ka) climate changes can be registered in deposits in upper fluvial reaches. On the contrary, the peaks in deposition in zones C2 and C3 follow rapid climate changes within 5 decades. These results suggest that in real landscapes, it is difficult to distinguish these short-term signals from long-term landscape geometry-related signals that are also ultimately co-determined by climatic changes. Combining geomorphological fieldwork and landscape evolution modelling may be of help in this pursuit.

Whereas sensitivity analysis indicated a considerable sensitivity of volumes of individual processes, and calibration efforts showed sensitivity of other types of outputs to changing parameter values, the results regarding da- and ka-lags in landscape response are rather persistent. Apparently, when looking at the dynamics of waves of sediment in the landscape, the interaction of five processes in this case study constrains landscape evolution possibilities to a certain range. This seems to contradict the intuitive notion that adding processes and parameters increases the range of possible outcomes.

5.6 CONCLUSIONS

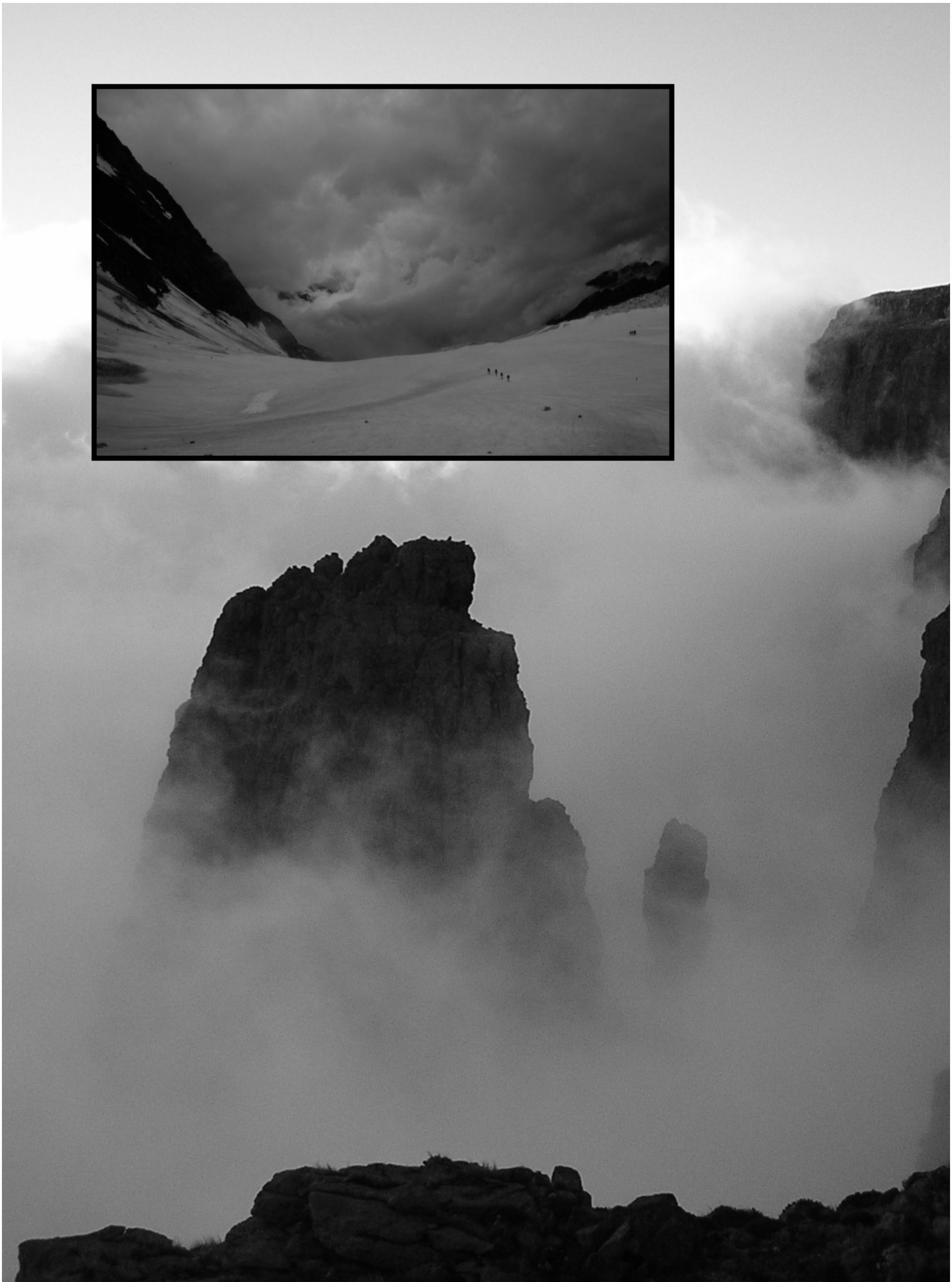
It is possible to combine existing and new descriptions of landscape forming processes into one LEM, and to use that model to study 50 ka landscape evolution, as demonstrated for the case study area. A direct combination with earlier fieldwork results, supplying input data, boundary conditions and calibration data, was one of the reasons that made this possible. In the model, five landscape forming processes interacted without supervision to predict the current landscape properties. This is rather novel and has not been done before in such a direct way (Pennock and Veldkamp, 2006).

The model was succesfully calibrated to three types of qualitative fieldwork conclusions simultaneously. Unfortunately, it was not possible to define a quantitative calibration procedure. Future geomorphological fieldwork aimed at a combination with LEM studies should both try to further elaborate more explicit qualitative calibration criteria, and adopt a predetermined quantitative sampling scheme independent from curiosity driven interest.

A validation-demonstration using an assumed palaeodem for comparison resulted in a relatively low Model Efficiency Factor on a cell-by-cell basis (0.22). Model Efficiency Factors increased when lumping by zones (0.48) and landscape elements (0.85).

Model results suggest that erosional and depositional phases may lag climatic drivers by several ka within a few hundred meters. For instance, climatic changes at the end of the LGM resulting in net erosion and a loss of soil thickness, register up to 6 ka later in the most downstream deposits, which up to that point received net sediment from upstream landscape elements. Only when erosion has reached bedrock in upstream areas, excess transport capacity is satisfied in the downstream zones, leading to the formation of impressive erosion gullies. This illustrates and supports Temme *et al.*'s (2008b) proposition that the extreme contemporary erosion in these parts of the area may be explained by lack of erodible material upstream.

On the other hand, climatic changes do sometimes lead to immediate landscape responses, as visible from the alternation of erosional and depositional phases at the end of the LGM. Both the short-term and the long-term signals are persistent outputs that occur over a range of reasonable calibration parameter values. Multi-process landscape evolution models can be an important tool in distinguishing these slow and fast responses, sketching a picture of slow and fast moving waves of sediment in landscapes. More explicit studies on this intriguing theme can only be made by designing new, iterative combinations of fieldwork and model studies.



CHAPTER 6

CAN UNCERTAIN LANDSCAPE EVOLUTION MODELS DISCRIMINATE BETWEEN LANDSCAPE RESPONSES TO STABLE AND CHANGED CLIMATE?

A MILLENIAL SCALE TEST

CHAPTER 6

CAN UNCERTAIN LANDSCAPE EVOLUTION MODELS DISCRIMINATE BETWEEN LANDSCAPE RESPONSES TO STABLE AND CHANGING FUTURE CLIMATE? A MILLENIAL-SCALE TEST

In the light of societal interest in the effects of climate change, geomorphologists face the task of discriminating between natural landscape changes and landscape changes that result from human-induced climate change. Landscape Evolution Models (LEMs) are the only tools available for this purpose, but their application for prediction of future landscapes is problematic. Calibration of LEMs on a sufficiently long palaeo-record of landscape change solves some of these problems, but large uncertainties in input (e.g. climate) records and process descriptions will remain.

Using one of the rare previous ka-scale LEM studies as a starting point, this chapter explores how uncertainty in LEM LAPSUS affects its ability to discriminate future 1-ka landscape change under stable climate from that under human-induced changed climate. LEM uncertainty is characterized by different levels of parameter uncertainty. Results indicate that even under high levels of parameter uncertainty, LEM LAPSUS is able to discriminate between landscape responses to stable and changed climate for some zones in the landscape. Even though confidence in particular model predictions remains limited, some explorative and relative conclusions about the effect of changed climate on landscape evolution of Okhombe valley are drawn.

6.1 INTRODUCTION

Landscapes respond to changes in driving factors directly and indirectly, with lags from decades to millenia (Veldkamp and Tebbens, 2001; Thomas, 2004). Climate is one of these driving factors and in the light of increasingly well-known human-induced climate change (IPCC, 2007), societal interest in subsequent changes in landscape dynamics is also increasing. This interest requires geomorphologists to discriminate between natural (often called "long-term") landscape changes and landscape changes that result from human-induced climate changes.

Comparisons of landscape dynamics under stable climate with those under changing climate in a *ceteris paribus* setting would be suitable to explore these differences. This type of experiments is not possible with real landscapes (e.g. (Douglass and Schmeeckle, 2007)and numerical geomorphological models are the only tools available for simulation. These models, better known as Landscape Evolution Models (LEMs, (Coulthard, 2001) calculate landscape change as the sum of contributions of multiple landscape forming processes (Chapter 4).

The use of LEMs to quantify human influence on future landscape dynamics is not without problems. To start with, model formulations with the landscape as spatial extent are necessarily strong simplifications of real world processes (Brasington and Richards, 2007). Parameters for these simplified formulations often lack real-world significance and must be estimated through calibration. Unfortunately, calibration is impossible when attempting prediction of future landscape evolution. In that case, parameter estimates must be taken from other research, preferably on the same landscape at similar spatial, temporal and process extent. Such research on a kilo-annum (ka) extent is rare, and moreover the assumptions and process descriptions developed in such research may not remain valid when climatic conditions change, even when climatic variables are included in the LEM. Finally, model input data may have large uncertanties, particularly future climate predictions.

It is therefore not surprising that LEMs have not before been used to assess the effect of human-induced climate change. (Willgoose and Riley, 1998) predicted 1 ka evolution of mining waste rock dumps in Australia using LEM SIBERIA, but climatic characteristics were kept stable in their model. Despite their potential (Van de Wiel *et al.*, 2007), LEMs at the moment are still imperfect tools for the study of the impact of human-induced climate change.

Using one of the rare previous ka-scale LEM studies as a starting point, the objective of this chapter is to explore how uncertainty in such admittedly imperfect LEMs affects their ability to discriminate future 1-ka landscape change under stable climate from that under human-induced changed climate.

LEM LAPSUS (Schoorl *et al.*, 2000; Schoorl *et al.*, 2002) is used for this purpose. LAPSUS was previously calibrated to simulate 50ka landscape evolution of the Okhombe valley (Temme and Veldkamp, in press), which means that limited confidence can be placed in process descriptions and parameter values. Here, that calibrated model is used to simulate future 1-ka landscape evolution of the valley.

To test the importance of LEM uncertainty, I assess how much variation can be induced to model parameters before the effect of this variation on model results becomes larger than the effect of climate change. Monte Carlo analysis and t-test are used for this purpose. Monte Carlo analysis determines the uncertainties in model outputs given the uncertainties in model inputs, by repeatedly computing model results with inputs drawn from their joint probability distributions (e.g. Temme *et al.*, 2008a).

Results of that analysis are used in t-tests to assess for which model outputs the difference between stable and changing climate is significant. These outputs are selected and used to discuss possible effects of climate change on the landscape in Okhombe valley.

The 1 ka temporal extent is chosen as an intermediate between geological and human-interest temporal extents. It is not possible to use a longer extent, because of the limited availability and reliability of information on climate change. Given the temporal resolution of 10 years, a shorter extent would result in a strongly limited number of timesteps and expectedly in less distinction between landscape responses.

6.2 METHODS

Model

LAPSUS (Schoorl *et al.*, 2000; Schoorl *et al.*, 2002) is a reduced-complexity, multi-process LEM that sees sinks as valid landscape elements (Temme *et al*, 2006). The model was adapted and calibrated to simulate 50-ka landscape evolution in the Okhombe Valley by Temme and Veldkamp (in press). Their model version combined five landscape forming processes: biological weathering, frost weathering, solifluction, creep and water erosion and deposition. Initial runs for 1 ka future landscape evolution indicated that solifluction and frost weathering played no role under the stable or predicted changed climatic conditions. Therefore, these two processes were not activated in this study. The three included processes use a total of 13 calibration parameters.

Each process was modelled using essentially simple cellular automaton representations, but the combination, interaction and iteration of these simple rules can result in complex, non-linear behaviour of the landscape system (*cf.* Van de Wiel *et al.*, 2007). Climate is the main driving factor for the landscape forming processes; directly through rainfall and indirectly through vegetation.

Vegetation is considered a key factor in landscape processes and a vegetation proxy is included in LAPSUS: V [-], the relative vegetation cover at or near ground level (Collins *et al.*, 2004). V is modelled in two steps (Temme and Veldkamp, in press).

First, spatially uniform potential relative vegetation cover $V_{pot,t}$ [-] is calculated as a function of rainfall and temperature:

$$V_{pot,t} = (V_{montane} + (V_{subalpine} - V_{montane}).\frac{\Delta T_t}{\Delta T_{LGM}}).\frac{\text{rainfall}_t}{\text{rainfall}_{50ka}} \qquad (6.1)$$

With $V_{montane}$ the relative vegetation cover of the montane vegetation that currently occurs in Okhombe valley (Killick, 1978) and $V_{subalpine}$ the relative vegetation cover of the subalpine vegetation (Killick 1978) that occurred in Okhombe valley in the Last Glacial Maximum (LGM). ΔT_{LGM} is the difference between current and LGM temperatures. Continued validity of this expression under the expected climatic conditions in the next 1000 years is not guaranteed. However, lacking other information, it was decided not to change it.

Then, spatially varying actual relative vegetation cover $V_{s,t}$ [-] is calculated as a function of $V_{pot,t}$ and spatially and temporally varying soilthickness:

$$V_{s,t} = V_{pot,t} .soilthickness_s + \frac{V_{pot,t}}{2} \qquad \text{for } 0.0 < \text{soil thickness} < 0.5 \qquad (6.2)$$

$$V_{s,t} = V_{pot,t} \qquad \text{for soil thickness} > 0.5 \qquad (6.3)$$

Table 6.1 summarizes the influences of rainfall, temperature and vegetation on the activity of the three landscape forming processes. More detailed information on process descriptions and parameters can be found in Temme and Veldkamp (in press), here the focus is on climatic drivers.

Table 6.1: Summary of direct and indirect influence of climate on landscape forming process activity in LAPSUS.

Process	Rainfall	Vegetation (f rainfall, temperature)
biological weathering	positive	positive
creep		positive
water-driven sediment redistribution	positive	positive for deposition negative for erosion

To simulate varying levels of model uncertainty, three scenarios were defined by making different assumptions for the standard deviations of all 13 model parameters available for calibration (Table 6.2). Standard deviations were set to 10%, 20% and 50% of the calibrated parameter values to yield low, medium and high uncertainty scenarios. Note that this procedure only takes model uncertainty due to parameter uncertainty into account, not model uncertainty due to incorrect or overly simplistic process descriptions, or due to incorrect input data.

For each uncertainty scenario, sets of parameters were drawn from their joint probability distribution, taking minima into account where needed to ensure realistic values (Table 6.2). No correlation between parameters was assumed. The resulting model versions were run with records for stable and changing climate from the year 2000 to the year 3000. Table 6.3 is the model setup report for these versions.

Table 6.2: Means, three assumptions for standard deviation and minimum values for the 13 model parameters used in LAPSUS.

parameter	unit	calibrated value	standard dev. low uncertainty	standard dev. medium uncertainty	standard dev. high uncertainty	minimum value
m	[-]	0.3	0.03	0.06	0.15	0.1
n	[-]	0.4	0.04	0.08	0.2	0.1
p	[-]	1.5	0.15	0.3	0.75	0.000001
K_act	[m^{-1}]	0.00003	0.000003	0.000006	0.000015	0.000001
P_act	[m^{-1}]	0.00004	0.000004	0.000008	0.00002	0.000001
K_veg	[m^{-1}]	0.000025	0.0000025	0.000005	0.0000125	0.000001
P_veg	[m^{-1}]	0.00004	0.000004	0.000008	0.00002	0.000001
evapmax	[m]	1.35	0.135	0.27	0.675	0
w_Po	[m^2 t^{-1}]	1.5	0.15	0.3	0.75	0
w_k1	[-]	4	0.4	0.8	2	0
w_k2	[-]	6	0.6	1.2	3	0
w_Pa	[m t^{-1}]	0.02	0.002	0.004	0.01	0
c_D	[m^2 t^{-1}]	0.3	0.03	0.06	0.15	0

For the three levels of uncertainty, probability distributions of stable and changing climate model results are compared. Comparisons were made using the mean change over the whole area, Sediment Delivery Ratio (SDR) and mean changes for seven sub-zones (Fig 1.5). T-tests were used to test the hypothesis that model results did not differ between stable and changing climate.

Table 6.3: Model setup report for LAPSUS.

Step	Choice
Spatial Extent	1.82 * 2.27 km = 4.13 km^2, water divide included, catchment mask applied
Temporal Extent	1000 a, from year 2000 to year 3000
Process Extent	3 (water erosion and deposition, creep, biological weathering) in all model versions.
Spatial resolution	10 m. Sinks not removed, landscape only medium of interaction, processes at same spatial resolution
Temporal resolution	10 a. All processes at same temporal resolution, in the order mentioned above
Process resolution	See (Temme and Veldkamp, in press) for details about the process descriptions.

Climate change

Future climate change is a topic that receives intense research interest. The most recent summary of work in this field is the Fourth Assessment Report of the Intergovermental Panel on Climate Change (IPCC), which focusses on climate predictions up to the year 2100. Few studies simulate climate change beyond the year 2100. Climate models are not sufficiently calibrated for use at the expected high CO_2 concentrations beyond this time and therefore are no longer reliable (e.g. (Hooss *et al.*, 2001). Among the studies that do look further ahead, (Plattner *et al.*, 2008) use a range of intermediate complexity models (EMICs) to simulate global temperature changes up to the year 3000.

Realizing that results for this period are explorative, the IPCC A2 scenario results from the Climber-2 EMIC (Petoukhov *et al.*, 2000; Ganopolski *et al.*, 2001) in Plattner *et al*'s work are used as a starting point to derive a climate change scenario for Okhombe valley from the year 2000 to the year 3000. For this scenario and this model, predicted mean global temperature changes are about 3.8 K at the year 2100 and about 5.6 K at the year 3000.

To arrive from these global estimates at local temperature estimates for Okhombe valley, the Climber-2 results are compared to spatially explicit results for Southern Africa for the year 2079 (Tadross *et al.*, 2005). The work of Tadross *et al* used a.o. the MM5 Regional Climate Model (RCM) to downscale results from global climate model HadAM3, forced with the A2 emissions scenario. Results from the MM5 simulation suggested that mean summer temperatures in Okhombe valley in 2079 would increase with about 3 K.

Assuming that mean annual temperatures follow the same pattern, and asumming a linear relation, the Climber-2 (global) temperature results are scaled to the MM5 (Okhombe) results:

$$\Delta T_{\mathrm{Okhombe},t} = \Delta T_{\mathrm{Okhombe},2079} * \frac{\Delta T_{global,t}}{\Delta T_{global,2079}} \tag{6.4}$$

The MM5 simulation also suggested that mean summer rainfall would increase with about 150 mm. Winter rainfall is not expected to change (Hewitson and Crane, 2006), so annual rainfall increase was assumed equal to summer rainfall increase. Even though a high fraction of rainfall in Okhombe valley is predicted to be convective (temperature-driven, (Tadross *et al.*, 2005), rainfall response to temperature changes is expected to be non-linear. Therefore, it is speculative to scale MM5 rainfall results for Okhombe with global Climber-2 temperature results (Tadross *et al.*, 2005). However, given the explorative objective of this study, and the lack of other predictions of rainfall in Okhombe valley beyond 2100, this was deemed acceptable:

$$\Delta rain_{\mathrm{Okhombe},t} = \Delta rain_{\mathrm{Okhombe},2079} * \frac{\Delta T_{global,t}}{\Delta T_{global,2079}} \tag{6.5}$$

This procedure resulted in the temperature, rainfall and vegetation records shown in Fig. 6.1. A comparison with palaeo-records of rainfall (Tswaing Crater, Partridge *et al.*, 1997) and temperature (Vostok, Petit *et al.*, 1999) shows that both rainfall and temperature predictions are not in the range of palaeo-climate over the last 50 ka.

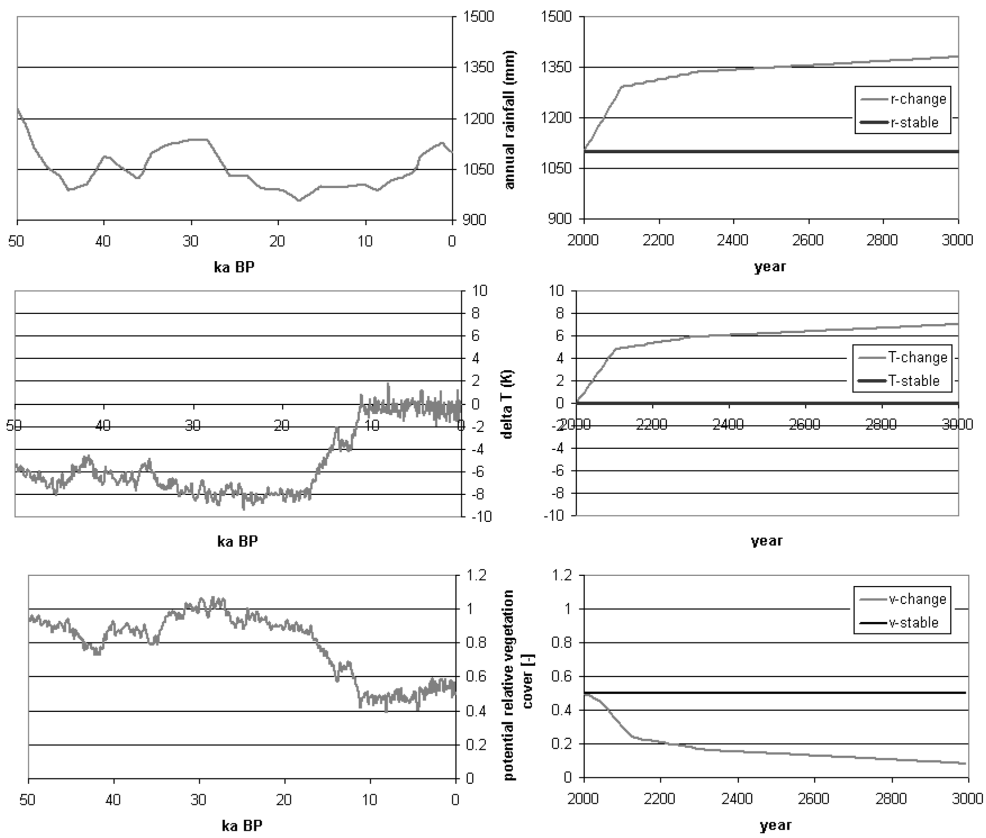


Fig. 6.1: Records of palaeo 50 ka and predictions of future 1 ka rainfall, temperature and potential relative vegetation cover for Okhombe Valley. The palaeo 50 ka records are for comparison, the future 1 ka stable and predicted change records are used in the model runs.

Research area

The Okhombe valley in KwaZulu-Natal, South Africa, lies close to the province's border with the Free State province and the kingdom of Lesotho (Fig. 1.2). The sedimentary landforms in the valley (Figs. 1.4 and 1.5) provide a depositional stratigraphy that was mapped and dated by Temme *et al.* (2008b) and modelled with LEM LAPSUS by (Temme and Veldkamp, in press). The combined landscape evolution conclusions of these studies are summarized in chapters 2 and 5.

At present, gullies actively erode the colluvia in Landscape Element (LE) C (Fig. 1.5). This threatens roads, houses and agricultural fields, which presents a grave problem for this area where people rely on natural resources for their subsistence. Hence, the future of landscape evolution in Okhombe valley is not only of scientific, but also of societal interest.

6.3 RESULTS

Model outputs

When assuming no uncertainty, the overall difference between the stable and changed climate scenarios is clear (Fig. 6.2): from initally similar rates, average erosion under changed climate increases strongly until it decreases from around 2150, whereas average erosion under stable climate slowly decreases from 2000. Erosion under changed climate at 3000 is still around 30% higher than erosion under stable climate. This is strongly related to the decrease in relative vegetation cover and the increase in rainfall, which cause stronger redistribution in the research area.

Deposition under changed climate (not shown) increases less than erosion, which causes that five-decade averaged SDR values under changed climate are lower; a smaller fraction of the eroded sediment is exported from the catchment.

Decadal variations are observed in both the stable and changed climate results. Note that these variations do not reflect climatic fluctuations (*cf.* Fig. 6.1). They result from the formation and filling up of small sinks, formed by the interaction of water erosion and deposition and creep. The SDR results were averaged over five decades (timesteps) to better allow recognition of long-term differences between climate scenarios.

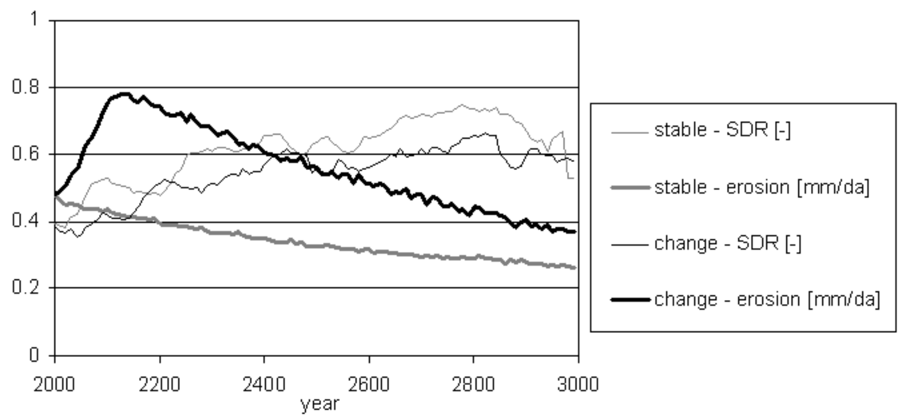


Fig. 6.2: Timeseries of mean erosion [mm/da] and five-decade averaged SDR [-] under stable and changed climate, assuming no parameter uncertainty.

The effect of parameter uncertainty on the summations of these results over time is assessed in the next section.

Monte Carlo analysis

Table 6.4 shows the averages and standard deviations of net altitude change and SDR for the original and uncertain model outputs from runs with stable and changed climate, as well as the probabilities that stable and changed climate results are not different.

Table 6.4: Means, standard deviations between stable and changing climates for overall model outputs and probability that stable and changed climate results are not different.

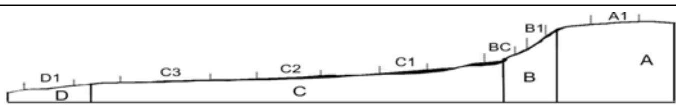
uncertainty	climate	sample	altitude change [m erosion]	Sediment Delivery Ratio [-]
no uncertainty	stable	n= 1	0.0520	0.582
	change	n= 1	0.0613	0.637
	p (stable = change)		0	0
low uncertainty	stable	n= 100	0.050 ±0.014	0.630 ±0.089
	change	n= 108	0.062 ±0.015	0.581 ±0.065
	p (stable = change)		<0.001	<0.001
medium uncertainty	stable	n= 161	0.056 ±0.026	0.639 ±0.167
	change	n= 92	0.071 ±0.032	0.604 ±0.144
	p (stable = change)		<0.001	0.08
high uncertainty	stable	n= 95	0.065 ±0.044	0.660 ±0.276
	change	n= 91	0.090 ±0.032	0.649 ±0.144
	p (stable = change)		<0.001	0.78

Importantly, it is very improbable that the mean change in altitude between stable and changed climate model versions is equal, even at the high parameter uncertainty assumption ($p < 0.001$). Mean change in altitude is consistently lower under stable climate scenarios than under changed climate scenarios, with a difference of about 0.01 m when no uncertainty is assumed. In contrast, probability that SDR is equal for stable and changed climate model results increases with parameter uncertainty to $p = 0.78$ at high uncertainty.

Apparently, LAPSUS is able to discriminate between mean changes in altitude but not between SDR under the two climate scenarios under all three scenarios of parameter uncertainty.

Table 6.5 details this analysis for the 7 zones in Fig. 1.5. In general, this shows that it is unlikely that stable and changed model results are equal for different zones in the research area. Even under the high uncertainty scenario, most probabilities that stable and changed climate results are equal, are below 0.1. However, a general increase of probabilities with increasing parameter uncertainty is visible, for instance in zone C2 (not shown in other zones where $p < 0.001$). In the low uncertainty scenario, $p < 0.001$ for all zones, in the medium uncertainty scenario for five zones, and in the high uncertainty scenario for three zones.

Table 6.5: For the seven zones D-A (Fig 1.5): means and standard deviations between stable and changing climates and probability that stable and changed climate results are not different.

uncertainty	climate	sample	D1 [m]	C3 [m]	C2 [m]	C1 [m]	BC [m]	B1 [m]	A1 [m]
									
no uncertainty	stable	n= 1	0.1351	-1.959	-0.007	0.1764	0.1183	0.2262	0.0521
	change	n= 1	0.1611	-2.273	0.1595	0.2199	0.1913	0.2165	0.0706
	p (stable = change)		0	0	0	0	0	0	0
low uncertainty	stable	n= 100	0.159 ±0.010	-1.785 ±0.284	-0.017 ±0.115	0.117 ±0.013	0.176 ±0.009	0.224 ±0.014	0.052 ±0.005
	change	n= 108	0.131 ±0.081	-2.283 ±0.169	-0.156 ±0.350	0.191 ±0.008	0.221 ±0.006	0.217 ±0.003	0.071 ±0.004
	p (stable = change)		<0.001	<0.001	<0.001	<0.001	<0.001	<0.001	<0.001
medium uncertainty	stable	n= 161	0.162 ±0.018	-1.530 ±0.648	-0.050 ±0.193	0.119 ±0.023	0.171 ±0.036	0.230 ±0.026	0.055 ±0.009
	change	n= 92	0.157 ±0.061	-2.045 ±0.628	-0.177 ±0.432	0.191 ±0.018	0.215 ±0.042	0.218 ±0.006	0.073 ±0.007
	p (stable = change)		0.41	<0.001	0.009	<0.001	<0.001	<0.001	<0.001
high uncertainty	stable	n= 95	0.159 ±0.051	-0.997 ±0.874	-0.148 ±0.368	0.114 ±0.061	0.136 ±0.103	0.235 ±0.069	0.062 ±0.020
	change	n= 91	0.145 ±0.061	-1.345 ±0.628	-0.256 ±0.432	0.187 ±0.018	0.198 ±0.042	0.221 ±0.006	0.078 ±0.007
	p (stable = change)		0.33	0.014	0.130	<0.001	0.06	<0.001	<0.001

Under the high uncertainty scenario, differences between stable and changed climate results are least clear in zones D ($p = 0.33$) and C2 ($p = 0.13$). Differences between stable and changed climate results are clearest in zones C1, B and A ($p < 0.001$).

Mean values of altitude change (overall and zones) and SDR vary with the level of uncertainty (Tables 6.4 and 6.5). For some results, mean values increase, for other results, mean values decrease with increasing uncertainty. This seemingly surprising result (mean values are expected to be independent from the level of uncertainty) is caused by the application of minimum values (Table 6.2). With increasing uncertainty, and hence increasing standard deviation, a larger portion of randomly drawn parameter values will be below the minimum and removed from the sample. The overall result of this is a net movement of the mean value of the sample away from zero, while the median value remains constant. This effect is strongest for parameters m and n (Table 6.2), where the minimum values are relatively close to the calibrated parameter value (Fig. 6.3).

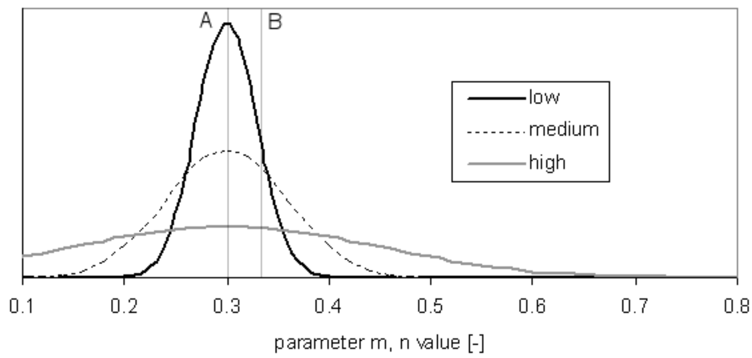


Fig. 6.3 : Movement of mean from A (for low uncertainty) to B (for high uncertainty), and away from zero with increasing standard deviations when minimum values of m and n (Table 6.2) are removed from sample.

A consistent movement of parameter values away from zero (and hence an increasing sample mean) with increasing uncertainty, can then cause a consistent, but non-linear change in model predictions. This change may be positive, as in Table 6.4 or negative, as in the results of zones BC and C2 in Table 6.5. This effect works in the same way for both climate scenarios.

6.4 DISCUSSION

Neither a large difference between stable and changed climate results, nor a low probability that results of stable and changed climate are equal, is the same as a high confidence in model predictions. As mentioned before, a high confidence in model predictions first requires model calibration, preferably under similar conditions. Such calibration increases confidence in parameter values as well as in model structure and process descriptions. Temme and Veldkamp's (in press) previous calibration of LAPSUS was performed with similar spatial, temporal and process extent, but under different climatic conditions. That calibration was based on comparisons of model results with timeseries of overall absolute and relative process activity, and with zonal process activity. It is therefore expected that especially these types of model outputs are realistic, which is why a selection of them was used in the present study.

Another source of uncertainty in model results is uncertainty in input values. In this research, considerable uncertainties accompany the predicted records of temperature and especially rainfall. These uncertainties propagate to the predicted relative vegetation cover record, which is also uncertain due to its unknown relation to future climate records. Uncertainty also accompanies other model inputs.

In summary, this research tested the influence of uncertainty in parameter values, assumed that the influence of uncertainty in model structure and process descriptions is minor for the types of outputs analysed, and ignored uncertainty in input values. Therefore, our results above allow at best an explorative, relative and zonal assessment of the impact of climatic change, as opposed to stability, on the landscape in the research area. In particular, some confidence can be placed in the simulated large relative increase in deposition in zone C3, and the large relative increase in erosion in zone C1 under changed climate (Table 6.5). An overall net decrease in altitude (> 1 cm, Table 6.4) is expected, as well as an overall increase in deposition (> 1cm, not shown).

These results, those in Chapter 2, and (Sonneveld *et al.*, 2005) have concluded that the erosion problems in Okhombe valley are already most distinct in zone C1. Our results suggest that this problem would increase under changing climate.

Note that these results have been obtained by comparing stable climate with predicted future climate under the A2 emissions scenario. The A2 emissions scenario is one of the most extreme emission scenarios used by IPCC (2007), and it is certain that the selection of less extreme scenarios would have resulted in less difference between stable and changed climate records for this study. In turn, that would have resulted in less difference and less confidence in difference between LEM results.

The results of LAPSUS for the stable climate scenario lack the uncertainties associated with predicting future climate. They can be seen as a baseline-scenario for future landscape dynamics.

6.5 CONCLUSIONS

Of the three types of uncertainty that influence LEM predictions of future landscape evolution, this research has tested the influence of parameter uncertainty, assumed that the influence of uncertainty in process descriptions and model structure is minor, and ignored uncertainty in input values (e.g. climatic records).

Results show that in this setup, for this spatial and temporal extent, LEM LAPSUS is able to discriminate between landscape evolution under stable and changing climate. When uncertainty in parameter values is low, LAPSUS makes that distinction ($p < 0.001$) for all studied model outputs, when uncertainty in parameter values is high, it makes that distinction for about half the studied outputs.

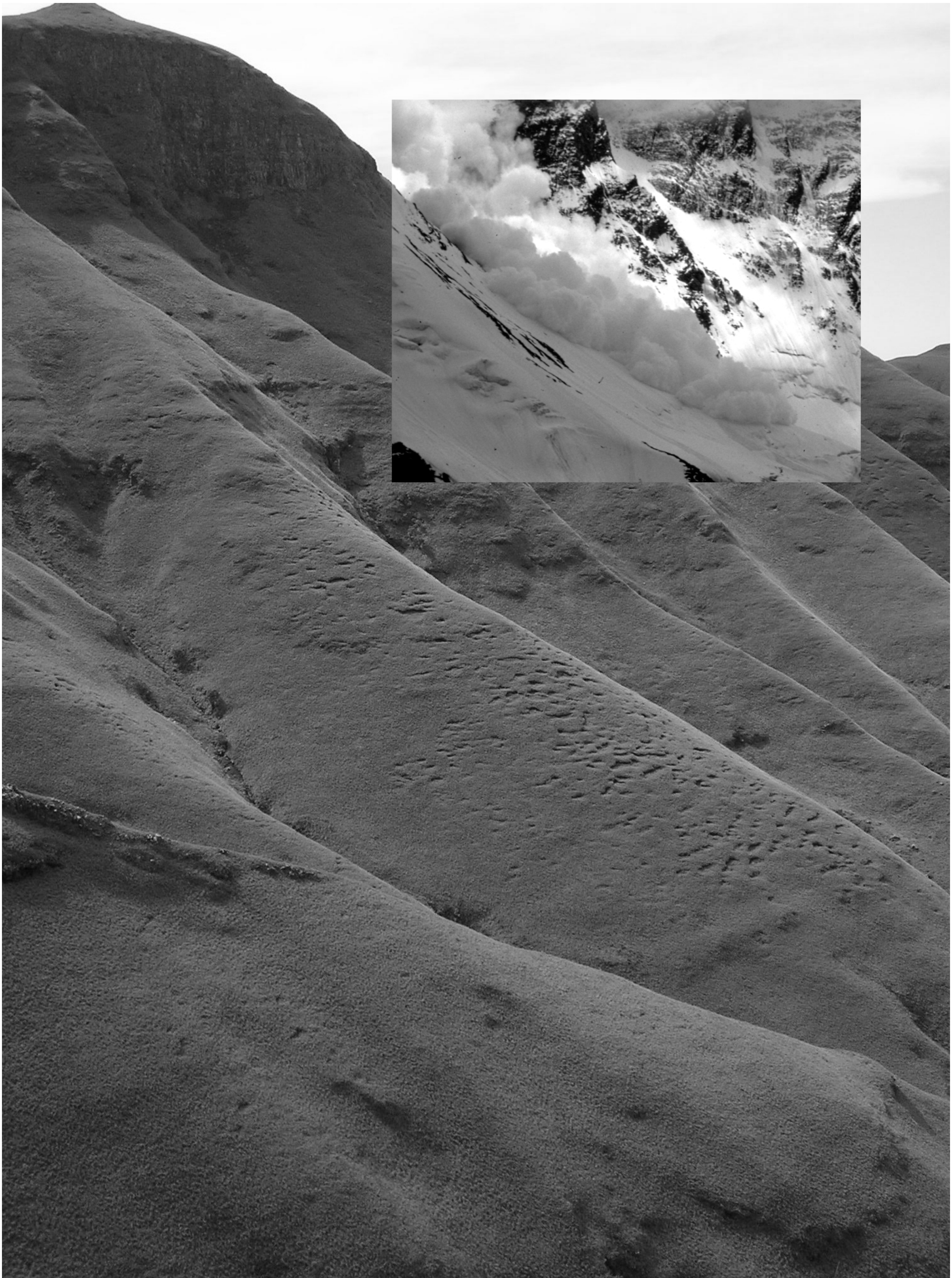
Actual landscape evolution predictions are speculative but indicate largest effects in landscape element C. In the upstream parts of this element (zone C1), a relative increase in erosion is predicted under changing climate. In the downstream parts (zone C3), a relative increase in deposition is predicted. Especially the increased erosion in zone C1 would lead to an exacerbation of the current erosion problems in a of Okhombe valley, where gully-systems already grow and develop new tributaries that threaten houses and roads (Sonneveld *et al.*, 2005).

Future research of the effect of climate change on landscape evolution is of large societal interest. Reductions in uncertainties from any or all of the abovementioned sources would allow for less speculative and more detailed conclusions, that could become statistically significant over shorter temporal extents. Strategies to achieve such reductions could include:

- wider adoption of ka-scale studies of previous landscape evolution,
- assessments of the influence of differences in (competing) process descriptions and

- multiple calibrations of LEMs in areas with different climatic conditions, to assess continued validity of process descriptions. The latter strategy trades time for space.

More research on long-term climate predictions could similarly reduce uncertainties.



CHAPTER 7

SYNTHESIS

CHAPTER 7

SYNTHESIS

7.1 INTRODUCTION

This chapter presents a synthesis of the conclusions reached in chapters 2-6 and tries to answer the overall research questions on a general level. Implications of these conclusions are explored.

7.2 LANDSCAPE EVOLUTION OF OKHOMBE VALLEY

For the combined conclusions about landscape evolution in the Okhombe valley (Figs 1.2, 1.4 and 1.5), the main and most reliable sources of information are fieldwork and subsequent laboratory analyses, which were presented in Chapter 2. Landscape evolution model results presented in Chapter 5 provide suggestions and refinements.

Starting around 50 ka and continuing until around 30 ka, with cooler temperatures and more rainfall than at present, the slow processes of solifluction and creep transported material from the steep upper slopes (LE B) to the areas of LE C that were immediately downstream. From this period, no deposits other than solifluction deposits were found in the research area. Model results concur and suggest that redistribution by water erosion and deposition was of minor importance in this period, especially in LE A. Model results also suggest that weathering rates were likely relatively high in this period, especially frost weathering rates in LE B.

At least two major mudflow events partly or completely covered the solifluction deposits at the end of this period, around 29 ka (incomplete preservation is probable). The origin of these mudflows was LE A, different from the origin of solifluction deposits. It is likely that oversteepening of the slopes of LE A during the earlier period, especially through frost weathering in the downstream LE B, created the potential for these mudflows. Mudflow activity was not included in the modelling exercises.

When temperatures and rainfall decreased towards the LGM, vegetation zones in the Drakensberg Foothills were lowered by about 1000m compared to present (Botha, 1996). As a result, grassland was likely replaced by denser shrubland. Overland flow and water erosion were inhibited. Judging from the general lack of deposits from this period and from model results, solifluction and creep were also much less active. Model results suggest that average soildepth in this period increased, due to continued weathering.

At the onset of warmer and wetter climate around 15 ka, shrubby vegetation retreated to higher altitudes and Okhombe valley was again covered with grassland. This decrease in vegetation cover, together with increased rainfall, resulted in higher rates of fluvial redistribution. During fieldwork, this was inferred from an absence of deposition in all but the lowest parts of the landscape. In these lowest parts, strong activity of meandering channels was observed in this period, in contrast to the LGM. Models results show a significant increase in overall water erosion activity, but lags of thousands of years in its influence on soildepth of different LEs.

Concerning these lags, model results suggest that the Holocene decrease in soilthickness resulting from erosion started almost simultaneously at 16 ka in zones A1, B1 and C1, but soildepth decreased only from around 13 ka in zone C2 and from around 10 ka in zone C3. This ka-scale lag in model results occurs over a range of parameters, even though its importance (expressed in Fig 7.1 as the difference in maximum soilthickness between zones B1-C3) and duration (expressed as the time between achievement of maximum soilthickness between zones B1-C3) change when changing uncertain model parameters.

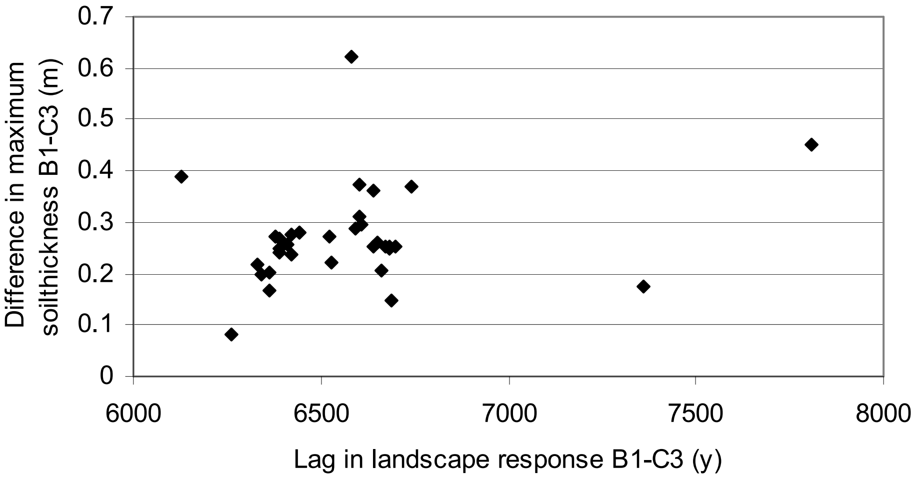


Fig. 7.1: Lag in landscape response and difference in maximum soilthickness between zones B1 and C3 (Fig 1.5) for model versions with parameter values ranging between 90% and 110% of calibrated values.

The lag – or in other words, the slowly moving wave of sediment - is caused by interactions in the soil-vegetation-landscape system. As overland flow starts eroding relatively thick soils in the higher LEs, its transport capacity is quickly reached. Lower in the landscape, where there are less steep slopes, transport capacity decreases and the eroded sediment is deposited. After hundreds or thousands of years, as the soils in the higher LEs get thinner and erodible material is exhausted, transport capacity is no longer reached in these areas and less deposition occurs in lower LEs –changing into erosion as time goes by.

Ka-scale lags at these small distances of a few hundred meters have not before been reported from fieldwork or modelling, but it is conceivable that similarly lagging responses can be found in other areas. Modelling results in Chapter 5 suggested that the following conditions are needed:

- A stepped landscape. The alternation of flat and steep slopes (LEs A – B – C) causes depositional conditions in LE C, enabling a local record of landscape response.

- A disconnected catchment. The lacking connection to Khombe River, caused by the dolerite in LE D, means that very little headward erosion into our catchment occurred and that the local record was preserved.
- A first-order catchment. It is likely that the magnitude of the ka-scale lag differs between first-order catchments, and that their combination in higher-order catchments leads to a confusion of signals (*cf.* Veldkamp and Tebbens, 2001). That may make ka-scale lags invisible.
- Model error can not be excluded as a possible reason for the simulated lag. Even though the observed behaviour occurs for a range of model parameters (Fig. 7.1), it is conceivable that it is a model artefact that did not occur in reality. This might be caused by erroneous or incomplete landscape forming process descriptions – particularly if fluvial processes are concerned, since these were not included in LAPSUS.

Between 15 and 10 ka, LAPSUS also models da-scale lags in Holocene sedimentary responses to climate change. These are different from the ka-scale lags because they are simulated simultaneously over the fieldwork area. Fieldwork has been unable to identify deposits belonging to this response in first instance, possibly because the signal has been removed by the ongoing and longer-term erosion.

No deposits were found after 7 ka. Presently, erosion is widespread in the research area. LAPSUS also suggests strong erosion and decreasing soildepth in this period.

Implications for the interpretation of deposits in KwaZulu-Natal

The Okhombe valley landscape reconstruction may be instrumental in interpreting deposits in other areas of KwaZulu-Natal or elsewhere that have similar characteristics. Three main groups of conditions can be identified, that in combination resulted in the deposits found in Okhombe valley. I discuss these three groups of conditions below, in order of decreasing occurrence in KwaZulu-Natal.

The first group of conditions relate to structural control. The stepped landscape and disconnected first order catchment mentioned above belong to this group and are general conditions for the formation and preservation of local deposits. Due to the common alternation of mud- and sandstone in lithologies of the Beaufort Group and wider in the Karoo Supergroup, intruded by dolerite (e.g. Verster, 1998), these characteristics are met in many small areas in KwaZulu-Natal. Where enough accommodation space has been available, local deposits are or can be present in these areas.

The second group of conditions relate to vegetation history (or palaeoecology) and indicate vegetation cover that has been higher in the LGM than in OIS3 or the Holocene. The combination of maximum vegetation cover with coldest temperatures and lowest rainfall in the LGM results in a stagnation of exporting processes and hence in a potential for significant change at the onset of the Holocene, as observed with ka-scale lags in Okhombe valley. Botha *et al.* (1992) suggested that vegetation zones were 1000 m lower in KwaZulu-Natal during the LGM, which would mean that this group of conditions applies to a wide zone along and below the Drakensberg foothills. This may include a zone along the Northern Drakensberg, along the border between KwaZulu-Natal and the Free State and hence the Voordrag site (Botha *et al.*, 1992; Clarke *et al.*, 2003).

The third group of conditions relate to the climate in OIS3. Relatively low temperatures (Petit *et al.*, 1999), total rainfall as at present (Partridge *et al.*, 1997), and likely reduced seasonality of rainfall (Scott, 2002; Chase and Meadows, 2007) belong to this group. In Okhombe valley, these conditions resulted in the dense deposition by solifluction in three phases between around 50 to around 30 ka. This group of conditions is probably the most restrictive, likely occurring only in an altitudinal zone along the Lesotho-KwaZulu-Natal Drakensberg foothills.

Combining these conditions limits the areas where landscape evolution history is most similar to Okhombe valley to small, few square-kilometre sized protected positions above about 1200 meters, in a zone along the Lesotho-KwaZulu-Natal Drakensberg Foothills. It is likely possible to exploratively map their occurrence with aerial photographs and DEMs, perhaps automatically in a GIS.

However, the particular conclusions concerning depositional stratigraphy and duration (not occurrence) of timelags in Okhombe valley will even be difficult to translate to these most similar sites because they likely also depend on catchment geometry.

In many lower-altitude sites in KwaZulu-Natal, the third and perhaps the second group of conditions are not met. Nevertheless, somewhat comparable deposits (colluvia with palaeosols in concave positions) have been found in these sites, which are typically defined as the Masotcheni Formation. These deposits have been provisionally mapped by Botha (1996). In Chapter 2, I have worked from the assumption that our deposits are comparable to Masotcheni Formation deposits, and concluded that different types of these deposits seem to exist.

Using the conditions above, I now try to elaborate on that conclusion and sketch a broad picture of the heterogeneity of hillslope deposits in KwaZulu-Natal. For clarity, I call these deposits, in sites that meet the structural control conditions, Masotcheni Formation deposits *sensu lato*. The first subdivision of these deposits can be based on the vegetation-history conditions. Sites that had shrubby vegetation in the LGM, likely preserved more deposits, or potential for change in this period. These deposits were subsequently exposed from the early Holocene onward, leading to a strong climate change signal.

Sites that had no shrubby vegetation in the LGM, likely experienced more export of deposits during that period, leading to decreased soildepths at the beginning of the Holocene and perhaps early exhaustion of depositional material. Therefore, their response to climatic improvement may have been less dramatic than in the other sites.

Of course, vegetation history is not the only factor determining the amount of deposits available in structurally controlled, disconnected first-order catchments at the beginning of the Holocene. Size, shape and antecedent conditions play an important role as well, and may override the difference attributable to vegetation history. However, generally speaking, I expect sites with shrubby vegetation in the LGM to react more strongly to Holocene climatic change than sites without shrubby vegetation in the LGM.

Note that the distinction between these two groups of sites is unlikely to be clear or binary, and that intermediate conditions may exist where sites have only partly experienced shrubby vegetation – in space or time.

Within the sites that were high enough and cold enough for shrubby vegetation in the LGM, a further subdivision may be based on the third group of conditions; the climatic factors in OIS3. In sites that were cold and humid enough in winter, like Okhombe valley, solifluction and creep resulted in mixed hillslope deposits that influenced subsequent landscape evolution in combination with water-driven redistribution.

In sites that were not cold and humid enough, the role of erosion and deposition due to overland flow would have been more dominant. It is conceivable that the amount and pattern of deposition in these sites was less than it would have been if solifluction and creep would also have been active.

Thus I have defined three groups of sites that together form the Masotcheni Formation deposits *sensu lato*. As touched upon above, this discrete set is unlikely to do justice to the continuous variation in landscapes and antecedent states. Instead, it should be seen as an attempt to characterize and help explain the variation present in the various deposits observed in KwaZulu-Natal.

The research in this thesis gives no basis to suggest which, if any, of these loosely defined groups of sites should be called Masotcheni Formation *sensu strictu*, but does suggest that the geomorphological history of Masotcheni Formation sediments in KwaZulu-Natal is more heterogenous than has been described to this point (Botha, 1996). In addition, it suggests that temperature has been a forcing factor (directly and through vegetation changes) in at least part of these sites. It is clear that more research, preferably fieldwork in combination with modelling, can provide refinement and validation of these suggestions. Such research should include a comprehensive comparison of our results with the elaborate descriptions of other sites by other authors.

7.3 LANDSCAPE EVOLUTION MODELLING AS A TOOL IN GEOMORPHOLOGY

The use of landscape evolution modelling in this thesis, and its combination with integrated fieldwork, are innovative in a number of ways that benefit its use as a geomorphological tool.

First, landscape evolution models have not before been used to simulate actual (as opposed to hypothetical)[10] landscape evolution on timescales of 10^4 years. Focussing on such a large temporal extent for the first time made it possible to include the major climatic and geomorphic changes from OIS 3 and the LGM to the Holocene in a combined fieldwork-LEM study. With a smaller temporal extent, the recognition of the very slow wave of sediment that constitutes one of the most surprising outcomes of this research, would not have been visible. The use of long-term LEMs to simulate and test hypotheses of both slow and fast landscape responses to climate change, and their interactions, has the potential to be important in the light of increasing societal interest in landscape dynamics and the effects of climate change (Chapter 6).

A LEM study over the complete temporal extent of a study fundamentally differs from time-slice studies, that take snapshots of landscape activity for different (e.g. climatological) conditions. These snapshots are unable to observe or explain long-term landscape interactions and feedbacks, such as those leading to slow-moving waves of sediment in landscapes or fluvial systems (Chapter 5 and Veldkamp and Tebbens, 2001).

[10] Simulating actual landscape evolution from past to present is sometimes called *postdiction* or *retrodiction*. The same action from present to future is more familiarly called *prediction*.

Second, this research has shown (Chapter 5) that the problem of meaningful spatial model calibration (which occurs already in studies for decades, Jetten *et al.*, 2003) may partly be solved with semi-qualitative calibration procedures, using conclusions from fieldwork studies. Although qualitative calibration was immature in this research, the further development of increasingly detailed histories of different aspects of landscape development during fieldwork (possibly in an iterative fieldwork-model framework, see below) will help calibrate ka-scale LEMs studies. This is all the more important when realizing that quantitative calibration data are difficult to obtain for these long periods.

One of the main difficulties with existing quantitative calibration data is that they are frequently gathered in exceptional sites that are meaningful for the development of landscape evolution theories (convenience sampling *cf.* de Gruijter *et al.*, 2006). For calibration and validation purposes, it is better to additionally sample in a regular grid or randomly (purposive resp. probability sampling *cf.* de Gruijter *et al.*, 2006). For our purposes, convenience sampling at exceptional sites serves the development of landscape evolution theories, purposive or probability sampling serve the validation of these theories. As an example, the application of this concept to Okhombe valley could add the following to the used convenience sampling design:

- Regular (purposive) sampling in the depositional area, for instance in a 100 * 100m grid. Depth of bedrock, and age, depth and dominant process of deposition would be measured for each of the deposits. These samples would be taken in pits dug in the deposits.
- Random (probability) sampling outside the depositional area, for instance 25 samples in total. Soildepth would be measured.

These measurements would results in a stronger and more quantitative dataset for model calibration, but they would only marginally improve the input palaeo-DEM (through known depth of bedrock in depositional area that was supposedly exposed at 50 ka) and not improve the input palaeo-soildepth map.

Unfortunately, the lack of quantitative calibration data also has a financial reason. The necessity of sampling in exceptional sites of immediate geomorphological interest often exhausts funds before purposive or probability samping can be started.

Third, the heterogenous landscape and large temporal extent of this research, encompassing widely varying climatic conditions, made it necessary to include five landscape forming processes in LAPSUS. This increased the number of parameters in the model, and hence, statistically speaking, the uncertainty about model outputs. However, the inclusion of processes also resulted in stability of outputs because it enabled crucial stabilizing feedbacks between processes. Single-process LEM studies obviously lack these interactions. The trade-off between the added stability and added uncertainty is a topic of interest in the future development of multi-process LEMs, and in their use in combination with fieldwork and other disciplines (see below).

Fourth, this research was possible because landscape forming processes were modelled in reduced complexity (*sensu* Brasington and Richards, 2007). Reduced complexity modelling consciously omits details from process descriptions, or builds new, simple descriptions that do not make use of all existing process knowledge. The advantage of reduced complexity modelling is mainly in the reduced number of parameters that need to be estimated or measured. This was particularly important for the multi-process ka-scale model that I designed, for which hardly any input was available over the full temporal extent.

The disadvantage of reduced complexity modelling is the danger of losing essential elements of process descriptions. Reduced complexity modelling is not a new idea, but this research demonstrates that it can be used to make multi-process ka-scale landscape evolution modelling work in combination with fieldwork.

An iterative fieldwork-modelling procedure

Combining the insights above and stepping beyond the limitations of this project, it is possible to propose a general flowchart for future geomorphological studies where fieldwork and modelling are combined (Fig. 7.2). In the flowchart, I assume that objectives, research questions and research area of such studies are known.

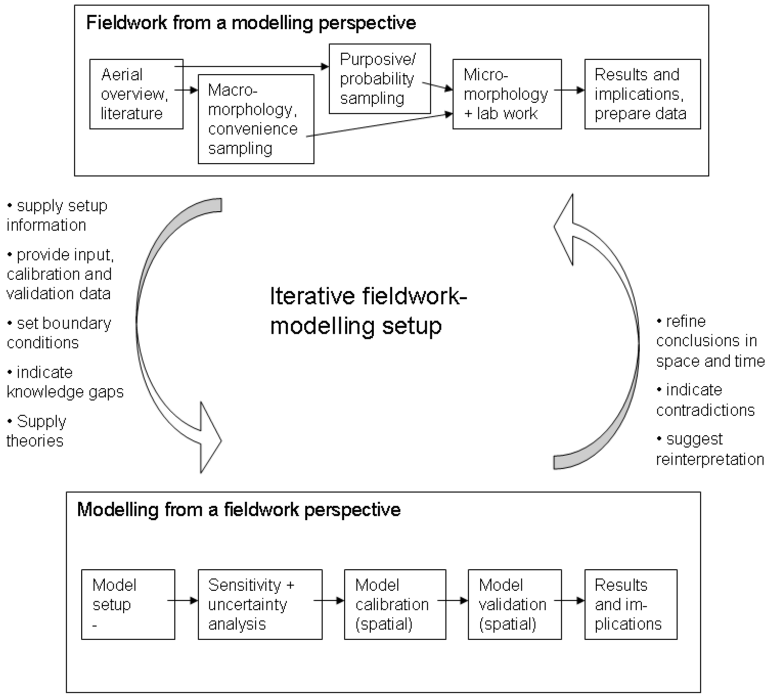


Fig. 7.2: Flowchart of iterative fieldwork-modelling setup in geomorphology.

At the highest level, the flowchart presents an iteration of fieldwork and modelling phases.

Fieldwork provides model studies with theories, setup information, different types of data and boundary conditions and, importantly, indicates gaps in knowledge. These gaps may be due to incompleteness or lack of accessibility of depositional records, or may indicate competing hypotheses of landscape evolution.

Models can formally implement theories and refine fieldwork conclusions in space and time, resulting in testable predictions. Importantly, modelling requires that the sometimes hidden assumptions used in fieldwork are made explicit and quantified. Contradictions in fieldwork-provided hypotheses can be indicated (falsification) and alternative interpretations of records may be suggested (like in Chapter 5).

In an iterative setup, this procedure may lead to increasing confidence and continued refinement of landscape evolution hypotheses. Even though fieldwork usually precedes the first modelling phase, it could be argued that more is to be gained by starting with a modelling phase. Advantages of this initial explorative modelling phase include a more complete awareness of the set of assumptions and data that need to be quantified, and a focus, during data gathering, on the data types most important to limiting model uncertainty.

The suggested iteration of modelling and fieldwork need not last *ad infinitum*. However, it seems wise to spend at least a second period in the field, after the first or second modelling phase which typically results in many new insights. At this point, it is important to note that depending on level of expertise and availability of colleagues for discussion, fieldwork phases themselves can have an iterative character, where hypotheses are repeatedly made, discussed and falsified. This holds to a lesser degree for modelling phases. However, the unique characters of both phases entails that much remains to be gained by combining them.

In the flowchart, I suggest that a fieldwork phase has five steps, most of which are standard practice in geomorphology. However, preparation for the modelling step requires that convenience sampling (at exceptional, reachable sites and outcrops, for development of hypotheses) is supplemented with purposive or probability sampling of input and calibration data. The sampling design for the latter may be informed with results from antecedent modelling phases.

A modelling phase also consists of five steps. First, the model must be prepared for use in the model setup step, for instance using the model setup scheme and report presented in Chapter 4. In this step, decisions are made about the number of processes included in the model. Then, sensitivity or uncertainty analysis must be carried out for the different parameters involved in the process descriptions, depending on the availability of information about the uncertainty of parameter estimates. These analyses can identify the most important sources of uncertainty in model results, which can help in focussing resources during the next fieldwork phase.

Model calibration changes certain parameters in order to match model results to reality as good as possible. The information from the sensitivity or uncertainty analysis is used in this step. Model validation finds out if the calibrated model is still valid for a second data set. For a fair validation, it is necessary that this second data set is comparable to the calibration data set in all aspects that are not included in the model[11]. It is unfortunately not typical to have such a second data set, mostly because of financial and logistical limitations. In our study in Okhombe valley, some promising, comparable research areas for

[11] This can be discussed the other way around: the range of possible validation data sets will be larger when LEMs include more processes that are activated depending on climatic and landscape conditions. Thus, the larger transferability of multi-process models is an argument in their favour. This evidently comes at the cost of more difficult, or less meaningful calibration due to the increased number of parameters.

validation were identified in an early stage, but not enough time was available to gather data in these areas.

Results and implications (falsifications) of model outputs for the theories that originally resulted from fieldwork are then gathered and used in the next fieldwork period.

Inductive and deductive aspects

The information flow in Fig. 7.2 can be characterized in more general terms. Fieldwork results in hypotheses about drivers and trajectories of landscape evolution after making observations about this evolution in some sites. Modelling uses and combines drivers and process descriptions to calculate landscape evolution. In other words, fieldwork has an inductive character, whereas modelling is a strongly deductive activity[12].

The proposed iterative fieldwork-model combination gives researchers a method and an opportunity to alternatively falsify (modelling) and improve (fieldwork) the hypotheses about drivers and trajectories of landscape evolution that are the ultimate goal. In inductive-deductive terms, fieldwork makes observations and creates theories. These theories are used to set-up the LEM. LEM outputs expose the complete set of implications of the theories, likely leading to contradictions and new questions for new fieldwork. Fieldwork then results in better, updated theories that are used to set-up a new LEM etc. Ideally, this procedure iteratively reduces the error until model outputs perfectly conform to reality.

Unfortunately, two other types of error make this impossible in practice. Next to the error in our theories (we do not perfectly know how a landscape works), there are errors in determining reality (we do not perfectly know which change has occurred in a landscape) and in building models (we can not perfectly calculate what we think is happening). This means that we can theoretically calibrate our models to perfection, but that we are validating our theories only to the extent that we are correct in determining reality and modelling our theories.

7.4 LANDSCAPE EVOLUTION MODELLING AS A TOOL IN LAND DYNAMICS

Land dynamics is the study of the spatial and temporal dynamics of landscapes with an emphasis on soils and landuse in a societal context. Therefore it is, unlike geomorphology, a strongly multidisciplinary undertaking. Yet, I pose that landscape evolution modelling can play an important role in land dynamics, too.

[12] Inductive science derives theories from observations, deductive science derives conclusions (observations) from theories. It is inductive science to conclude that ice is cold after *observing* cold ice every time you checked. It is deductive science to conclude that ice is cold, *given that* ice is frozen water and that below-zero temperatures are perceived as cold. Therefore, you do not get cold hands when only doing deductive science. In geomorphology, you do not get dirty hands when only doing deductive science.

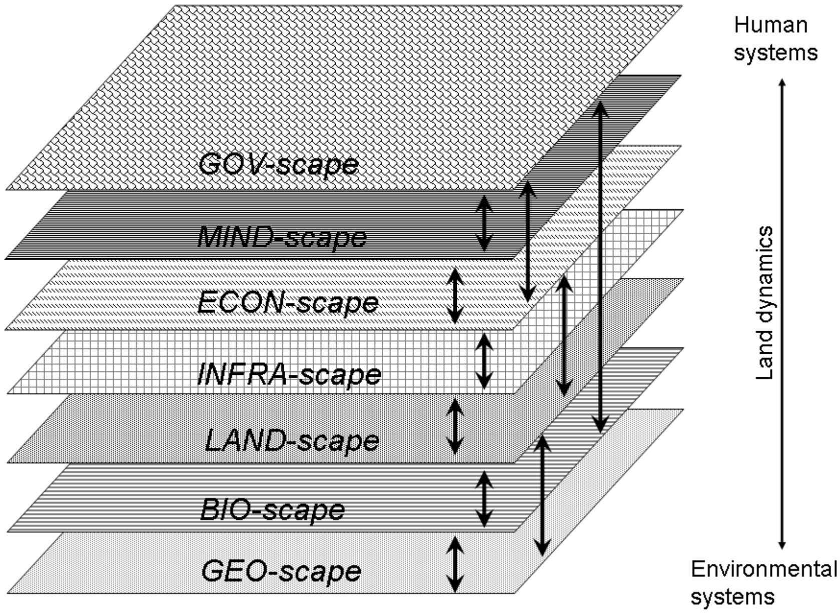


Fig. 7.3: Perspectives on land ("scapes") and interactions between these perspectives are the multidiscipinary setting of land dynamics. After Veldkamp (JLUS).

Below, I focus on one of the main characteristics of landscape evolution models that makes them suited for this role: the interactions and feedbacks that are inherent in these models. Fig 7.3 is a graphical summary of the field of land dynamics that shows the different perspectives on land (the "scapes") and, pertinent to our discussion, that interactions exist between these perspectives. Here, I shall use interactions between the landuse perspective and the biophysical perspective (land- and bio-scapes) as a starting point to discuss feedbacks, but the line of reasoning extends to other interactions.

Some examples of the influence of landuse on the biophysical world were given in Chapter 1, but interactions and feedbacks go both ways. For instance, tillage does not only influence soil erosion, but the subsequent limitations in soildepth may make the land less suitable for cropping and hence lead to abandonment or other changes in landuse and land management. It may be argued that even the impression of decreased suitability can lead to changing landuse or –management (Claessens *et al.*, 2008). Note that Chapters 5 and 6 made clear that a decrease in suitability (land degradation from the human perspective) can result from purely natural causes, and/or from human activity.

From a modelling point of view, the study of the importance of feedbacks between different perspectives on land requires the integration of models that describe aspects of these sub-disciplines. A suitable method for this integration is loose coupling (e.g. Antle and Stoorvogel, 2006), which leaves contributing disciplinary models intact and focusses on the development of model interfaces[13]. Loose coupling makes no particular demands on the models involved, and LEMs are evidently suited for this purpose. LAPSUS in its current versions may be particularly suited because type and format of in- and outputs can be easily changed.

Feedbacks however, are not limited to the interaction of the different perspectives in Fig 7.3. It is a central argument of this thesis and the LAPSUS modelling approach that feedbacks exist in the landscape system itself. For instance, a negative feedback limits erosion through the exhaustion of available soil material.

In general, negative feedbacks lead to system stability. Positive feedbacks lead to amplification of change. Both types of feedbacks exist in the landscape and in landscape evolution models, although negative feedbacks dominate. An example of a positive feedback is an increase of weathering rates with increasing soildepth, which leads to a further increase in soildepth (Fig. 5.1). If that feedback would be valid under all conditions, an infinite and explosive increase in soildepth could be expected, but Fig 5.1 shows that beyond a certain level of soildepth, the feedback is reversed: a further increase in soildepth leads to a decrease in weathering rates. This leads to a slower increase in soildepth, and a relatively larger role for other landscape forming processes (e.g. erosion).

The speed at which a feedback operates is another important factor. Erosion is instantly increased when rainfall increases, but vegetation needs time to respond to an increase in rainfall. Even more time is required for vegetation to influence soildepth through weathering. Antecedent conditions influence the speed of feedbacks. Strong erosion in one year (or timestep), leads to less soildepth in the next year, but only to less erosion when bedrock is reached. This is an example of a non-linear response of erosion to soildepth decrease, where the response only exists after a certain threshold soildepth is reached. The time to reach bedrock may be small, large or infinite, depending on initial soildepth, the activity of other processes and position in the landscape.

The feedbacks above are easily recognized and understood because they are directly used in landscape forming process descriptions. Other feedbacks may become visible only as an emergent property of model results (Chapters 4, 5 and 6) and are less easily understood. These emergent properties make landscape evolution models so useful: it is difficult to predict them in a mind experiment.

An example of an emergent property is the simulated wave of sediment that slowly moved through the landscape in Okhombe valley between 16 ka and 10 ka. The post-LGM increase in transport capacity is initially satisfied in the highest parts of the landscape, and deposition of that sediment occurs in the lowest parts of the landscape. As increasingly less sediment is available in the higher parts, erosion there is limited (negative feedback), and the transport capacity surplus is satisfied progressively lower in the landscape, leading eventually to erosion instead of deposition in the lowest parts.

On the highest level, model outputs themselves are emergent properties that result from many fast and slow interactions between the set of included landscape forming processes. I argue that the stability of these outputs is better guaranteed in multi-process landscape evolution models, than in single-process

[13] Interface is meant here not as a Graphic User Interface, but as a formal definition of the exchange of inputs and outputs between models.

models, due to the larger amount of (negative) feedbacks between processes. This proposition could be tested by comparing the sensitivity of selected model outputs (emergent properties) to parameter values for one landscape forming process, in the absence or presence of other processes in the model.

Some may argue that the interactions and feedbacks in landscape evolution play a role on temporal extents that exceed the human and policy timeframes so much that they are irrelevant to them. However, as shown in Chapters 5 and 6, it is entirely believable (though not proven in this thesis) that current landscape activity is the result of feedbacks in the landscape system reacting to a change in a (climatic or other) input many policy cycles, generations, in fact thousands of years ago.

Nevertheless, process descriptions in LAPSUS in this project were designed for use at a temporal extent of thousands of years, and hence limited to the use of inputs that were available over this timeframe. An increased level of detail in these descriptions would allow for more, and more meaningful interfaces with other perspectives on a shorter extent (Fig 7.3). For instance, it could be argued that the relative vegetation cover used in Chapters 5 and 6 holds not enough promise for interactions between landuse (e.g. agriculture) and landscape, and that an approach that includes more detail in the description of vegetation, would be more suited.

In order to profit from both the important long-term feedbacks in the landscape, and a higher level of detail on the short term, a vari-resolution landscape evolution model can be proposed[14]. Drawing from the work in Chapter 4 to detail this proposal, in such a vari-resolution landscape evolution model spatial, temporal, and/or process resolution would be varied *during model runs* to allow for both a long-term geomorphological perspective, as well as short-term interactions with human systems. This would allow the use of more detailed input records (of e.g climate, landuse) in the more recent portions of the temporal extent.

This exciting proposition would broaden existing multi-temporal-resolution approaches (e.g. LEM CAESAR, Coulthard *et al*, 2002). In the broader field of land dynamics, it holds promises for the interaction and transfer of information between perspectives (Fig. 7.3) that operate at different temporal extents. It must be noted that vari-resolution landscape evolution models do not exist at the moment, and that technical issues must probably be solved before their use is possible.

[14] As opposed to "multi-scale" approaches. Disregarding the ambiguity surrounding the word "scale" , these approaches typically work at distinct resolutions in different studies ("multi-resolution"), instead of with varying resolutions in time, space and process during one study. A notable exception is the CAESAR LEM (Coulthard et al, 2002), that varies temporal resolution during model runs.

Synthesis

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SUMMARY

The title of this thesis is "Understanding landscape dynamics over thousands of years : combining field and model work, with a case study in the Drakensberg Foothills, KwaZulu-Natal, South Africa". As the title clearly states, the overall objective is an increased knowledge of landscape dynamics through the combination of fieldwork and landscape evolution modelling.

Fieldwork is the topic of Chapter 2. The 50 kilo-annum (ka) landscape evolution of the research area in Okhombe valley in the Drakensberg Foothills is studied. Results are presented from extensive fieldwork in Okhombe valley, combined with laboratory work.

Starting around 50 ka and continuing until around 30 ka, with cooler temperatures and more rainfall than at present, the slow processes of solifluction and creep transported material from the steep upper slopes of the research area to the concave areas that were immediately downstream. At least two major mudflow events partly or completely covered the solifluction deposits at the end of this period, around 29 ka. When temperatures and rainfall decreased toward the Last Glacial Maximum, grassland was likely replaced by denser shrubland. Overland flow and water erosion were inhibited. At the onset of warmer and wetter climate around 15 ka, shrubby vegetation retreated to higher altitudes and Okhombe valley was again covered with grassland. This decrease in vegetation cover, together with increased rainfall, resulted in higher rates of fluvial redistribution. Presently, erosion is still widespread in the area.

The knowledge of landscape evolution was put to the test in a landscape evolution model in Chapter 5. Chapters 3 and 4 prepared the LAPSUS[15] model for this task by discussing two important aspects of landscape evolution modelling.

Chapter 3 presents a method to deal with an important conceptual and technical issue in long-term landscape evolution modelling. Conventional models consider depressions in Digital Elevation Models (DEMs) spurious, and remove them before modelling. Long-term multi-process landscape evolution models predict depressions, that therefore must be considered non-spurious. A method is detailed that allows these models to identify and include these depressions in dynamic landscapes. Identification first finds sinks, then adds neighbouring cells to the corresponding depression until a saddle is crossed. Inclusion of depressions in the dynamic landscape led to a procedure to deal with flows of water and sediment into and out of depressions. Depressions can be completely or partly filled with sediment. Partial filling, from each of the neighbouring cells, takes the shape of an above- and below-water delta with user-defined slope.

Chapter 4 discusses ways to more formally list, make and report choices involved in setting-up multi-process landscape evolution models. This discussion is necessary now that models are increasingly combining multiple processes in one study. Choices in model set-up must be made regarding the extent and resolution of time, space and processes. A scheme is presented that can guide workers in making these choices, and tests to determine case-optimal set-ups are discussed using four case studies.

[15] LandscApe ProcesS modelling at mUlti dimensions and Scales

In Chapter 5 , LAPSUS is used with the lessons from Chapters 3 and 4 in mind, to test the landscape reconstruction developed in Chapter 2. Adding to existing process descriptions, the processes of creep, solifluction and biological and frost weathering were developed for LAPSUS. A sensitivity analysis was performed, both for individual processes and for the overall model. Model calibration was trial and error and of qualitative nature. It attempted to simultaneously match model results to fieldwork conclusions for three outputs: zonal process activity over time, relative process activity over time and zonal development of soildepth. After calibration, model results suggested that a very slow wave of sediment moved through the landscape after the onset of the Holocene. Waves of sediment this slow have not been reported before. It is also suggested that erosion following this wave is continuing until today. Chapter 5 also shows that landscape evolution model results allow significant refinements of single-process interpretations of deposits, and can fill in erosional hiatuses in stratigraphical records.

Chapter 6 goes one step further and tests whether the LAPSUS version of Chapter 5 is able to discriminate between landscape responses to stable and changed climate for the next millenium in Okhombe valley. This is an important first step in the use of landscape evolution models in the assessment of the effect of human-induced changing climate. Results of landscape evolution models are, of course, uncertain. This chapter tests the influence of parameter uncertainty, assumes that the influence of uncertainty in process descriptions and model structure is minor, and ignores uncertainty in input values (e.g. climatic records). LAPSUS was run hundreds of times, using random parameter values drawn from their joint probability distributions for three levels of assumed uncertainty and for stable and changed climate. Results indicate that LAPSUS can discriminate between the two climate scenarios in most cases, even at the highest level of parameter uncertainty. An explorative, uncertain and relative conclusion about changes in landscape evolution as a result of climate change can be drawn: erosion will likely be stronger in the concave positions, and deposition will likely be stronger further downstream than under stable climate.

Chapter 7 combines results of the previous chapters. A subdivision of similar deposits in KwaZulu-Natal in four types is proposed using knowledge about the conditions that resulted in the deposits in Okhombe valley. Then, four innovations in landscape evolution modelling that the work in chapter 3-6 has contributed to, are summarized. These innovations are combined into a proposal for iterative model-fieldwork combinations in geomorphology. Eventually the focus is on the role that landscape evolution models can play in studies of land dynamics, given their inherent complex systems' properties.

SAMENVATTING

De titel van dit proefschrift is "Het begrijpen van landschap dynamiek over duizenden jaren: een combinatie van veld en model werk met een studie in de uitlopers van de Drakensberg, KwaZulu-Natal, Zuid-Afrika. Zoals de titel duidelijk aangeeft, is het hoofddoel het vergroten van onze kennis over landschapsdynamiek door een combinatie van enerzijds veldwerk en anderzijds landschaps evolutie modeleren.

Hoofdstuk 2 gaat over veldwerk. De 50 kilo-annum (ka) landschaps evolutie van het onderzoeksgebied in de Okhombe vallei, in de uitlopers van de Drakensberg, wordt er bestudeerd. Resultaten van uitgebreid veldwerk in de vallei worden gepresenteerd in combinatie met laboratorium resultaten.

Beginnend rond 50 ka, en doorgaand tot ongeveer 30 ka, toen temperaturen lager waren en er meer regen viel dan tegenwoordig, werd materiaal van de steile, hogergelegen hellingen in het gebied omlaag getransporteerd naar de komvormige gebieden eronder door de langzame processen solifluctie en creep. Minimaal twee grote modderstromen bedekten deze sedimenten geheel of gedeeltelijk aan het eind van deze periode, rond 29 ka. Toen temperatuur en regenval afnamen richting het Laatste Glaciale Maximum, werd het grasland in de vallei vervangen door dichter struikgewas. Daardoor werden oppervlakkige afstroming en water erosie verminderd. Toen het klimaat weer warmer en natter werd rond 15 ka, trok het struikgewas zich weer terug naar grotere hoogtes en werd de Okhombe vallei weer bedekt met grasland. Deze afname in vegetatiebedekking zorgde er samen met de toegenomen regenval voor dat de fluviatiele herverdeling van sediment toenam. Tegenwoordig is erosie nog steeds wijdverspreid in het gebied.

Deze kennis van landschaps evolutie werd getest met een landschaps evolutie model in Hoofdstuk 5. Hoofdstukken 3 en 4 bereidden het LAPSUS model[16] voor op deze taak door het bediscussieren van twee belangrijke aspecten van landschaps evolutie modelering.

Hoofdstuk 3 laat een methode zien om om te gaan met een belangrijk conceptueel en technisch probleem in lange-termijn landschaps evolutie modelering. Bestaande modellen gaan ervan uit dat depressies in digitale hoogte modellen foutief zijn, en zij verwijderen deze foutjes voor het daadwerkelijke modelleren. Lange termijn landschap evolutie modellen voorspellen juist depressies, die dan noodzakelijkerwijs als niet-foutief moeten worden beschouwd. Een methode wordt beschreven die deze modellen in staat stelt om dat soort depressies te identificeren en ze zelfs te gebruiken in dynamische landschappen.

Identificatie vindt eerst de centra van depressies, en voegt dan telkens buurcellen toe totdat een zadel-cel wordt gevonden. Gebruik van depressies leidde tot een procedure die het mogelijk maakte om te gaan met de instroom en uitstroom van water en sediment. Depressies kunnen dan volledig of gedeeltelijk gevuld worden met sediment. Gedeeltelijk vullen gebeurt vanuit elk van de buurcellen afzonderlijk en zorgt voor een boven- en onder-water vorm van een delta, met een helling die de gebruiker kan instellen.

[16] Acroniem voor Landschap process modeleren op meerdere schaal niveaus en dimensies (LandscApe ProcesS modelling at mUlti dimensions and Scales)

Hoofdstuk 4 bediscussieert manieren om keuzes, die gemaakt worden in het voorbereiden van multi-proces landschaps evolutie modellen, te structureren, maken en rapporteren. Deze discussie is noodzakelijk geworden nu modellen steeds vaker gebruik maken van meerdere processen in één studie. In het voorbereiden moeten keuzes worden gemaakt betreffende de omvang en resolutie van tijd, ruimte en processen. Een schema wordt gepresenteerd dat onderzoekers kan helpen in het maken van deze keuzes. Tests om de optimale modelconfiguratie voor een studie vast te stellen, worden uitgelegd met behulp van vier voorbeeld-studies.

In Hoofdstuk 5 wordt LAPSUS, met de lessen van Hoofdstukken 3 en 4 in gedachte, gebruikt om de landschaps reconstructie van hoofdstuk 2 te testen. In een toevoeging op al eerder gemodelleerde processen, werden nu de processen creep, solifluctie en biologische en vorst verwering ontwikkeld voor LAPSUS. Een gevoeligheidsanalyse werd uitgevoerd voor deze individuele processen en voor het model als geheel. Het afstellen van het model gebeurde handmatig en was kwalitatief. Er werd geprobeerd om drie soorten model resultaten tegelijkertijd te laten corresponderen met veldwerk conclusies: zonale process activiteit door de tijd, relative process activiteit door de tijd en zonale bodemdiepte ontwikkeling. Na dit afstellen, suggereerden model resultaten dat een erg langzaam golf van sediment door het gebied bewoog na het begin van het Holoceen. Dit soort langzame golf werd nog niet eerder waargenomen in ander onderzoek. Ook werd gesuggereerd dat de erosie die volgde op deze golf tot de dag van vandaag doorgaat. Hoofdstuk 5 laat verder zien dat resultaten van landschaps evolutie modellen het mogelijk maken om aanzienlijke verfijningen aan te brengen in enkel-proces interpretaties van sedimenten. Bovendien kunnen ze erosie-hiaten in stratigrafische archieven invullen.

Hoofdstuk 6 gaat een stap verder en test of de LAPSUS versie van Hoofdstuk 5 in staat is om onderscheid te maken tussen landschaps reactie op stabiel en veranderend klimaat voor het volgend millenium in de Okhombe vallei. Dit is een belangrijke eerste stap in het gebruik van landschaps evolutie modellen in het inschatten van het effect van door mensen veroorzaakte klimaatsverandering. Resultaten van landschaps evolutie modellen zijn natuurlijk onzeker. Dit hoofdstuk test de invloed van parameter onzekerheid, neemt aan dat de invloed van onzekerheid in process beschrijvingen en model structuur klein is en negeert onzekerheid in invoergegevens (bijvoorbeeld klimaatvoorspellingen). LAPSUS werd honderden keren gebruikt, met parameter waardes die willekeurig werden getrokken uit hun gezamenlijke kansverdelingen voor drie niveaus van aangenomen onzekerheid en voor stabiel en veranderd klimaat. De resultaten laten zien dat LAPSUS in de meeste gevallen onderscheid kan maken tussen de twee klimaat scenarios, zelfs op het hoogste niveau van onzekerheid in parameters. Een verkennende, onzekere en relatieve conclusie over veranderingen in landschapsevolutie als gevolg van klimaatsverandering kan getrokken worden: erosie zal waarschijnlijk sterker zijn in de komvormige posities, en depositie zal waarschijnlijk verder stroomafwaarts sterker zijn dan onder stabiel klimaat.

Hoofdstuk 7 combineert de resultaten van de vorige hoofdstukken, en bouwt erop verder. Gebruikmakend van de kennis over de voorwaarden die hebben geleid tot de sedimenten in de Okhombe vallei, wordt een onderverdeling van vergelijkbare sedimenten in KwaZulu-Natal voorgesteld. Daarna worden vier innovaties in landschaps evolutie modelering samengevat waar het werk in hoofdstukken 3-6 toe hebben bijgedragen. Deze innovaties worden gecombineerd in een voorstel voor iteratieve model-veldwerk combinaties in geomorfologie. Uiteindelijk komt de nadruk te liggen op de rol die landschaps evolutie modellen kunnen spelen in landdynamiek studies, gegeven hun inherente eigenschappen van complexe systemen.

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ABOUT THE AUTHOR

Arnaud Josephus Alexander Maria Temme was born on the 22nd of April 1978 in Montfort, in the province of Limburg in the Netherlands. His youth was spent reading and roaming the fields and forests, in retrospect developing a sense of landscape. He followed secondary education at the Bisschoppelijk College Schöndeln in Roermond, where he got a brief moment of local fame when he took - and passed - exams in eleven instead of the usual seven subjects. In 1996, he moved to Wageningen where he studied both Geoinformation Science and Soil, Water and Atmosphere. His thesis subjects were “Tortonian sedimentation in the Lower Guadalhorce Basin, S-Spain” (2001) and “The sensitivities and impossibilities of using a landscape model with low resolution and medium-quality data: case study in East-Kenya” (2002). In 2003, he obtained MSc’s in Geoinformation Science (*cum laude)* and Soil Inventory and Land Evaluation. During these years, Arnaud frequently worked as a student assistant for both MSc programmes.

In the last year of his MSc’s, Arnaud worked as an apprentice in the industrial world, at Grontmij Geoinformation. Despite having a great time there, he decided to stay in Wageningen to pursue a parttime PhD, starting in september 2003.

Temme is a keen mountaineer and adventure racer. In 2001, he was expedition leader of the first Dutch team to climb three 6000+ m Himalayan peaks. That year, he was elected Sportsman of the year at Wageningen University. He is currently chief instructor for the Royal Netherlands Climbing and Mountaineering Union, teaching mountaineering courses in the Alps and the Netherlands.

PE&RC PhD Education Certificate

With the educational activities listed below the PhD candidate has complied with the educational requirements set by the C.T. de Wit Graduate School for Production Ecology and Resource Conservation (PE&RC) which comprises a minimum total of 32 ECTS (= 22 weeks of activities)

Review of Literature (5.6 ECTS)

- Researching vegetation-landuse-soil-landscape interactions:a review of literature (2003)

Writing of Project Proposal (7 ECTS)

- Soil-vegetation-landscape dynamics: quick and slow soil landscape feedbacks in natural and used systems; KwaZulu Natal, RSA (2004)

Laboratory Training and Working Visits (2.3 ECTS)

- Working visit Flume experiments; UU (2005)
- Lab training Netherlands Centre Luminescence dating; TU-Delft/IRI/NCL (2006)

Post-Graduate Courses (13 ECTS)

- Field excursion of the conference on Paleosolos: memory of ancient landscapes and living bodies of present ecosystems; University of Florence, Italy (2004)
- Land Science; PE&RC/LAD (the Netherlands) (2005)
- Preparation Land Science; PE&RC/LAD (2006)
- Land Science: bringing theory and concepts into practice PE&RC (South Africa) (2007)
- Field excursion Highland Conference (Ethiopia); University of Mekelle, Ethiopia and Catholic University of Leuven, Belgium (2007)

Competence Strengthening / Skills Courses (3.3ECTS)

- Scientific Writing (Grossman); PE&RC/WGS (2003)
- Time Planning and Project Management; PE&RC/WGS (2004)
- PhD assessment; PE&RC/WGS (2005)

Discussion Groups / Local Seminars and Other Scientific Meetings (7.2 ECTS)

- SPAM: Spatial Methods (2004-2007)
- Landslide symposium graduation Lieven Claessens (2005)
- NCL Symposium: Luminescence dating applications and research (2005)
- Wageningen-Leuven discussions (2005-2007)
- NAC9 (2008)

PE&RC Annual Meetings, Seminars and the PE&RC Weekend (3.6 ECTS)

- PE&RC-day (5x)
- PE&RC weekend (2x)
- Trend and ethics in scientific writing (v/d Vijver, Hartemink) (2004)

International Symposia, Workshops and Conferences (13 ECTS)

- International symposim on spatial data quality (Enschede, the Netherlands) (2003)
- Field conference Malaga Basin (Malaga, Spain (2004)
- Paleosols: memory of ancient landscapes and living bodies of present ecosystems (Florence, Italy) (2004)
- The Quaternary Research Association Third International Postgraduate Symposium (Brussels, Belgium) (2004)
- SASQUA Annual Meeting (Bloemfontein, South Africa) (2005)
- Highland: Environmental change geomorphic processes, land degradation and rehabilitation in tropical and subtropical highlands (Mekele, Ethiopia) (2006)
- EGU 2008 (Vienna, Austria) (2008)

Courses in which the PhD Candidate Has Worked as a Teacher

- Soils and Landscapes of the world 2005-5 (France-Germany); LAD 10 days
- Field practical Land Dynamics 2006-5 (Spain); LAD 20 days
- Frontiers in Land Science 2008-4 (Netherlands; LAD 2 days
- Field practical Land Dynamics 2008-5 (Spain) ; LAD 14 days
- Land Science PhD course 2007 (South Africa); PE&RC/LAD 1 day