# Arid landscape dynamics along a precipitation gradient

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# Arid landscape dynamics along a precipitation gradient

## Addressing vegetation – landscape structure – resource interactions at different time scales

A case study for the Northern Negev Desert of Israel

Eke Buis

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# Voorwoord

Toen ik aan mijn promotie begon in 2003 dacht ik nog dat ik dit voorwoord als eerste van mijn proefschrift zou schrijven. Maar niets bleek minder waar. Nu ik eindelijk de rest heb geschreven en gedaan, is het tijd om dit te schrijven. Het was een lange tijd, deze vijf jaar, en tegelijkertijd zo kort. Een weg met pieken en dalen en lange hellingen omhoog. In Nederland en in het mooie en bijzondere Israel. Vooral mijn verblijf in Oud Jeruzalem was erg indrukwekkend. Hoewel het niet altijd even makkelijk was, heb ik veel geleerd, over hoe wetenschap te bedrijven, over politiek op het werk en in het Midden Oosten en vooral ook over mezelf. En als je vraagt of ik het weer zou doen… Ja, het was misschien niet de makkelijkste weg, maar wel een goede.

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Eke, 3 augustus 2008

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# 1 General introduction

## 1.1 Landscape dynamics

The subject of landscape dynamics describes the interactions and feedbacks forming a landscape. The term landscape is widely used, but only vaguely defined. The English word landscape was first recorded in 1598. It originated from a Dutch painters' term invented during the $16^{th}$ century, when Dutch artists were becoming masters of the landscape genre. The Dutch word “landschap” had earlier meant simply ‘region’ or ‘tract of land' (Renes, 1999). In the artistic sense a landscape describes 'a picture depicting scenery of land' (Wikipedia, 2008). However, the definition of landscape as used in geomorphological, ecological and erosion studies is wider than just a spatial or artistic characterization. It takes a broad view whereby a landscape can be defined as the visual features of an area and the interactions between its different elements, like physical elements as landforms, living elements as flora and fauna, abstract elements as climate and human elements as buildings (Renes, 1999; Wikipedia, 2008).

In this thesis landscape is merely defined as the physical environment of a certain stretch of land with the biological community in it (Begon et al., 1996). A landscape is formed over time as a resultant of the interactions and feedbacks among landscape structure, organisms and resource flows (Fig. 1.1). The landscape structure is the basis on which the landscape is formed, and results from the long-term geological and tectonic settings of an area combined with geomorphological processes such as incision, weathering and rock fall. The landscape structure is therefore the topography of an area formed by the bedrock, with loose stones and the deeper soil layers. The resources, e.g. sediments, water and nutrients, are taken up, transformed and transported by gravitational processes, wind, water and biota, and represent the dynamic, non-biological, part of the landscape, including the topsoil. The availability of resources differs in time and place, depending on the balances of in and output. Organisms, e.g. animals, higher plants and cyanobacteria, only occur when sufficient resources are available and operate in the upper soil layers and at the surface. The organisms can be divided in functional surface cover types; groups of organisms with similar ecology, instead of similar taxonomy (Wilson, 1999). These functional surface cover types regulate or are regulated by ecosystem processes and have different distinct functions within the ecosystem (Walker, 1992; Walker, 1995).

In semi-arid regions, like the Negev Desert, the interactions and feedbacks between the three parts of a landscape are mainly related to the availability and redistribution of water (Burke et al., 1998; Yair and Shachak, 1982). The position and extent of the bedrock and soil in the landscape, the landscape structure, influences the effect and intensity of the hydrological processes, whereby bedrock outcrops increase and soil cover decreases the generation of runoff (Kutiel et al., 1998; Yair and Kossovsky, 2002). Runoff also redistributes sediments and can affect landscape structure and organisms alike, by incision of the bedrock or by damaging vegetation (Morgan, 1995). It causes feedbacks between resource dynamics and landscape structure, whereby an increase in bedrock outcrop amplifies runoff formation and therefore erosion downslope (Yair and Kossovsky, 2002). In deserts the local availability of water is important for all organisms. Ecosystem engineers (Jones et al., 1994) are organisms that directly or indirectly modulate the availability of resources for other organisms, and are therefore involved in landscape dynamics. In the northern Negev Desert of Israel three groups of ecosystem engineers can be distinguished: biological crust-forming micro-organisms, higher plants and burrowing animals. Shrubs, for instance, influence resource dynamics by increasing infiltration rate and decreasing runoff volume, and by collecting nutrients and sediments below the canopy of shrubs forming "islands of fertility" (Bhark and Small, 2003; Schlesinger and Pilmanis, 1998; Shachak et al., 1998). This last process can influence landscape structure by changing micro-topography and patterns of runoff and erosion. The landscape structure, on its turn, can influence organisms by providing niches such as crevasses in the bedrock allowing rooting (Yair and Shachak, 1982).

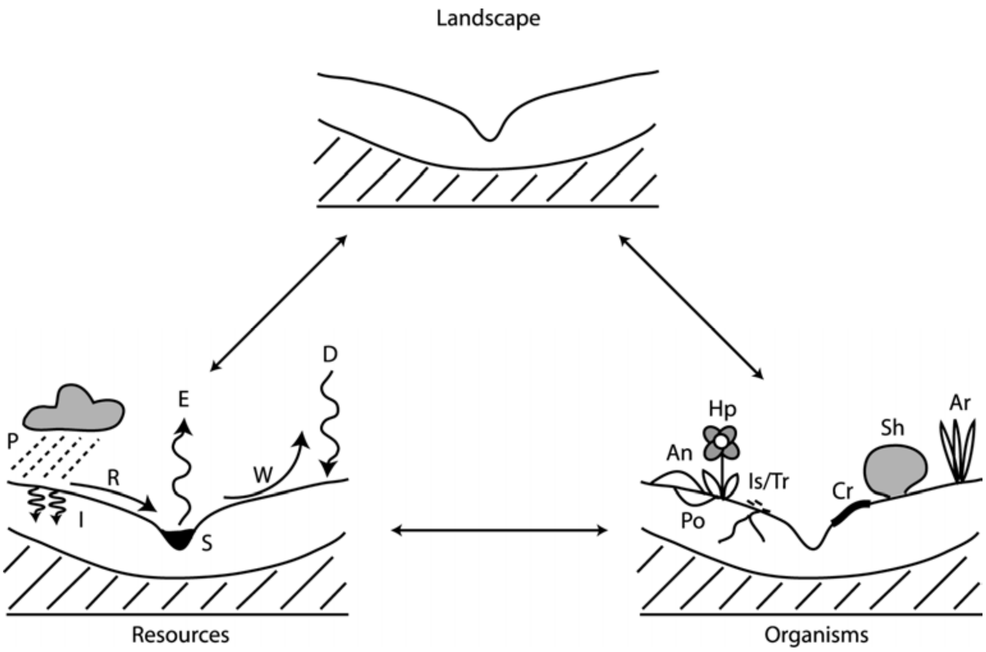


Fig. 1.1. Schematic drawing of the interactions and feedbacks between landscape structure, resources and organisms. P: precipitation, E: evaporation, I: infiltration, R: runoff, S: sedimentation, D: dust deposition, W: wind, Hp: herbaceous plants, Sh: shrubs, Ar: Asphodelus ramosus, Cr: crust, An: ants, Po: porcupines and Is/Tr: isopods, termites and scorpions.

Landscape dynamics occurs within the boundaries set by climate, humans and tectonics. Climate change is an important driver of landscape dynamics. Different climates will therefore often result in very different landscapes, for example limestone regions can form karst landscapes in humid climates as in Slovenia, but will under arid conditions lack karstic features like in the Negev Highlands. Since the Late Holocene human influence is significant as well. A clear historical example is the formation of fen-meadow landscapes in the Netherlands (Rienks and Gerritsen, 2005). More recent examples include the extreme gully erosion in South African rangelands (Sonneveld et al., 2005). To conclude different landscapes will form under different climatological circumstances and human land use intensities.
The interactions between precipitation and vegetation cover are one of the most dominant processes influencing landscape dynamics (Botha, 1996; Eriksson et al., 2006; Roberts and Barker, 1993). In a natural situation the climate driven interactions between precipitation and vegetation result in cycles of aggradation and incision (Knox, 1972). However, human land (mis) management often amplifies climate-driven aggradation and incision cycles, causing strong land degradation and desertification (Foster et al., 2007; Rustomji and Pietsch, 2007; Viles and Goudie, 2003). Especially semi-arid and arid regions are vulnerable for this land degradation and desertification processes (Roberts and Barker, 1993), decreasing the biological and economic productivity and complexity of these dryland ecosystems (UN, 1994). These dryland regions cover approximately 40% of the earth, and are home to one fifth of the human population (Reynolds and Stafford Smith, 2002). Therefore a profound knowledge of the natural processes of landscape dynamics and the effects of humans on these dynamics is of high importance. Seen in the light of future climate changes, especially interdisciplinary studies covering the geomorphological, climatological, ecological and human dimensions of landscape dynamics are needed to increase the knowledge on desertification and enable sustainable management, avoiding further degradation of the land.

## 1.2 Modelling landscape dynamics

### *1.2.1 Erosion models*

Models are widely used in studying landscape dynamics (Coulthard et al., 2005; Peeters et al., 2006; Schoorl et al., 2002). In this study I focus on two types of models: erosion models and on landscape evolution models. The model used in this study, LAPSUS, calculates landscape dynamics based on water erosion and sedimentation (Schoorl et al., 2000), tillage erosion (Heuvelink et al., 2006) and land sliding (Claessens et al., 2007), and is applicable to both short

term short term erosion studies, as to long-term landscape evolution simulations. Firstly I discuss both model types, and next describe the LAPSUS model.
Soil erosion can be caused by e.g. water (direct rainfall and runoff), wind and tillage (Aksoy and Kavvas, 2005). Accordingly, erosion models can be divided in models which simulate wind erosion (e.g. Goossens and Riksen, 2004), water erosion (e.g. Morgan et al., 1998) and models which incorporate tillage erosion as well (e.g. Heuvelink et al., 2006; Van Oost et al., 2000). erosion models differ strongly in process description, scale and applicability. The models can be physically based, empirical or a combination of the two (Aksoy and Kavvas, 2005). Physical based models often use a mass conservation equation as basis (e.g. LAPSUS (Schoorl et al., 2000)), while empirical models are founded on large data sets (e.g. USLE (Wischmeier and Smith, 1987)). Use of empirical models is therefore limited to the region of which the data was gathered, while physical models are more widely applicable. Within the group of (more) physical based models the spatial and temporal scales used cause essential differences. Models focusing on plot level in general only need to simulate erosion to represent natural processes, while models simulating at catchment level need to incorporate sedimentation as well (Schoorl et al., 2000; Siepel et al., 2002). Upscaling of plot scale oriented models to catchment scale should therefore be carefully done, as the intensity and complexity of processes generally increases with scale (Jetten et al., 1999). The time scale varies strongly as well. Some models simulate one event using precipitation intensities per minute, while other models use total event or yearly precipitation values and can handle longer time series (Claessens et al., 2007; Morgan et al., 1998). Models using precipitation intensities are only suited for areas with high data availability, and are difficult to use for long-term modelling (Jetten et al., 1999). Many erosion models are relatively complex and have a large number of parameters, resulting in high data demand. Parameter values can be obtained by direct field measurements or by model calibration. The quality and availability of the field-measured data has strong implications for the results and applicability of a model, and might lead to uncertainties and errors. For spatial models input maps are often created from a limited amount of field data, whereby several assumptions need to be made causing spatial uncertainty propagation (Jetten et al., 1999). Estimation of parameters by model parameterization causes additional errors and uncertainty (Schmidt and Preson, 2003). Keeping models simple and reducing number of parameters is therefore important (Mulligan and Wainwright, 2004). Additionally, the more complex the model, the harder it is to calibrate and validate it (Brasington and Richards, 2007). Therefore the applicability of complex models is often limited to the area for which it was made. Simpler models are mostly more widely applicable, though optimal results might be less good. The “best” model appears therefore to be the model with the greatest predictive power and the least process complexity (Mulligan and Wainwright, 2004; Peeters, 2007).

### *1.2.3 Landscape evolution models*

Landscape evolution models are widely used and developed to explore the formation and dynamics of landscapes at longer time scales, in addition to more traditional geomorphological field methods of landscape reconstruction (Braun and Sambridge, 1997; Coulthard et al., 2005; Favis-Mortlock et al., 1997; Tucker et al., 2001; Tucker and Slingerland, 1997; Willgoose et al., 1991). Often sediment redistribution based on runoff (or a conceptualization of runoff) is the basis of the model. In some models more diffuse processes of sediment redistribution on slopes are incorporated too, e.g. soil creep (Coulthard and Macklin, 2001). Depending of the specific area, and spatial and temporal scales, different processes are included in the models, varying from water erosion to tectonics. Most models handle whole catchments or regions. The differences in model construction make the models suited for different situations. Landscape evolution models are often physically based with empirical parameters. Temporally large differences exist between the models: both in used time steps, as more practically in run time. Similar to erosion models a difficulty is often the selection of the appropriate values of the parameters used. The use of field-measured parameters is hampered by spatial and temporal issues. Data gathering of large regions is time-consuming and expensive, while reconstructing historical parameter values is tricky at best. Therefore most parameters are quantified by model calibration. Often the spatial component of calibration data is lacking, because reconstructions are often based on spot data. Using historical reconstruction involves uncertainties caused by sediment removal out of the catchment and hiatuses: once sediments are removed, correct relocation of sediments in the catchment cannot be done. Additionally comparisons with current rates are only possible by using assumptions about the stability of e.g. topography and climate. Model calibration can result in another complexity: similar landscapes can be simulated with different parameter values, a phenomenon known as *model equifinality*. Model equifinality implies that different palaeo-landscapes may result in one particular present landscape type. This has direct implications for a major aspect of landscape evolution modelling: the reconstruction of palaeo-digital elevation model (DEM) for the model. Spatial data on the palaeo-topography of the study site is often unavailable, or too scarce to reconstruct a correct palaeo-DEM (Rommens et al., 2005). It is therefore commonly assumed that topography changed only marginally and the current DEM is used as input for the model. Another solution is backward modelling, starting from the current topography and simulating backwards in time (Peeters et al., 2006). Although this method can be used in specific situations, it has some serious technical problems mainly related to formation of artificial depressions in the DEM and interfering processes. The backward modelling method appears only applicable for simple models, whereby only one process is simulated (Peeters et al., in preparation).

### 1.2.4 The LAPSUS model

*Background of the model*

LAPSUS is a relatively simple gradient driven and physically-based process model, using a limited number of input parameters (Schoorl et al., 2000). It is spatially explicit and uses a digital elevation model as basis. Both short and long-term applications can be made with varying time steps per run (often annually). The model structure of LAPSUS follows a parsimonious approach (Brasington and Richards, 2007), making the model not more complex than absolutely necessary (Mulligan and Wainwright, 2004). Originally, LAPSUS was developed to simulate erosion and sedimentation processes in the Mediterranean region of Southern Spain, whereby tillage erosion was included as well. Later LAPSUS has been successfully tested in several field studies in varying climates, and was expanded to include different processes such as landslide formation (e.g. Claessens et al, 2005; Haileslassie et al, 2005; Schoorl et al, 2006).

The water erosion and sedimentation module of the model has two fundamental assumptions: 1) the potential energy of surface water flow is the driving force for sediment transport and 2) the difference between sediment input and output of a grid cell is equal to the net increase in storage (continuity equation for sediment movement) (Schoorl et al., 2000). The process description is derived from early works of Kirkby (Kirkby, 1971) and Foster and Meyer (Foster and Meyer, 1972; Foster and Meyer, 1975), who use 2D formulas to calculate water erosion and sedimentation. For the LAPSUS model the formulas are adapted to be able to simulate spatial (3D) water erosion and sedimentation (Schoorl et al., 2000). The formulas discussed below are based on the 2D formulas of Kirkby and Foster and Meyer and with the accompanying units (Foster and Meyer, 1972; Foster and Meyer, 1975; Kirkby, 1971).

*Water redistribution*

The discharge $Q$ ($m^2$ $time^{-1}$) (or in the 3D model in $m^3$ $m^{-2}$ $time^{-1}$ or m $time^{-1}$) consists of the effective precipitation and the runon from higher slopes calculated for the centre of a grid cell. Effective precipitation is calculated by correcting precipitation by an evaporation fraction and subtracting infiltration. Both precipitation and infiltration are usually constant values over the whole catchment and thus effective precipitation as well. It is however possible to use soil type, land use or e.g. elevation dependent values. Discharge towards lower neighbouring grid cells is calculated following the multiple flow principle of routing discharge water (Freeman, 1991; Holmgren, 1994; Quinn et al., 1991):

$$f_i = \frac{(\Lambda)_i^p}{\sum_{j=1}^{\max 8} (\Lambda)_j^p} \tag{1.1}$$

Where fraction $f_i$ of the amount of flow out of a grid cell in direction $i$ is equal to the difference in slope gradient Λ in direction $i$ powered by factor $p$, divided by the summation of slope gradient Λ for all lower neighbours $j$ powered by $p$ (see also Schoorl et al., 2000). For higher $p$, the steepest slope gradient will be more dominant, whereby the multiple flow routing changes to steepest decent routing if $p \rightarrow \infty$. The method of flow diverging used influences the discharge, as grid cells which would receive all discharge in case of steepest descent flow routing, receive less water when using multiple flow routing. Subsequently gully discharge and formation are influenced as well (Schoorl et al., 2000). Multiple flow routing mimics the diverging characteristics of water flow over convex surfaces and re-sedimentation more realistic than steepest descent, and is therefore used in LAPSUS (Quinn et al., 1991; Schoorl et al., 2000).

*Sediment redistribution due to water*

After calculating discharge $Q$ the sediment transport capacity $C$ ($m^2$ $time^{-1}$) in the grid cell can be calculated as function of discharge and slope following:

$$C = \alpha \cdot Q^m \cdot \Lambda^n \tag{1.2}$$

Whereby Λ is the slope gradient (∂z/∂x) (-) and $m$ (-) and $n$ (-) are constants giving an indication of the system studied: $m = 0$ and $n = 1$ suggests soil creep, while $m = n = 3$ suggests large rivers (Kirkby, 1971; Kirkby, 1987). Dummy variable α ($time^{(m-1)}$ $m^{-2(m-1)}$) with value 1 is used to correct the unit of discharge $Q$ in case $m$ is unequal to 1.

If $m >> n$, the formula of transport capacity $C$ will depend mainly on discharge $Q$ (Eq. 1.2). As on a simple imaginary slope discharge $Q$ increases downslope, the transport capacity $C$ increases as well downslope. The system is in that case detachment limited (except at the top of the slope) and resulting erosion and sedimentation depends mainly on $K_{es}$. $P_{es}$ comes only in to play if sufficient material has been eroded before. If $m << n$, the formula of transport capacity $C$ will depend mainly on slope gradient Λ. Therefore on steep slopes transport capacity $C$ is high and the amount of erosion depends on $K_{es}$ (the system is detachment limited). However on flat slopes transport capacity $C$ will be small and the system is transport limited and the values of $K_{es}$ and $P_{es}$ are less relevant. The effect of $K_{es}$ and $P_{es}$ on erosion and sedimentation depends in this situation on the position along the slope. However, the same can be achieved by manipulating $K_{es}$ and $P_{es}$.

The sediment transport rate $S$ (m$^2$ time$^{-1}$) is calculated following the integrated continuity equation for sediment movement (Eq. 1.3 and 1.4). The composition of the used exponential power term in the formula depends on the balance between the transport rate of sediment already in transport $S_0$ (m$^2$ time$^{-1}$) (incoming sediment fluxes of all higher neighbours in the grid cell) and sediment transport capacity $C$: if $S_0 < C$ erosion results, while when $S_0 > C$ sedimentation results. When the grid cell is eroded the following formula for sediment transport rate $S$ is used:

$$S = C + (S_0 - C) \cdot e^{-dx \cdot D / C} \tag{1.3}$$

When sediments are deposited in the grid cell the following formula for sediment transport rate $S$ is used:

$$S = C + (S_0 - C) \cdot e^{-dx \cdot T / C} \tag{1.4}$$

whereby the transport rate of sediment $S$ over grid cell length $dx$ (m) is calculated by comparing sediment transport capacity $C$ with transport rate of sediment already in transport $S_0$ (m$^2$ time$^{-1}$) minus sediment transport capacity C, reduced by an exponential power resulting from grid cell length, detachment capacity $D$ or settlement capacity $T$ and sediment transport capacity $C$.

Detachment capacity $D$ (m time$^{-1}$), representing how easy sediment is eroded of the surface, is calculated as function of discharge $Q$ and slope gradient $\Lambda$ following:

$$D = K_{es} \cdot Q \cdot \Lambda \tag{1.5}$$

whereby $K_{es}$ (m$^{-1}$) is a lumped surface factor indicating erodibility of the surface. Settlement capacity $T$ (m time$^{-1}$), representing how easy sediment is deposited on the surface, is calculated following:

$$T = P_{es} \cdot Q \cdot \Lambda \tag{1.6}$$

whereby $P_{es}$ (m$^{-1}$) is a surface factor indicating lumped sedimentation characteristics.
By comparing the sediment transport rate $S$ of the grid cell with the sediment already in transport $S_0$ the change in sediment transport rate $dS$, and thus erosion or sedimentation, can be calculated following:

$$dS = S - S_0 \qquad (1.7)$$

whereby a negative $dS$ indicates sedimentation and a positive $dS$ erosion. $dS$ can be recalculated to erosion or sedimentation in meter by dividing it by the grid length $dx$ (m) and multiplying it by the time step (time).

The comparison of the exponential power determines how much of the difference between transport capacity $C$ and transport rate of sediment $S$ can be “satisfied” in the grid cell. Depending on the values of the variables involved, the resultant of the exponential power varies between 0 and 1. In extreme situations when $dx$ and $D/T$ combined are much larger than $C$, the exponential power approaches zero and transport rate of sediment $S$ is equal to sediment transport capacity $C$. Then maximum erosion or sedimentation is reached. However, in the other extreme when $dx$ and $D/T$ combined are much smaller than $C$, the exponential power approaches 1 and transport rate of sediments $S$ is equal to the transport rate of sediments already in transport $S_0$ and no erosion or deposition occurs. In less extreme situations the model is likely to simulate sediment transport rate $S$ close to transport capacity $C$. In case $S_0 < C$ less sediment is exported than the transport capacity $C$ would allow based on the sediment transport rate of the grid cells above and less than the maximum erosion is eroded. In case of $S_0 > C$ more sediment is transported than would be allowed based on the grid cells above and less than the maximum sediment is deposited. The exponential power therefore results in under-concentrated and super-concentrated flows in the model, smoothing erosion and deposition over the slope. Obviously the outcome of the exponential power comparison is very influential for erosion and sedimentation. Comparing Eq. 1.2 and 1.5/1.6 it is clear that discharge $Q$ and slope gradient $\Lambda$ are involved in both the transport capacity $C$ and in the calculations of detachment capacity $D$ or settlement capacity $T$. This means that in a situation when $m = n = 1$, the term in the exponential power reduces to $dx \cdot K_{es}$ or $dx \cdot P_{es}$. When $m$ and $n$ are larger, the effect of the transport capacity $C$ on the exponential power term increases. The outcome of the exponential power term is in that situation harder to predict.

*Tillage erosion and sedimentation*

Tillage erosion per tillage pass is assumed to be linear with slope gradient $\Lambda$ in LAPSUS (Schoorl et al., 2004), using the equation proposed by Govers et al. (1994):

$$S_{till} = k_{sf} \cdot \Lambda \qquad (1.8)$$

where $S_{till}$ is the net downslope soil flux per tillage operation (kg $m^{-1}$), $k_{sf}$ is the tillage transport coefficient (kg $m^{-1}$) along the slope and $\Lambda$ the slope gradient (m $m^{-1}$). Govers et al. (1994) calculates coefficient $k_{sf}$ as:

$$k_{sf} = k_{td} \cdot Bd \cdot PL \tag{1.9}$$

where $k_{td}$ is the tillage transport coefficient (m), $Bd$ is soil bulk density (kg $m^{-3}$) and $PL$ (m) is the depth of the plough layer. Since LAPSUS calculates soil redistribution in 2D height instead of weight, these two expressions combine into:

$$S_{till} = k_{td} \cdot \Lambda \cdot PL \tag{1.10}$$

with $S_{till}$ in $m^3$ $m^{-1}$. In calculating tillage erosion from a grid cell to its downslope neighbours, LAPSUS assigns weights to pairs of grid cells using the multiple flow principle explained above. $S_{till}$ can be recalculated to meter by dividing $S_{till}$ by the grid length $dx$ (m).
After each iteration the digital elevation model and soil depth map are corrected for net erosion and sedimentation (m $time^{-1}$), dust deposition (m $time^{-1}$) and other possible processes. Sinks, both artificial and natural, in the DEM can cause serious problems in landscape modelling and are often removed in advance (Martz and Garbrecht, 1998). LAPSUS handles sinks within the model, and treats sinks as a natural phenomenon. The sinks are filled with the sediments eroded upstream which enter the sink during each run (Temme et al., 2006).

## 1.3 Study sites

### *1.3.1 The Negev*

The Negev is located at the edge of the Arabo-Nubian shield (Fig. 1.2). During the Phanerozoic and Oligocene the Tethys Ocean (positioned in the current Mediterranean region) periodically covered the Negev, controlled by mild vertical tectonic oscillations (Bruins, 1986). Marine sediments were deposited during transgressions, and lacustrine and fluvial sediment were deposited during regressions (Evenari et al., 1982b). In the Triassic tectonic deformation started, which ceased at the end of the Cretaceous. It resulted in a series of faults and folds (Bruins, 1986). After the last major Eocene transgression extensive erosion formed a flat landscape during the Oligocene (Ben-David et al., 2002). During the Oligocene to Pliocene the area was subject to new tectonic movements and the Arava rift valley formed as part of the Syrio-African rift system. The rift subsided to 400 meter below sea level. In the Late Pliocene to Middle Pleistocene the tectonic activity and tilting decreased (Ben-David et al., 2002; Bruins, 1986; Garfunkel and Ben-Avraham, 1996).

Nowadays metamorphic and igneous rocks of Precambrian age are exposed in the southern Negev as part of the Arabo-Nubian shield. The surface of the rest of the Negev is mainly covered by limestones, conglomerates, flints and shales. In the northwest loess and sand were deposited in the Early Pleistocene, covering the older topography as a blanket, a process still continuing today (Bruins, 1986; Evenari et al., 1982b). In the rest of the Negev the loess accumulated mainly in the gullies and lower lying flat plains (Yaalon and Dan, 1974).

The Negev Desert has a semi-arid climate in the north and an arid climate in the south (Fig. 1.2). The annual precipitation decreases from at average 300 mm in the northwest to 25 mm in the south and has a high variability (Bruins, 1986). The precipitation is concentrated in the winter months between November and March (Evenari et al., 1982b). In the north-western Negev the temperature in January is at average 12°C, while it is 27°C in August. In the south in January the average temperature is 16°C versus 33°C in August. The precipitation – potential evapotranspiration ratio is 0.390 in the north-western Negev and 0.009 in the south (Bruins, 1986). The strong climate gradient causes a strong gradient in vegetation cover and type as well. In the northwest vegetation cover can be extensive, while in the south it is restricted to depressions and wadi-beds where more water is available (Evenari et al., 1982b). In the Northern Negev vegetation is of the Irano – Turanian type (between 290 and 125 mm annual precipitation), with a transition to Saharo – Arabian type to the south (less than 100 mm annual precipitation) (Shem-Tov et al., 1999; Ward and Olsvig-Whittaker, 1993).

### *1.3.2. Studied catchments*

Four small catchments were selected situated along a semi-arid to arid precipitation gradient ranging from the Northern Negev Desert to the Negev Highlands in the centre of the Negev (Fig. 1.2). The underlying bedrock outcrops of the catchments consists dominantly of limestone with flint, chalk and/or dolomite (Bowman et al., 1986; Bruins, 1986; Dan et al., 1970; Yair and Shachak, 1982). Intensity of bedding and crevices varies per catchment and per layer. On top of the bedrock, loess has been deposited during the Quaternary (Bruins, 1986). Soils are formed within the (redeposited) loess deposits (silty to loamy). Especially in the southern catchments soil formation is very slow.

#### *Lehavim*

The northernmost and mesic catchment is Lehavim (31°20´N, 34°45´E), northeast of Beer Sheva. It receives at average 280 mm annual precipitation. This first order catchment has a size of 8 hectares and is steeply incised (Fig. 1.3). Shallow stony regoliths are found, with admixtures of aeolian material at an average soil depth of 0.23 ± s.d. 0.35 m (Chapter 2) (Yair and Kossovsky, 2002). The catchment is intensively grazed by Bedouin herds of sheep, goats and camels.

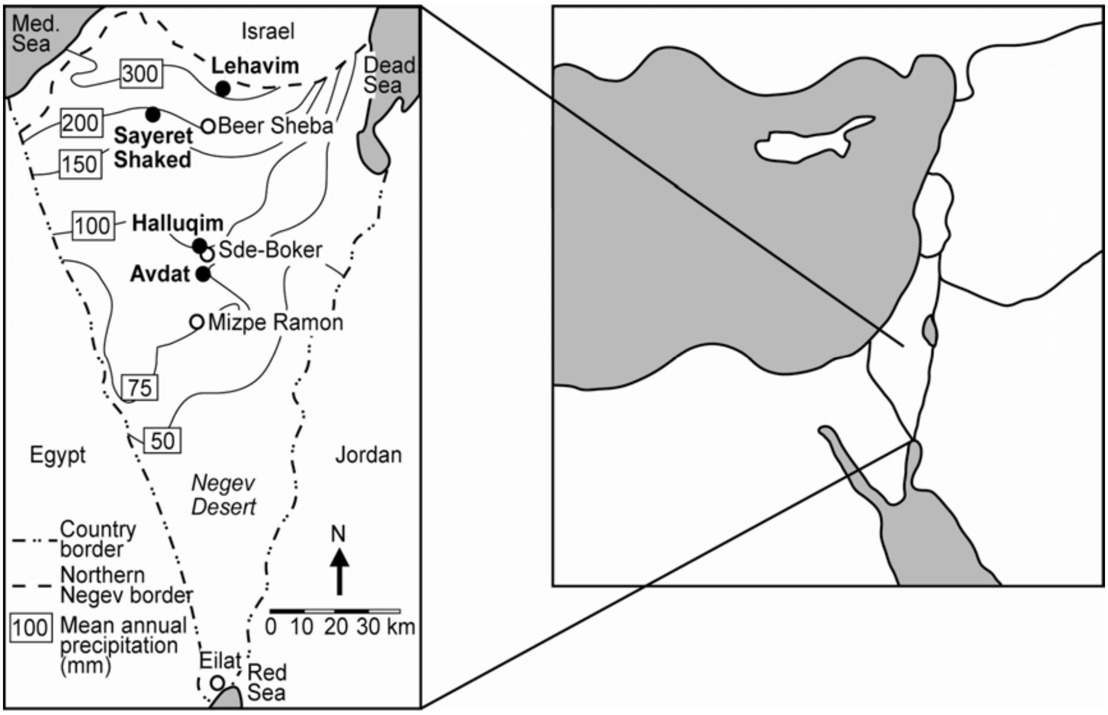


Fig. 1.2 Position of the studied catchments in the Negev De sert of Israel (after Stern, et al., 1986).

*Sayeret Shaked*

The second 12 hectares large catchment is located in the Sayeret Shaked Park west of Beer Sheva (31°17´N, 34°37´E). It is a second order catchment receiving in average 200 mm annual precipitation. The landscape consists of gentle sloping hills. Sandy loess was deposited up to 15 meter thick in the Late Pleistocene (until 13 ka BP) by dust loaded rainstorms, and is still being deposited until today in lower amounts (Issar and Bruins, 1983; Issar, 1990; Shachak and Lovett, 1998). The deposited loess was subject to several soil formation, aggradation and incision phases, resulting in paleosol sequences and relocation of the Early Pleistocene drainage system (Avni et al., 2006; Bruins and Yaalon, 1979; Yaalon and Dan, 1974). The average soil depth is 0.81 ± s.d. 0.82 m (Chapter 2). Livestock has been excluded since 1987 (Boeken and Shachak, 1998).

*Halluqim*

Halluqim (30°52´N, 34°46´E) is located west of Sde-Boker in the Negev Highlands and receives in average 93 mm annual precipitation (Yair and Kossovsky, 2002). This first order catchment is steeply incised and covers 3.5 hectares (Fig. 1.3). The lower part of the area is covered with several meters thick stony Pleistocene colluvium (Wieder et al., 1985). The higher parts are almost devoid of loess cover, which concentrates in crevices in the rock and small depressions on the rock surface. The soils are of aeolian origin and have an average depth of 0.11 ± s.d. 0.16 m (Chapter 2) (Yaalon and Dan, 1974). The area is currently not managed, apart for extensive grazing by Bedouin herds.

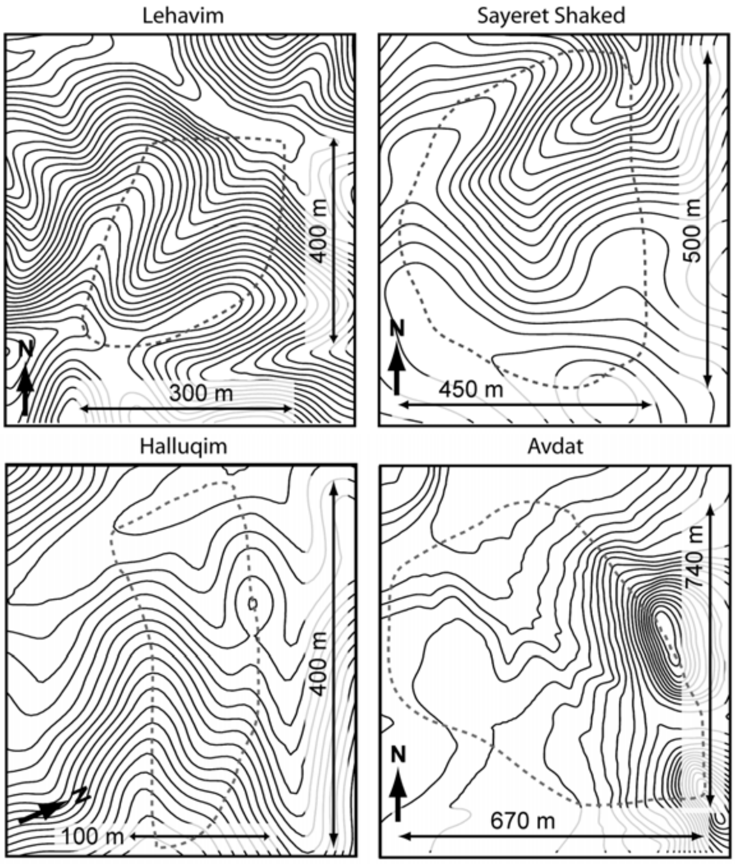


*Fig. 1.3. Digital elevation model of the four studied catchments. Elevation lines in Lehavim, Halluqim and Avdat at 2.5 m interval, in Sayeret Shaked at 1 m interval. Striped lines indicate approximate catchment borders.*

*Avdat*

The southernmost and driest catchment receives in average 87 mm annual precipitation and is situated near the ancient town of Avdat, close to Halluqim (30°47´N, 34°45´E) (Evenari et al., 1980). It has two steep rock outcrops at one side of the 30 ha catchment, while the remaining area is relatively flat (Fig. 1.3). Most of the catchment is covered with a thin layer of loessic deposits mixed with limestones and chert pebbles and has an average soil depth of 0.25 ± s.d. 0.29 m (Chapter 2) (Bruins, 1986; Dan et al., 1981). Moderate grazing occurs by Bedouin herds.

## 1.4 Objectives and research questions

The objective of this thesis is to study and model landscape dynamics of semi-arid and arid catchments in the Northern Negev Desert of Israel, combining geomorphological, ecological, climatological and human aspects of landscape dynamics. The focus of this study is on the interactions and feedbacks among landscape structure, functional surface cover types (functional in terms of water use and redistribution through the landscape) and flows of water and sediment. Different spatial and temporal scales will be covered, ranging from small scale shrub – crust interactions to catchment-wide water redistribution, as well as from single precipitation events to long-term simulations of 1600 years.

The interactions and feedbacks among landscape structure, resource flows and organisms differ strongly throughout the world, as they depend on climate, human influence and tectonics. It is therefore unachievable to discuss landscape dynamics worldwide. Even a more focused discussion of only arid and semi-arid regions would require much more research than could be accommodated in a single project. I will focus on the landscape dynamics of the Northern Negev, with emphasis on the four studied catchments. In this study tectonics was not considered. Though during the Oligocene to Pliocene strong regional tectonics and tilting resulted in the formation of the Arava Rift valley, since the Middle Pleistocene the studied catchments are tectonically stable (Ben-David et al., 2002; Garfunkel and Ben-Avraham, 1996).

This study will add to the knowledge of natural processes of landscape dynamics in dryland regions and the influence of climate change and humans on the landscape. The objective can be divided into the following sub-objectives, with their respective research questions:

1. Increase insight in how landscape structure controls functional surface cover types and how climate and catchment characteristics influence the outcome.
   - How can the biological surface cover be separated in functional surface cover types based on their unique functionality in the landscape?
   - Which landscape structure variables control the functional surface cover types and how?
   - What is the influence of biological interactions on the functional surface cover types?
   - Are functional surface cover types controlled by climate and catchment characteristics?

2. Develop a multi-scale landscape dynamics model suited for semi-arid to arid regions with focus on the Negev Desert, based on LAPSUS.
   - Which processes should be adapted and added to make LAPSUS suited for a semi-arid and arid climate, and to include functional surface cover types?
   - What is the functionality and sensitivity of the adapted LAPSUS?

3. Test the hypothesis that shrub mounds are formed by erosion and sedimentation in a limited climate range and only under certain circumstances.
   - By which processes and under which circumstance are shrub mounds formed in Sayeret Shaked?
   - Can LAPSUS be used to simulate shrub mound formation in Sayeret Shaked, thereby proving its functionality as a landscape dynamics model?

4. Unravel the phases of aggradation and incision in the semi-arid catchment of Sayeret Shaked and clarify the influence of humans and climate fluctuations on these phases.
   - Is there a relation between amplitude of climate fluctuations and cycles of aggradation and incision?
   - What is the influence of human occupation on these cycles and what are the consequences for the future?

5. Simulate the infill history of Sayeret Shaked and quantify the effects of climate fluctuations and human influence, divided in pastoralism and rainfed agricultural, on aggradation and incision.
   - Is LAPSUS able to simulate the history of the valley fill, with emphasis of spatial and temporal quality?
   - Which processes have to be included to reconstruct the history of Sayeret Shaked?
   - If land use is important, which land use type has the most influence?

## 1.5 Outline of the thesis

The schematic outline of the thesis is shown in figure 1.4. The thesis comprises seven chapters, including the introduction. The thesis can be separated in three parts.

*First part: System framework* In the first part, chapter 2, a statistical analysis is done of the relationships between landscape structure and vegetation in the four catchments. The landscape is described in landscape structure variables including topographical characteristics, soil depth, surface coverage of bedrock outcrops and of loose surface stones. The organisms are represented by the four functional surface cover types typical in the region: shrubs, *Asphodelus ramosus*, herbaceous plants and crusts. The relationships between functional surface cover types and the landscape structure variables are discussed, as well as the biological interactions among the functional surface types themselves. This chapter gives insight in the landscape dynamics along a precipitation gradient and provides a system framework for the remainder of the thesis.

*Second part: Model framework* The second part, chapter 3 and 4, focuses mainly on simulating the dynamics of water and sediment in the catchments. In chapter 3 a first application of LAPSUS in the Negev Desert is described. The LAPSUS model is adapted to fit the demands of an arid climate, whereby runoff is principally handled as saturation overland flow. A sensitivity analysis is executed to examine the functionality and applicability of the adapted water redistribution module. Additionally a comparison is made between water redistribution patterns in rocky and soil covered catchments under similar climate conditions with focus on landscape structure – resource interactions.
In chapter 4 the LAPSUS model is taken a step further to incorporate influence of vegetation on resource dynamics. Vegetation cover is incorporated in the water redistribution module, representing Hortonian overland flow as well. The ecosystem engineering functionality of shrubs is studied for the catchment of Sayeret Shaked. The process of shrub mound formation is simulated on a hypothetical test slope at short and long time scales (ranging from one event to hundred years). Finally the effect of climate on shrub mound formation is simulated and discussed based on scenario studies.

*Third part: Long-term application* In the last part, chapter 5 and 6, the system knowledge and modelling framework is applied at a longer time scale. In chapter 5 the aggradation and incision history of the valley fill of Sayeret Shaked is discussed, whereby the influence of climate fluctuations and human occupation on the landscape dynamics in the last 40 000 years is studied. The aggradation and incision phases are correlated to climate and human occupation records, by OSL dating and potsherds.
In chapter 6 the modelling framework of chapter 3 and 4 is used to simulate the aggradation and incision history of Sayeret Shaked between about 800 BC and 800 AD, as reconstructed in chapter 5. This enables a quantitative study to the effect of human land use on landscape dynamics and evolution.
In the final chapter, chapter 7, the main conclusions and synthesis are provided, as well as future research challenges. Additionally the results of the study are put in a broader perspective.

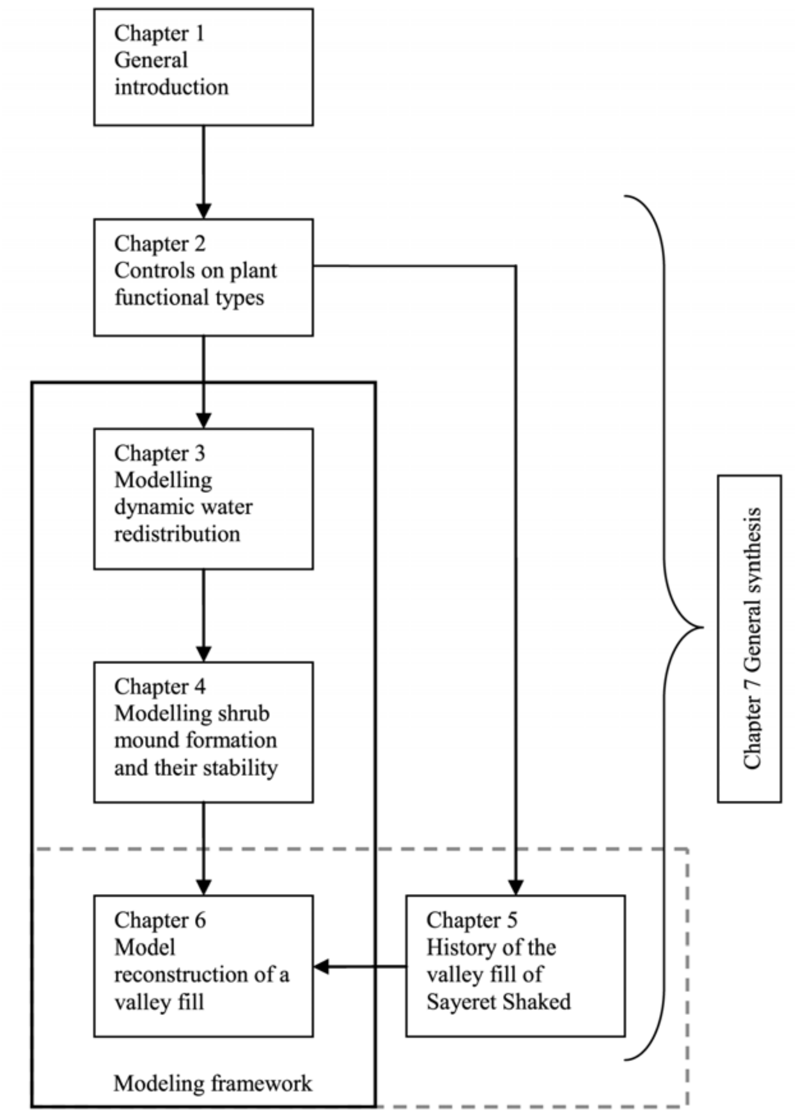


Fig. 1.4 Schematic outline of the thesis

# 2 Controls on plant functional surface cover types along a precipitation gradient

*The controls on functional surface cover types are studied in four catchments along a semi-arid to arid precipitation gradient in the northern Negev Desert of Israel. First, four functional surface cover types are selected, based on their unique functionality in terms of water use and redistribution: shrubs, Asphodelus ramosus, other herbaceous plants and surface crusts. The percentage of surface covered by these functional surface cover types is estimated, as well as of bedrock outcrops and loose surface stones. Additionally data is collected on soil depth, relative elevation, insolation, slope, profile and plan curvature, and overlain with surface cover maps. Relations between functional surface cover types and landscape structure variables are analyzed with descriptive statistics. The landscape structure variables bedrock, relative elevation, soil depth and surface stones explain most of the cover variance in the catchments. In catchments with many bedrock outcrops and surface stones, functional surface cover type is best explained by the landscape structure variables. In catchments with homogeneous soils reaching beyond the root zone, biological interactions between functional surface cover types are more important. Along the precipitation gradient the explanatory power of the biological variables decreases with decreasing precipitation, while the explanatory power of landscape structure variables appears unrelated. Only in homogeneous semi-arid catchments can regular vegetation patterns develop, in arid and heterogeneous catchments irregular vegetation patterns dominate.*

Based on: E. Buis, A. Veldkamp, B. Boeken, and N. van Breemen. Controls on plant functional surface cover types along a precipitation gradient in the Negev Desert of Israel. Under revision for Journal of Arid Environments.

## 2.1 Introduction

Many semi-arid and arid areas around the world are covered by patchy vegetation (Aguiar and Sala, 1999). These patches can form patterns like spots, stripes and labyrinths (Rietkerk et al., 2004). Previously research often focussed on regular vegetation patterns, which are typically formed on flat or smoothly sloping lands with homogeneous soils (Gilad et al., 2004; Valentin et al., 1999). Feedbacks between vegetation cover and water results in formation of regular vegetation patterns, often reflected in a shrub – crust landscape (HilleRisLambers et al., 2001; Von Hardenberg et al., 2001). In these landscapes water, sediments and nutrients are redistributed from the crust surfaces to the shrubs (Bhark and Small, 2003; Schlesinger and Pilmanis, 1998; Shachak et al., 1998). Irregular vegetation patterns are rarely studied, although they cover large parts of the semi-arid and arid world and occur frequently in the Negev Desert of Israel as well (Van de Koppel and Rietkerk, 2004). Little knowledge exists about the controls governing the position of vegetation in these irregular patterns. Obviously water availability and redistribution are very important (Burke et al., 1998; Von Hardenberg et al., 2001). Different types of surface cover, e.g. shrubs or crusts, influence water redistribution differently by the variations in infiltration rate between these types. It results in redistribution of water, like in shrub – crust landscapes (Schlesinger and Pilmanis, 1998). Landscape structure, reflected in topography of the area, bedrock outcrops and soil depth, influences runoff formation by the position and occurrence of bedrock outcrops, and influences runoff direction and speed by the slope and curvature of the area (Yair and Kossovsky, 2002). This influences water redistribution and availability, and promotes patterns of moist and dry positions (Kutiel et al., 1998). As water scarcity hinders vegetation occurrence, in dryer climates vegetation occurrence is less controlled by biological interactions. This is confirmed by modelling studies indicating that no patterns are formed in arid areas, as vegetation is barely able to maintain itself (Van de Koppel and Rietkerk, 2004; Von Hardenberg et al., 2001). Therefore we hypothesize that in drier ecosystems the position of vegetation is dominantly controlled by water redistribution caused by landscape structure instead of by biological interactions.

In semi-arid and arid regions water availability and redistribution processes operate dominantly at the surface. The surface area can be divided in several surface covers, based on difference in functionality in relation to water use and redistribution in the landscape. Two surface covers, bedrock outcrop and loose surface stones, are considered part of the landscape structure of the catchments. Bedrock outcrops promote water availability downslope (Yair, 1990). Loose surface stones have varying controls on ecosystem functioning (Poesen and Lavee, 1994). They can enhance infiltration, porosity by mulching, improve micro-climate and protect seedlings from herbivores. Contrarily they can decrease infiltration, increase water redistribution, increase erosion, increase temperature and cover the rootable soil by desert pavement (Brakensiek and Rawls, 1994; Cerda, 2001; Kutiel et al., 1998; Mandal et al., 2005; Wood et al., 2005). The functioning of the loose surface stones in the ecosystem seems to depend on the cover density and position on top of, or inserted in, the soil surface (Cerda, 2001; Poesen and Lavee, 1994). Determination of position of loose surface stones in the studied catchments, requiring very detailed surveys, was to time consuming for the spatial extent of this study. The biological surface covers are divided in functional surface cover types; groups of organisms with similar ecology, instead of similar taxonomy (Wilson, 1999). These functional surface cover types regulate or are regulated by ecosystem processes and have different functions within the ecosystem (Walker, 1992; Walker, 1995). Grouping of species to a functional surface cover type is based on morphological and physiological attributes and similar functionality of species in the studied ecosystem (Hawkins and MacMahon, 1989). In our study we distinguished four functional surface cover types: 1) shrubs, 2) *Asphodelus ramosus* (Miller, Liliaceae), 3) (other) herbaceous plants and 4) surface crusts. These functional surface cover types were distinguished based on their water use and redistribution functionality. It resulted in a differentiation based on rooting depth and type, influencing porosity and infiltration rate of the soil, and on longevity of the organisms, which is of relevance for long-term landscape processes. 1) Shrubs grow slowly and can reach ages of a few hundred years (Evenari et al., 1982b). Shrubs have fine roots and tend to root deeply (Schreiber et al., 1995). 2) *Asphodelus ramosus* is a Mediterranean perennial geophyte, which can reach ages up to nine years (Diaz Lifante, 1996). It has thick tuber-like roots (up to 1.5 cm diameter), which tend to grow laterally as well as in length, and grow within the first 15 cm of the soil in big clumps (Sawidis et al., 2005). 3) Herbaceous plants are composed of annuals and non-woody perennials (hemicryptophytes and geophytes), excluding *Asphodelus ramosus* (Boeken and Shachak, 1994). Herbaceous plants live up to a few years. The fine roots are mostly concentrated in the upper parts of the soil. 4) Surface crusts occur in the studied catchments predominantly as flat biological crust (cyanobacteria (*Microcoleus vaginatus* and *Nostoc* species), mosses and/or lichens) with patches of physical crust on disturbed positions (Belnap, 2003; Eldridge et al., 2000; Zaady et al., 1998).

This study focuses on irregular vegetation patterns and aims to increase our knowledge on the controls governing position of functional surface cover types in these areas. Therefore four catchments are selected in the northern Negev Desert of Israel along a semi-arid to arid precipitation gradient; namely Lehavim, Sayeret Shaked, Halluqim and Avdat (Fig. 1.2 and §1.3.2). This enables me to study the controls both at catchment scale and compare it over the precipitation gradient.

# 2.2 Material and methods

*2.2.1 Data collection*

Data was collected during fieldwork done in February and March 2005 at the end of the rainy season (Table 2.1). The year 2005 was relatively wet in the northern catchments (e.g. Sayeret Shaked received 334 mm instead of 200 mm average), while the southern catchments received less than average (e.g. Halluqim received 71 mm instead of 93 mm). Surface cover maps of the catchments were made by visually subdividing the catchments in observation units (of varying size) with similar surface coverage, with initial focus on bedrock outcrop and shrub cover. Per observation unit, visual estimates were made of the percentage surface cover of the surface covered by bedrock outcrop, loose stones on the surface, shrubs, *Asphodelus ramosus*, herbaceous plants and crusts. Afterwards the observation units were digitized in density maps for each surface cover type. DEM’s were made based on digitized topographical maps of 1:4500 to 1:20 000 depending on availability (ESRI© ArcMap™ 9.2). Additionally a 1:1000 hand measured elevation map was used for Sayeret Shaked. Maps of relative elevation (elevation minus lowest elevation in the catchment), slope, plan curvature, profile curvature and aspect were extracted out of the digital elevation models. The plan curvature measures the curvature of the surface perpendicular to the maximum slope direction and influences convergence (negative values) and divergence (positive values) of runoff. The profile curvature represents the rate of change of slope for each cell in the direction of slope. It affects the acceleration (negative values) and deceleration (positive values) of runoff (Claessens et al., 2006; Wilson and Gallant, 2000). Aspect was derived by calculating the direction of maximum rate of change in elevation per grid cell and is expressed in positive degrees from 0 – 359.9 degrees, measured clockwise from the north. Aspect was transformed to insolation by recalculation to a north - south scale (180° instead of 360°), whereby eastern slopes and western slopes received the same value. Soil depth was measured by auguring or digging at randomly chosen points, for which GPS coordinates were recorded (UTM). Data was extracted out of the maps at the topographical position of the soil depth measurements to enable statistical comparison of spot and spatial data sets.

*2.2.2 Data analysis*

First, the collected data per catchment was analysed with descriptive statistics. Second, factor analyses was used to detect and describe underlying structures between the variables in the data, using principal component extraction with varimax rotation with Kaizer normalization (Lesschen et al., 2005). Only variables with a factor loading > 0.590 in the rotated component matrix were used for the data interpretation. Third, linear regressions using manual variable selection were made for each functional surface cover type to investigate the strength of the relationship between the functional surface cover type and the independent variables. Collinearity diagnostics were used to test independency of variables (VIF < 1). F-statistics ($P \leq 0.075$) were used to evaluate the significance of additional variables to the regression model. Where needed, data was transformed to obtain a normal frequency distribution. For the surface cover data (percentage) an angular transformation was used to improve normal distribution (Sokal and Rohlf, 1995). All statistical analyses were performed in SPSS (© SPSS Inc.). The precipitation was recalculated to precipitation per available soil surface (mm / available soil surface). This value gives a better indication of available water for cover types than normal precipitation, as it corrects for the large water redistribution from bedrock outcrops (Kutiel et al., 1998; Yair, 1992b).

### *2.2.3 Infiltration capacity measurements*

Infiltration capacity was measured for shrubs, *Asphodelus ramosus*, herbaceous plants and crust, using a single ring infiltrometer (FAO guidelines, Walker, 1989). This was only done in Sayeret Shaked, as here deep homogeneous soils (0.81 ± s.e. 0.08 m) and all four functional surface cover types were found. Per functional surface cover type five replicas were done, which were used to compile an average infiltration capacity curve by estimating a power function regression curve.

Table 2.1 Mean ± standard error of all variables per catchment

| **Area** | **Lehavim** | **Sayeret Shaked** | **Halluqim** | **Avdat** |
|---|---|---|---|---|
| **Precipitation/available soil surface** | 328 mm | 202 mm | 161 mm | 93 mm |
| **Variable** | n = 35 | n = 115 | n = 30 | n = 135 |
| Shrub cover (%)# | 14.4 ± 1.36 | 18.94 ± 1.41 | 8.8 ± 0.62 | 14.19 ± 0.73 |
| Asphodel cover (%)# | 10.8 ± 1.11 | 7.61 ± 0.77 | 0.4 ± 0.24 | - |
| Herbaceous plant cover (%)# | 27.8 ± 3.31 | 35.64 ± 1.82 | 11.03 ± 2.46 | 8.24 ± 0.59 |
| Crust cover (%)# | 18.14 ± 1.57 | 29.96 ± 1.87 | 15.20 ± 2.23 | 33.04 ± 1.25 |
| Surface stone cover (%)* | 14.26 ± 0.88 | 7.04 ± 0.71 | 22.23 ± 3.60 | 37.60 ± 1.46 |
| Bedrock outcrop cover (%)* | 14.6 ± 1.82 | 0.80 ± 0.51 | 42.33 ± 6.33 | 6.61 ± 0.97 |
| Soil depth (m)* | 0.23 ± 0.06 | 0.81 ± 0.08 | 0.11 ± 0.03 | 0.25 ± 0.02 |
| Relative elevation (m)* | 31.47 ± 2.80 | 10.62 ± 0.44 | 18.44 ± 2.56 | 14.53 ± 0.97 |
| Slope (°)* | 10.56 ± 0.53 | 4.09 ± 0.21 | 10.86 ± 0.76 | 6.01 ± 0.41 |
| Plan curvature ($m^{-1}$)* | -0.14 ± 0.06 | 0.03 ± 0.03 | -0.13 ± 0.23 | 0.06 ± 0.03 |
| Profile curvature ($m^{-1}$)* | -0.01 ± 0.09 | 0.01 ± 0.03 | 0.17 ± 0.12 | 0.01 ± 0.04 |
| Insolation (°)* | 141.13 ± 22.09 | 68.94 ± 4.74 | 80.80 ± 8.21 | 65.76 ± 2.96 |

** Landscape structure variables, # biological variables*

# 2.3 Results & discussion

*2.3.1 Functional surface cover types*

*Distinction of functional surface cover types*

The four functional surface cover types vary strongly in infiltration capacity and water redistribution properties (Fig. 2.1). *Asphodelus ramosus* causes a high infiltration capacity, while crusts cause a low infiltration capacity. Infiltration capacities beneath shrubs and herbaceous plants have intermediate values. The high infiltration capacity near *Asphodelus ramosus* is caused by laterally growing roots causing upheaval of the soil (up to 5.75 ± 0.81 cm, n = 8), causing all direct rainfall to infiltrate immediately. Also shrubs and herbaceous plants tend to increase soil porosity by rooting and to enhance biological activity (Angers and Caron, 1998). Although most precipitation infiltrates underneath shrubs and herbaceous plants, runoff can form during more extreme events. Of these four functional surface cover types only crusts decrease infiltration capacity and increase runoff (Eldridge et al., 2002). Therefore crusts act as a source of water, sediment and nutrients, while the vegetated areas act as sinks of these resouces (Aguiar and Sala, 1999; Bhark and Small, 2003; Schlesinger and Pilmanis, 1998; Shachak et al., 1999). Especially below the long-living shrubs, these source – sink relations result in concentration of sediments below the shrub canopy, which can cause formation of small raised mounds (Shachak and Lovett, 1998). Herbaceous plants do not form mounds, because they occupy different positions each year (Kutiel et al., 1995). So these four functional surface cover types play different roles in the redistribution of resources across the landscape.

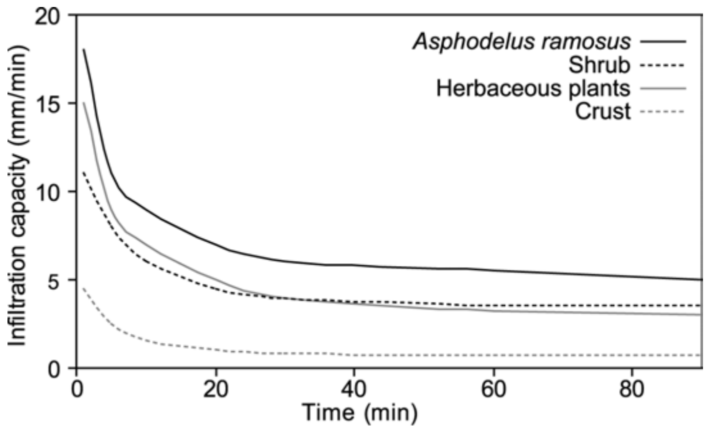


Fig. 2.1 Average infiltration capacity curves (mm $min^{-1}$) for four functional surface cover types.

*The functional surface cover types along a precipitation gradient*

The surface cover of the four catchments grades from a high vegetation cover in the wet north to a low vegetation cover in the dry south (Table 2.1 and Fig. 2.2). In the wetter catchments (Lehavim and Sayeret Shaked) *Asphodelus ramosus* and other herbaceous plants are more common than in the dryer catchments (Halluqim and Avdat). In the dry catchments in the South, *Asphodelus ramosus*, a Mediterranean species, occurs only where additional water is supplied by runoff from bedrock outcrops higher on the slope. This situation occurs in Halluqim (Yair, 1992b), but *Asphodelus ramosus* is lacking in the equally dry but less rocky catchment of Avdat. The herbaceous plant cover is reduced in the dryer catchments as well, even though the species differ along the precipitation gradient (Kutiel et al., 1995). Remarkably, the percentage of shrub cover appears unconnected to precipitation. This might be related to a change in dominant shrub species along the precipitation gradient, enabling the functional surface cover type shrub to maintain its cover percentage (Shem-Tov et al., 1999). The percentages of bedrock outcrop, surface stones and crusts decrease with increasing precipitation (Table 2.1 and Fig. 2.2).

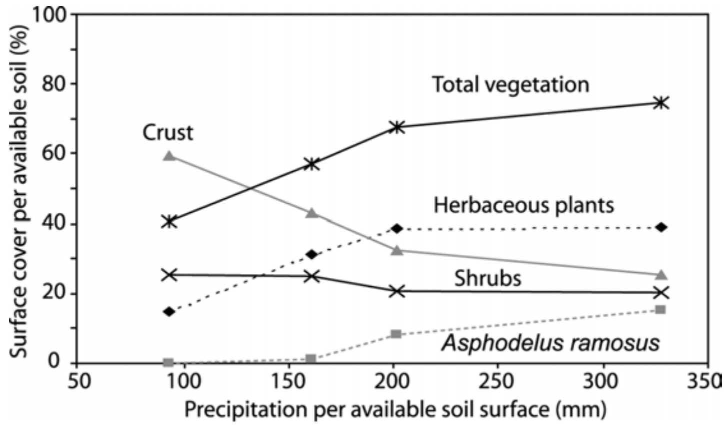


Fig. 2.2 The relation between precipitation per available soil surface (mm) and surface cover of functional surface cover types per available soil (%) is given for four functional surface cover types and total vegetation cover.

*2.3.2 Analyses of functional surface cover types at catchment scale*

*Factor analysis*

The factor analysis of all catchments results in four or five significant factors explaining between 66.4 and 84.2% of the total variance (Table 2.2). Communalities of the variables are given in the appendix. In Lehavim five significant factors explain 84.2% of the total variance.

Table 2.2 Results of factor analysis of each studied catchment. Only variables with a significant factor loading > 0.590 are shown

| **Catchment:** | **Lehavim** | | **Sayeret Shaked** | |
|---|---|---|---|---|
| **Explained variance** | 84.2% | | 66.4% | |
| Factor 1 | Explained variance 20.3% | Factor loading | Explained variance 20.7% | Factor loading |
| | Herbaceous plants | -0.896 | Soil depth | -0.782 |
| | Bedrock | 0.825 | Herbaceous plants | -0.740 |
| | Plan curvature | 0.742 | Insolation | 0.709 |
| | | | Surface stones | 0.696 |
| Factor 2 | Explained variance 20.0% | Factor loading | Explained variance 20.5% | Factor loading |
| | Surface stone | 0.935 | Crust | 0.843 |
| | Insolation | 0.838 | Shrub | -0.738 |
| | Shrub | -0.792 | Profile curvature | -0.717 |
| Factor 3 | Explained variance 16.1% | Factor loading | Explained variance 15.4% | Factor loading |
| | Relative elevation | -0.887 | Relative elevation | -0.771 |
| | Profile curvature | 0.882 | Slope | 0.762 |
| | | | Asphodel | -0.662 |
| Factor 4 | Explained variance 15.4% | Factor loading | Explained variance 9.8% | Factor loading |
| | Asphodel | 0.824 | Bedrock | -0.910 |
| | Slope | 0.723 | | |
| | Soil depth | 0.598 | | |
| Factor 5 | Explained variance 12.4% | Factor loading | | |
| | Crust | -0.964 | | |

The factors can be interpreted as: 1) a herbaceous plant versus bedrock / plan curvature factor, 2) a shrub versus surface stone / insolation factor, 3) a relative elevation versus profile curvature factor, 4) an *Asphodelus ramosus* / slope / soil depth factor and 5) a single crust factor, suggesting that crusts have no association with any of the included variables in Lehavim. The four functional surface cover types are described in separate factors. In Sayeret Shaked four significant factors explain 66.4% of the total variance. The factors can be interpreted as: 1) a herbaceous plants / soil depth versus surface stones / insolation factor, 2) a crust versus shrub / profile curvature factor, 3) an *Asphodelus ramosus* / relative elevation versus slope factor and a single bedrock factor. Crust and shrubs are related. In Halluqim the four significant factors, which explain 77.3% of the total variance, can be interpreted as: 1) a crust / surface stones / soil

Table 2.2 Continued

| **Catchment:** | **Halluqim** | | **Avdat** | |
|---|---|---|---|---|
| **Explained variance** | 77.3% | | 70.7 | |
| Factor 1 | Explained variance 25.2% | Factor loading | Explained variance 23.7% | Factor loading |
| | Surface stones | 0.791 | Slope | 0.845 |
| | Crust | 0.739 | Relative elevation | 0.775 |
| | Bedrock | -0.729 | Bedrock | 0.740 |
| | Soil depth | 0.695 | | |
| | Relative elevation | -0.602 | | |
| Factor 2 | Explained variance 17.6% | Factor loading | Explained variance 19.1% | Factor loading |
| | Profile curvature | 0.846 | Surface stone | -0.924 |
| | Plan curvature | -0.839 | Herbaceous plants | 0.806 |
| Factor 3 | Explained variance 17.3% | Factor loading | Explained variance 15.8% | Factor loading |
| | Insolation | 0.835 | Profile curvature | 0.807 |
| | Shrub | 0.646 | Plan curvature | -0.784 |
| | Slope | -0.594 | | |
| Factor 4 | Explained variance 17.2% | Factor loading | Explained variance 12.1% | Factor loading |
| | Herbaceous plants | 0.868 | Shrub | 0.836 |
| | Soil depth | 0.612 | | |
| | Bedrock | -0.596 | | |

depth versus bedrock and relative elevation factor, 2) a profile curvature versus plan curvature factor, 3) a shrub / insolation versus slope factor and 4) a herbaceous plants / soil depth versus bedrock factor. *Asphodelus ramosus* occur only at 6 out of 30 measurement points and does not significantly explain any of the total variance in the catchment. Both crust and herbaceous plants are associated with bedrock and soil depth. In Avdat four significant factors explain 70.7% of the total variance. The factors can be interpreted as: 1) a bedrock / slope / relative elevation factor, 2) a herbaceous plants versus surface stone factor, 3) a plan curvature versus profile curvature factor and 4) a single shrub factor, suggesting independence of shrubs to the other variables. The functional surface cover type crust appear to have no explaining variance in the catchment. All plant functional surface cover types are described in separate factors.

The factor analysis demonstrates a large difference in explained variance per functional surface cover type and variable contribution among the catchments (Table 2.2). The factors including the plant functional surface cover types, explain less variance with decreasing precipitation. The explained variance of the landscape structure variables and crusts increases with decreasing precipitation. Only in Sayeret Shaked two functional surface cover types appear related (crust and shrub). This relationship seems reflected in the shrub – crust landscape in Sayeret Shaked, and results from interacting processes between the two functional surface cover types (Shachak et al., 1998). In Halluqim crust and herbaceous plants are both associated with bedrock and soil depth. This connection can be explained by the high percentage of bedrock at the surface (42.33 ± 6.33%), which strengthens the connection between the functional surface cover types. Shrubs are less influenced by these variables as shrubs can utilize the crevasses in the bedrock (Schreiber et al., 1995; Yair and Shachak, 1982). The factor analysis demonstrates that the occurrence of the functional surface cover types could be best explained by a unique set of variables in each catchment. It reflects the uniqueness of each of the catchments in structure and pattern of topography, soil depth and surface characteristics.

*Regression models*

In Lehavim the regression analyses demonstrates that the four functional surface cover types can be explained well by the landscape structure variables (Table 2.3). Shrubs are related to surface stones and bedrock ($R^2$ = 0.67). *Asphodelus ramosus* plants are mainly related to soil depth ($R^2$ = 0.24). Herbaceous plants are related to soil depth, bedrock and slope at a $R^2$ of 0.82, while crusts are related to soil depth as well ($R^2$ = 0.65). Soil depth explains most of the variance in Lehavim. Soil depth has a positive effect on herbaceous plants. Deeper soils have a higher water storage capacity and resources availability, which stimulates herbaceous plant grow during wet years. *Asphodelus ramosus* and crusts have a negative relation with soil depth. These negative relationships might be (partly) related to the indirect effect of the negative relationship between herbaceous plants and soil depth, as both *Asphodelus ramosus* and crusts have a negative relation with herbaceous plants.

Table 2.3 Regression model of Lehavim for three functional surface types ([a] significant at 0.01 level)

| | Landscape structure variables | | | Biological variables | | |
|---|---|---|---|---|---|---|
| **Functional surface type** | **$R^2$** | **Variables** | **Std. β** | **$R^2$** | **Variables** | **Std. β** |
| Shrub | 0.67[a] | Surface stone | -0.743[a] | 0.34[a] | Asphodel | 0.584[a] |
| | | Bedrock | 0.354[a] | | | |
| Asphodel | 0.24[a] | Soil depth | -0.491[a] | 0.53[a] | Herbaceous plant | -0.729[a] |
| Herbaceous plant | 0.82[a] | Soil depth | 0.547[a] | 0.70[a] | Crust | -0.482[a] |
| | | Bedrock | -0.458[a] | | Asphodel | -0.470[a] |
| | | Slope | -0.235[a] | | | |
| Crust | 0.65 [a] | Soil depth | -0.806[a] | 0.54 [a] | Herbaceous plant | -0.735[a] |

*Asphodelus ramosus* cover is better predicted by biological interactions with herbaceous plants ($R^2 = 0.53$) than by the landscape structure variables ($R^2 = 0.24$). For the other functional surface cover types the landscape structure variables explain more of the variance than the biological variables (Table 2.3).

In Sayeret Shaked the landscape structure hardly explains the variance in functional surface cover types (Table 2.4). Shrubs are related to profile curvature at a $R^2$ of 0.16. *Asphodelus ramosus* plants are related to relative elevation at a $R^2$ of only 0.11. Herbaceous plants are explained best by surface stones and bedrock ($R^2 = 0.41$) and crust by relative elevation and surface stones ($R^2 = 0.31$). Due to the deep, uniform soils and the gentle topography, water redistribution by runoff mainly depends on the presence or absence of surface crusts. Therefore the landscape structure hardly influences functional surface cover types. The most important variables in landscape structure are relative elevation and surface stone cover. Crusts have a positive relation with relative elevation and surface stones. On the higher flat areas in Sayeret Shaked circumstances are harsh for vegetation because no water is redistributed. Therefore crusts are promoted on these positions. Surface stones reduce soil volume and reduce water storage capacity and resource availability, as is reflected in the negative relation between surface stones and herbaceous plants. Also here crusts are favoured. The explained variance of the biological variables is much higher. It results in a $R^2$ of 0.66 for shrubs, a $R^2$ of 0.54 for herbaceous plants and a $R^2$ of 0.74 for crusts, whereby all other functional surface cover types influenced the value of $R^2$ (Table 2.4).

Table 2.4 Regression model of Sayeret Shaked for four functional surface types ([a] significant at 0.01 level)

| | Landscape structure variables | | | Biological variables | | |
|---|---|---|---|---|---|---|
| **Functional surface type** | **$R^2$** | **Variables** | **Std. β** | **$R^2$** | **Variables** | **Std. β** |
| Shrub | 0.16[a] | Profile curvature | 0.400[a] | 0.66[a] | Crust | -0.920[a] |
| | | | | | Herbaceous plant | -0.513[a] |
| | | | | | Asphodel | -0.373[a] |
| Asphodel* | 0.11[a] | Relative elevation | 0.330[a] | - | - | - |
| Herbaceous plant | 0.41[a] | Surface stone | -0.550[a] | 0.54[a] | Crust | -0.959[a] |
| | | Bedrock | -0.318[a] | | Shrub | -0.704[a] |
| | | | | | Asphodel | -0.428[a] |
| Crust | 0.31[a] | Relative elevation | 0.420[a] | 0.74[a] | Shrub | -0.708[a] |
| | | Surface stone | 0.345[a] | | Herbaceous plant | -0.537[a] |
| | | | | | Asphodel | -0.340[a] |

** Asphodel is unpredictable with biological variables*

Position of functional surface cover types appeared related to position of the other functional surface cover types. The strong improvement in explained variance for both shrubs and crusts are reflected in the results of the factor analysis (factor 2) and seems to represent the interactions and feedback processes between shrubs and crusts (Table 2.2) (Bhark and Small, 2003; Schlesinger and Pilmanis, 1998). No significant correlation was observed between *Asphodelus ramosus* and other cover types. These results combined with the low explaining variance of the landscape structure variables, demonstrate that occurrence of *Asphodelus ramosus* is independent of the studied landscape structure and biological variables.

In Halluqim the explanatory power of the landscape structure variables differs strongly per functional surface cover type (Table 2.5). Shrubs are related to bedrock at a $R^2$ of only 0.15. *Asphodelus ramosus* cannot be significantly related to any of the landscape structure variables, just as in the factor analysis (Table 2.2). Herbaceous plants are related to bedrock at a $R^2$ of 0.49 and crusts are related to bedrock as well at a $R^2$ of 0.75 (Table 2.5). All functional surface cover types are negatively influenced by bedrock. This must be attributed to the high percentage of bedrock at the surface, which limits the space available for plant growth (Table 2.1). The occurrence of shrubs is better explained by the crust cover ($R^2$ = 0.36), which seems to point to similar interactions as in Sayeret Shaked. Except for shrubs, landscape structure variables best explain cover types (Table 2.5).

Table 2.5 Regression model of Halluqim for three functional surface types ([a] significant at 0.01 level, [b] significant at 0.05 level)

| Functional surface type | Landscape structure variables | | | Biological variables | | |
|---|---|---|---|---|---|---|
| | $R^2$ | Variables | Std. β | $R^2$ | Variables (%) | Std. β |
| Shrub | $0.15^b$ | Bedrock | $-0.382^b$ | $0.36^a$ | Crust | $0.602^a$ |
| Asphodel* | - | - | - | - | - | - |
| Herbaceous plant | $0.49^a$ | Bedrock | $-0.700^a$ | $0.27^a$ | Crust | $0.535^a$ |
| Crust | $0.75^a$ | Bedrock | $-0.866^a$ | $0.55^a$ | Shrub<br>Herbaceous plant | $0.535^a$<br>$0.441^a$ |

** Asphodel is unpredictable with landscape structure variables and biological variables*

Also in Avdat the explanatory power of the landscape structure variables differs (Table 2.6). Shrubs can be related to surface stones, slope, bedrock and insolation at a $R^2$ of 0.23. Herbaceous plants are related to surface stones, insolation, slope and soil depth at a $R^2$ of 0.52, while crusts are related to surface stones, bedrock, slope and insolation at a $R^2$ of 0.62. Cover of surface stones is the most important explaining variable for all functional surface cover types and influences all types negatively. Surface stones cover 37.60 ± 1.46% of the surface in Avdat, at some positions forming a desert pavement (Table 2.1). This high surface cover influences the other surface cover types by limiting rooting space and biological interactions. In Avdat the functional surface cover types have no explanatory power mutually (Table 2.6).

Table 2.6 Regression model of Avdat for three functional surface types ([a] significant at 0.01 level)

| Functional surface type | Landscape structure variables | | | Biological variables | | |
|---|---|---|---|---|---|---|
| | **$R^2$** | **Variables** | **Std. β** | **$R^2$** | **Variables (%)** | **Std. β** |
| Shrub | 0.23[a] | Surface stone | -0.390[a] | <0.1 | - | - |
| | | Slope | 0.382[a] | | | |
| | | Bedrock | -0.243[a] | | | |
| | | Insolation | -0.229[a] | | | |
| Herbaceous plant | 0.52[a] | Surface stone | -0.593[a] | <0.1 | - | - |
| | | Insolation | -0.220[a] | | | |
| | | Slope | 0.213[a] | | | |
| | | Soil depth | 0.182[a] | | | |
| Crust | 0.62[a] | Surface stone | -0.573[a] | <0.1 | - | - |
| | | Bedrock | -0.483[a] | | | |
| | | Slope | -0.207[a] | | | |
| | | Insolation | 0.197[a] | | | |

*2.3.3 Controls on functional surface cover types at catchment scale*

The landscape structure variables explain most of the cover variance in Lehavim, and the least in Sayeret Shaked (Table 2.3 – 2.6 and Fig. 2.3). The variables with the highest predictive power for the catchments are soil depth (Lehavim), bedrock (Halluqim) and surface stones (Sayeret Shaked and Avdat). The topographical variables, like relative elevation, insolation and profile curvature, appear of less relevance for the functional surface cover types at catchment scale. These variables influence water availability by influencing water redistribution (slope, plan curvature and relative elevation) or evaporation (insolation). However, although I expected that water availability is of high influence for plant functional surface cover types in these (semi) desert environments (Boeken et al., 1995), the previously mentioned variables are not important at catchment scale as they describe mainly catchment wide processes of water redistribution and availability. Earlier studies, field evidence and the infiltration measurements demonstrate that, as runoff infiltrated quickly on the soil covered slopes, water redistribution is often a local process instead of a slope or catchment wide process (Kutiel et al., 1998; Yair and Kossovsky, 2002). These local water redistribution processes are mainly influenced by surface characteristics, as bedrock outcrops, surface stones and soil depth, which therefore have the highest explanatory power (Yair and Shachak, 1982). *Asphodelus ramosus* cover is in all catchments (almost) impossible to predict by landscape structure variables, partly because of lack of observations. Water availability is very important for *Asphodelus ramosus*, as is reflected in the cover percentage of *Asphodelus ramosus* along the precipitation gradient (Table 2.1 and Fig. 2.2). Different processes are of relevance for *Asphodelus ramosus* in the different catchments and no overall relations can be distinguished.

The biological variables have the highest explanatory power in Sayeret Shaked and the lowest in Avdat (Table 2.3 – 2.6 and Fig. 2.3). Overall the biological variables explains less than the landscape structure variables in Lehavim, Halluqim and Avdat. Only in Sayeret Shaked this is the opposite. Sayeret Shaked has homogeneous surface characteristics and deep soils reaching beyond the rooting zone of shrubs (Schreiber et al., 1995). Water redistribution is limited to infiltration – runoff interactions between functional surface cover types. Therefore biological interactions are more important than the landscape structure. In the wetter catchments all functional surface cover types appear to influence each other, while in Halluqim only crusts appear to influence the other plant functional surface cover types. The lower vegetation cover in Halluqim appears to limit biological interactions between plant functional surface cover types, while the relative large cover of crusts increased its importance (Fig. 2.2).

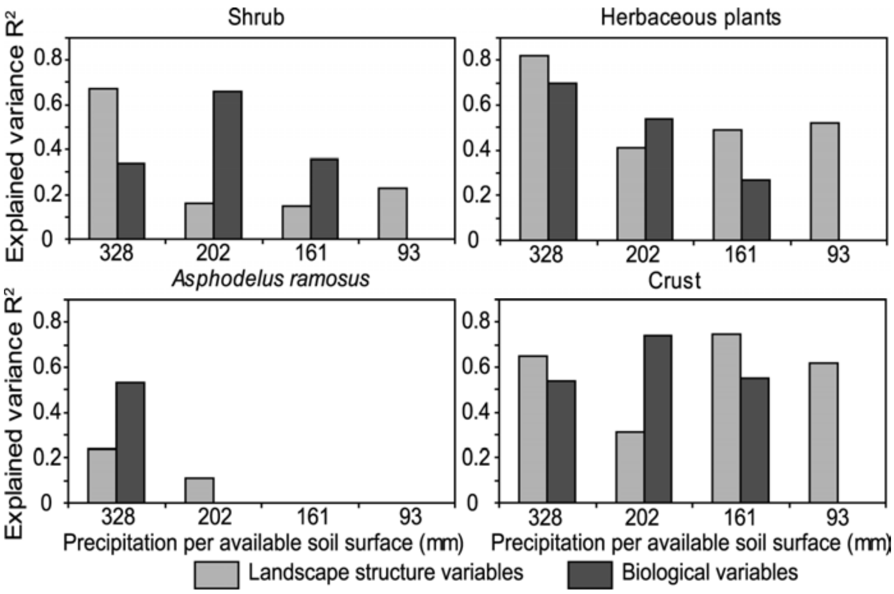


Fig. 2.3 Explained variance $R^2$ of functional surface cover types by landscape structure variables and by biological variables along the precipitation gradient (mm / available soil surface). Lehavim (328 mm), Sayeret Shaked (202 mm), Halluqim (161 mm) and Avdat (93 mm).

### *2.3.4 Controls on functional surface cover types along a precipitation gradient*

For occurrence of shrubs, herbaceous plants and *Asphodelus ramosus* the explained variance of the factor analyses decreases with decreasing precipitation (Table 2.2). In the regressions the explained cover variance of the functional surface cover types is lower in the dryer catchments as well (Fig. 2.3). Here cover of the plant functional surface cover types is less (Fig. 2.2) (Kutiel et al., 1995). A strong positive relationship between explained variance of the biological variables and the total vegetation cover per available soil surface (shrubs ($R^2$ = 0.56), herbaceous plants ($R^2$ = 0.99) and crusts ($R^2$ = 0.72)), explains the reduction in explained variance by the reducing vegetation cover (Fig. 2.2 and 2.3). Biological variables best explain the occurrence of shrub and crust cover in Sayeret Shaked. The occurrence of herbaceous plants and *Asphodelus ramosus* increases with increasing precipitation. These observations illustrate the difference in characteristics and functionality of the functional surface cover types. In the wetter catchments plants of the cover types appear to encounter more competition, while in the dryer catchments resource stress controls the occurrence and position of the cover types more (Kutiel et al., 1998; Kutiel et al., 1995). In catchments with less vegetation cover, less interactions between plants occur. It demonstrates that in wetter catchments the functional surface cover types, and especially the plant functional surface cover types, interact.

The explained variance of the landscape structure variables is independent of precipitation, as is expected (Fig. 2.3). But it strongly depends on bedrock cover, which emphasized the dominance of local water redistribution processes for the occurrence of the functional surface cover types (Fig. 2.4). For Lehavim, Sayeret Shaked and Avdat a strong relationship exists between bedrock outcrops in the catchment and explained variance of the landscape structure variables ($R^2$ of 0.91 for shrubs, a $R^2$ of 0.97 for herbaceous plants and a $R^2$ of 0.74 for crusts). When Halluqim is included in the analyses the relationships with shrubs and herbaceous plants result in a $R^2$ of 0.01 or less, while crust give a $R^2$ of 0.60. Apparently if 47% of the surface is covered by bedrock outcrops rooting is hampered and use of redistributed water inefficient, strongly decreasing the explained variance. Between surface stone cover and the explained variance of the landscape structure variables no relationship can be found, except a weak relation with crusts ($R^2$ = 0.32). There is however a strong negative relation between the explained variance of the biological variables and surface stone cover ($R^2$ between 0.80 and 0.91 for the functional surface cover types). This is probably caused by the obstructing effect of surface stone on the interactions between functional surface cover types. A strong negative relationship between soil depth and the explained variance of the landscape structure variables for crust ($R^2$ = 0.99), demonstrates that in soils reaching beyond the root zone only biological interactions influenced water redistribution and by that crust occurrence. The landscape structure variables are therefore much less relevant.

Relative elevation has a positive relationship with explained variance of the landscape variables ($R^2$ of 0.85 for shrub, $R^2$ of 0.94 for herbaceous plants and $R^2$ of 0.31 for crust). It describes catchment topography and influenced catchment wide processes of water redistribution, which are relevant for shrubs and herbaceous plants.

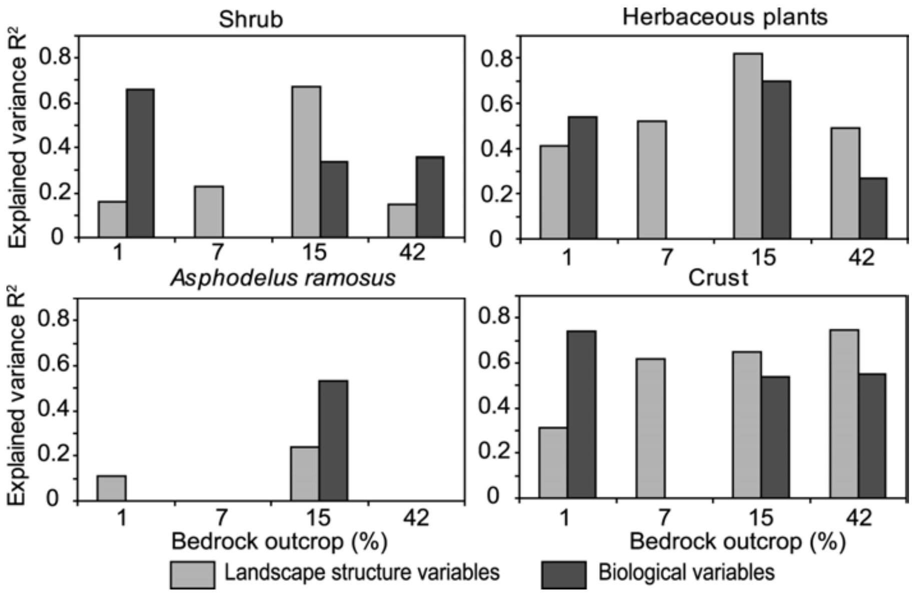


Fig. 2.4 Explained variance $R^2$ of functional surface cover types by landscape structure variables and by biological variables in relation to bedrock (%). Sayeret Shaked (1%), Avdat (7%), Lehavim (15%) and Halluqim (42%).

In the dryer catchments (< 200 mm precipitation per available soil annually) biological interactions are strongly reduced by the low vegetation cover (Fig. 2.2 and 2.3). The lack of biological interactions restricts formation of regular vegetation patterns, and the vegetation cover is dominantly influenced by the landscape structure. In the wetter catchments (> 200 mm precipitation per available soil annually), on the other hand, vegetation occurrence can be influenced by both biological interactions and landscape structure. Regular vegetation patterns caused by biologically induced redistribution of water, appear only in catchments with a homogeneous surface characteristics and with soils deeper than the average root zone. In heterogeneous catchments with an alternation of bedrock outcrops and soil patches, the landscape structure dominates the vegetation patterns via water redistribution (Kutiel et al., 1998). This effect of bedrock outcrops is already clear at 1% bedrock cover (Fig. 2.4), and is strongest at a bedrock cover of approximately 15%. At still higher percentages of bedrock cover, this effect is less evident as the plant growth is limited by limitations for rooting and use of the redistributed water is inefficient. In heterogeneous catchments vegetation patterns become irregular. Areas with such irregular vegetation patterns occupy large parts of the semi-arid and arid world, because of the common occurrence of bedrock outcrops and shallow soils. Most model studies of vegetation patterns focus only on the homogeneous areas. Addition of landscape structure in these models could improve the applicability and might enable simulations of irregular vegetation patterns.

## 2.4 Conclusions

In each catchment the landscape structure has a unique effect on the functional surface cover types. In Lehavim the occurrence of the functional surface cover types is best described by soil depth, in Sayeret Shaked by relative elevation and surface stone cover, in Halluqim by bedrock cover and in Avdat by surface stone cover as well. These variables influence the redistribution of water over the land surface and therefore the occurrence of vegetation and crusts. In catchments with more bedrock at the surface, the occurrence of the functional surface cover types is best predicted by the landscape structure variables. Only in a homogeneous catchment with soils reaching beyond the root zone biological interactions appear more relevant for the occurrence of functional surface cover types. Along the precipitation gradient the cover of herbaceous plants and *Asphodelus ramosus* reduces with decreasing precipitation. The functional surface cover types can be less well explained by the biological variables in dryer catchments as well. The explanatory power of the landscape structure variables appears unrelated to precipitation, but strongly increases with increasing surface cover of bedrock outcrops. In heterogeneous or arid catchments irregular vegetation patterns are formed, as the landscape structure governs water redistribution and occurrence of functional surface cover types. Only in homogeneous semi-arid catchments biological interactions are strong enough to develop regular vegetation patterns.

# Appendix chapter 2

Communalities of variables in the factor analyzes

| Variable | Unit | Lehavim | Sayeret Shaked | Halluqim | Avdat |
|---|---|---|---|---|---|
| Asphodelus ramosus cover | % | 0.787 | 0.654 | 0.639 | - |
| Bedrock outcrop cover | % | 0.899 | 0.859 | 0.965 | 0.706 |
| Crust cover | % | 0.945 | 0.746 | 0.858 | 0.795 |
| Herbaceous plant cover | % | 0.913 | 0.663 | 0.840 | 0.745 |
| Insolation | ° | 0.902 | 0.604 | 0.704 | 0.737 |
| Loose surface stone cover | % | 0.889 | 0.659 | 0.667 | 0.855 |
| Plan curvature | $m^{-1}$ | 0.673 | 0.409 | 0.839 | 0.878 |
| Profile curvature | $m^{-1}$ | 0.849 | 0.537 | 0.796 | 0.663 |
| Relative elevation | m | 0.828 | 0.788 | 0.629 | 0.777 |
| Shrub cover | % | 0.891 | 0.723 | 0.672 | 0.772 |
| Slope | ° | 0.680 | 0.677 | 0.755 | 0.750 |
| Soil depth | m | 0.802 | 0.647 | 0.914 | 0.303 |

# 3 Modelling dynamic water redistribution patterns

*In arid climate regions redistribution of runoff water is very important for vegetation development. The process of water redistribution at catchment scale is studied with the landscape evolution and erosion model LAPSUS. LAPSUS, formerly applied in Mediterranean climates, is modified to deal with the arid climate of the Northern Negev Desert of Israel. Daily model runs are used instead of yearly model runs, and the infiltration module is adapted to better represent the spatial diversity in water availability in an arid catchment. The model is calibrated for two small catchments in the Negev Desert of Israel, Halluqim and Avdat. First, a sensitivity analysis of the modified LAPSUS was done. Especially pore volume of the soil appears to have a strong influence on the modelling results. Second, the capability of LAPSUS to deal with varying surface characteristics was assessed by comparing the water redistribution patterns in the two catchments with field data. Simulation results demonstrate that the catchments respond very different to precipitation. Water redistribution is larger in the dominantly bedrock covered Halluqim compared to the dominantly sediment covered catchment of Avdat. Consequently, Halluqim has more positions with water accumulation than Avdat, and can sustain a larger vegetation cover including Mediterranean species. Finally the modelled infiltration patterns are spatially compared with vegetation cover in the catchments. The results indicate that there is a broad agreement between infiltration and vegetation patterns, but locally there is a strong mismatch indicating that part of the involved processes are still missing in the model.*

Based on: E. Buis and A. Veldkamp, 2008. Modelling dynamic water redistribution patterns in arid catchments in the Negev Desert of Israel. Earth Surface Processes and Landforms 33, 107-122. DOI: 10.1002/esp.1531. ® Wiley.

# 3.1 Introduction

Many landscape evolution models simulate water erosion and sedimentation processes based on water redistribution (De Roo and Jetten, 1999; Morgan et al., 1998; Sun et al., 2002). A good representation of water redistribution processes and patterns is therefore essential. However, most of these models are validated by means of total sediment production and/or total discharge of a plot, slope or catchment and not on spatial water redistribution patterns (De Roo and Jetten, 1999; Morgan et al., 1998; Sun et al., 2002). As such spatial water redistribution is often underexposed in model studies. This chapter focuses on these water redistribution processes and patterns only.

Water is redistributed when runoff is generated. Locations with low infiltration rate and low water storage capacity are potential sources for runoff whereas locations with higher infiltration rates and a larger water storage capacity are potential sinks for water (Janeau et al., 1999; Lyford and Qashu, 1969; Schlesinger and Pilmanis, 1998). In arid areas with a homogeneous soil cover local redistribution of water occurs dominantly by shrub – crust interactions. Crusts enhance runoff production by reducing infiltration rate (Hortonian overland flow), while shrubs collect runoff water because of a higher infiltration rate (Boeken and Shachak, 1994; Eldridge et al., 2000; Schlesinger and Pilmanis, 1998). However, many desert regions in the world, including the Negev Desert of Israel, are dominantly rocky deserts where large patches of bedrock occur at the surface. In these areas redistribution of water occurs mainly by runoff from bedrock covered areas. These bedrock surfaces are practically impermeable for water and produce runoff even at very low precipitation intensities (Yair and Kossovsky, 2002). The additional runon infiltrates in neighbouring down slope soil patches, as long as storage capacity of the soil is sufficient. If the maximum storage capacity is reached the runoff is further redistributed to surrounding deeper soils (saturation overland flow). By run-on soil moisture is locally increased as well as soil volume (by sedimentation of previously eroded sediments). Patterns of runoff and runon depend strongly on position and extent of the bedrock outcrops (Calvo-Cases et al., 2003). The patterns are often discontinuous as most runoff infiltrates only after a short distance, limiting water redistribution to local slopes (Fitzjohn et al., 1998; Kuhn and Yair, 2004; Lavee et al., 1998; Yair and Raz-Yassif, 2004). When bedrock cover and/or magnitude of precipitation events increase, the runoff concentrates to overland flows, which increase in duration, length and volume (Yair and Kossovsky, 2002). Catchments with more bedrock at the surface have more water redistribution and locally more available water than the average precipitation and can therefore sustain denser and more diverse vegetation (Kadmon et al., 1989; Olsvig-Whittaker et al., 1983). Annual precipitation alone is often insufficient for survival. The additional runon formed by water redistribution is essential and more relevant for vegetation development than the average precipitation quantity itself.

In this study LAPSUS is used (Claessens et al., 2005; Schoorl et al., 2000; Temme et al., 2006). It is a landscape process model, which calculates erosion and sedimentation processes at catchment scale based on water redistribution, tillage translocation and land sliding. LAPSUS includes not only erosion but also infiltration and sedimentation and changes the landscape based on the model results, while it needs only a limited amount of input data. These features make LAPSUS more suited for this research than other existing erosion models (Cerdan et al., 2001; De Roo and Jetten, 1999; Morgan et al., 1998; Peeters et al., 2006; Siepel et al., 2002; Sun et al., 2002). The calculation method for erosion and sedimentation in LAPSUS has been previously tested in several field studies of varying climates (e.g. Claessens et al., 2005; Haileslassie et al., 2005; Schoorl et al., 2006; Schoorl and Veldkamp, 2001; Schoorl et al., 2002). The results indicate that LAPSUS is well capable of modelling erosion and sedimentation processes in short and long-term exercises and at different spatial resolutions and extents.

Until now the water redistribution module in LAPSUS got little attention. In this study LAPSUS is modified to handle water redistribution within the boundaries of an arid climate. To assess the performance of the modified LAPSUS firstly a sensitivity analysis of the water redistribution module is done. Secondly the capability of LAPSUS to deal with varying surface characteristics is tested by comparing the water redistribution patterns of two contrasting catchments with field data. The catchments are very similar in climate and size, but differ strongly in surface characteristics. Thirdly the model results will be compared with herbaceous plant cover in the catchments.

## 3.2 Material and Methods

### *3.2.1 Catchments*

In this study I focussed on the two southern arid catchments, Halluqim and Avdat (Fig. 1.2 and §1.3.2). Both catchments receive similar amounts of precipitation.

*Halluqim*. Halluqim is a steeply incised first order catchment of 3.5 hectare (Fig. 3.1a and §1.3.2). The lower part of the area is covered with several meters thick stony colluvium (Wieder et al., 1985). The higher parts are almost devoid of loess cover. Bedrock comes at the surface at 42% of the area (Table 3.1). Consequently soils are shallow (at average 0.11 ± s.d. 0.16 m). The surface is for 56% covered by soils of 0.05 m deep or less (including bedrock surfaces), for 31% by soils of 0.05 to 0.20 m deep and for 13% by deeper soils. Vegetation covers 20% of the surface at the end of the rainy season. After correcting the vegetation coverage for available soil (thus excluding bedrock) Halluqim has a vegetation coverage of 35%. *Asphodelus ramosus* individuals occur in Halluqim, in contrast to Avdat, but only in minor amounts (Table 3.1).

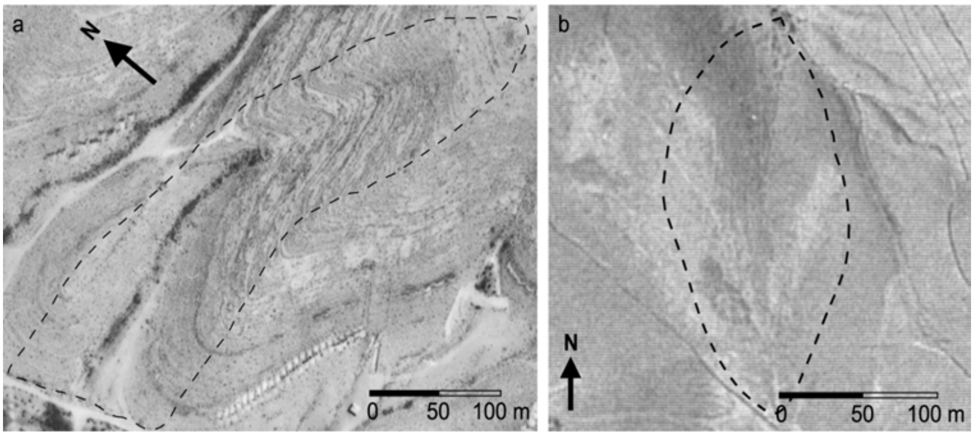


Fig. 3.1 Aerial photographs of Halluqim (a) and sub-catchment of Avdat (b). Dotted line indicates catchment boundary.

*Avdat*. In Avdat a first order sub-catchment of 2.5 hectare was selected (Fig. 3.1b and §1.3.2). The sub-catchment, positioned on the side of a plateau, is largely covered with a thin layer of loessic deposits mixed with limestone pebbles (Bruins, 1986; Dan et al., 1981). Average soil depth is 0.21 ± 0.15 m, whereby only 6% of the surface is covered by soils of 0.05 m or less, 44% is covered by soils of 0.05 – 0.20 m and 50% is covered by deeper soils. In contrast to Halluqim bedrock comes to the surface at only 5% of the sub-catchment (Table 3.1). Loose surface stones occupy another 38%, while vegetation cover is limited to 19% of the surface. After correcting for available soil, still only 20% of the sub-catchment is covered by vegetation.

Table 3.1. Mean surface cover percentage (± standard deviation) of the surface for six surface covers in Halluqim and the sub-catchment of Avdat

| **Study site** | **Halluqim** | **Avdat sub-catchment** |
|---|---|---|
| Shrub | 8.8 ± 3.9 | 11.6 ± 8.9 |
| Asphodelus ramosus | 0.3 ± 1.1 | 0.0 ± 0.0 |
| Herbaceous plants | 9.8 ± 12.0 | 7.5 ± 5.7 |
| Crust | 13.5 ± 12.5 | 38.2 ± 13.0 |
| Loose surface stones | 20.3 ± 19.7 | 38.1 ± 13.4 |
| Bedrock | 47.3 ± 34.6 | 4.6 ± 7.7 |

### *3.2.2 Modifications of the LAPSUS model*

In this study LAPSUS is modified to assess water redistribution patterns in arid climates (Chapter 1). Firstly LAPSUS is adjusted to an arid climate by changing the used time step from annual model runs to daily event based runs. In arid climates precipitation is concentrated in a limited amount of showers per year, while erosion occurs dominantly during extreme events (Mulligan, 1998). By modelling each precipitation event separately, these extreme events become more pronounced and reality is better approached.

Secondly the infiltration module of LAPSUS is elaborated to improve representation of spatial diversity in water redistribution and availability within arid catchments. In the modified 3D LAPSUS model, infiltration $I$ (m time$^{-1}$) is dependent on the available water in a grid cell by the following relationship:

$$I = I_f \cdot Q \tag{3.1}$$

Discharge $Q$ (m time$^{-1}$) is a summation of precipitation on a grid cell plus runon, whereby evapotranspiration and drainage are assumed zero. This assumption is applicable as Yair and Lavee (1985) demonstrated for Halluqim that during a storm, when cloudiness is high and air temperature low, the potential evapotranspiration is insignificant and has no effect on the rainfall-runoff relationship. Subsurface drainage is set to zero as well, as in this study we focus on processes active during single events, and therefore longer term processes as drainage are ignored. The infiltration fraction $I_f$ (-) is an empirical fraction regulating the Hortonian overland flow production. One millimetre of precipitation is needed to wet the surface without contributing to runoff (even of bedrock areas) (Yair, 1990). Therefore one millimetre is subtracted of the discharge to correct for surface wetting.

Spatial variability in water redistribution is additionally influenced by water storage capacity of the soil, which regulates the saturation overland flow. Infiltration is corrected for available storage capacity per grid cell by multiplying soil depth with the pore volume ($\phi$ in m$^3$ m$^{-3}$) of the soil, giving the maximum possible infiltration volume (m time$^{-1}$). At this stage the effect of antecedent soil moisture is not covered by the model. After each event the soil depth map is corrected for net erosion or sedimentation of each grid cell.

### *3.2.3 Data collection*

Input data for the model was collected during fieldwork done in February and March 2005 at end of the rainy season. Surface cover density maps (%) of the catchments were made for bedrock outcrop, loose stones on the surface, shrubs, *Asphodelus ramosus*, herbaceous plants and crusts (§2.2.1). DEM's were based on a topographical map of 1:10 000 with elevation lines at five metre interval. Additionally a 1:1000 elevation map with one metre height interval was used for the DEM of Avdat (Evenari et al., 1964). Soil depth (m) was measured by auguring or digging at randomly chosen points, for which GPS coordinates were recorded (UTM). The soil depth map was made by interpolating (Inverse Distance Weighted method) the measured soil depth points taken in the field combined with additional soil depth points for bare bedrock areas (soil depth is zero) based on the bedrock cover map. A very good agreement was found between the percentage of very shallow soils (<0.005 m) in the interpolated soil depth map and the percentage of bedrock in the bedrock cover map for Halluqim ($R^2$ = 0.96) and for Avdat ($R^2$ = 0.93). All maps were made with a grid cell size of 4x4 m. Afterwards the maps were aggregated to larger grid cell sizes up to 25x25 m to investigate scale dependency (using Nearest Neighbour method for integer data and Bilinear method for float data).

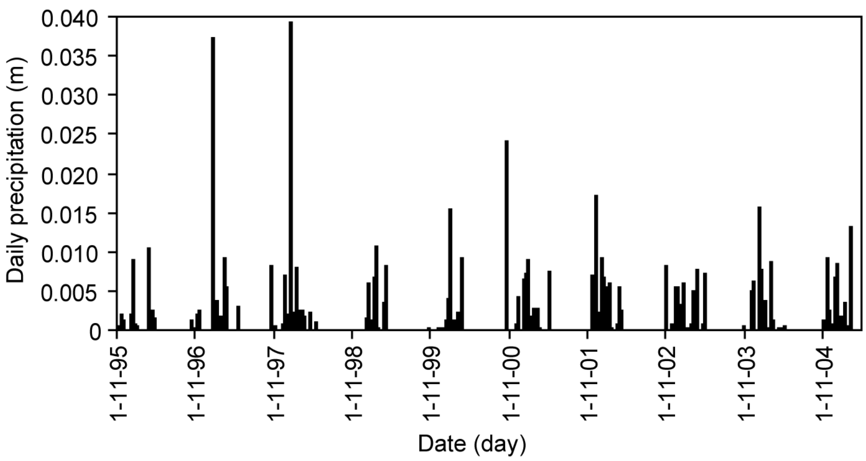


Fig. 3.2 Daily precipitation of the rain seasons 1995/1996 to 2004/2005 (m) (after Zangvil and Klepach, 2007).

As model input the daily precipitation data of the rain season 2003/2004 and 2004/2005 were used (Fig. 3.2), measured at the Sde-Boker Meteorological Site (Zangvil and Klepach, 2007). The Meteorological Site is situated close to both catchments (approximately 2.5 kilometres from Halluqim and 7.5 kilometres from Avdat) and gives highly accurate daily precipitation sums. Only events of more than one millimetre are used as at least one millimetre is needed to generate runoff (Yair, 1990).

### 3.2.4 Modelling exercises

Three parameters were used to calibrate the model for water redistribution; conversion factor $p$ (Equation 1.1), infiltration fraction $I_f$ (Equation 3.1) and pore volume $\phi$. During several exercises a standard scenario is used (Table 3.2). For this standard scenario a conversion factor of $p = 1$ is used as multiple flow routing mimics redistribution patterns better than steepest descent (Quinn et al., 1991; Schoorl et al., 2000). Infiltration fraction $I_f$ was based on field data of both catchments. For Halluqim 25 rainfall-runoff events were measured at the catchment outlet by Yair, resulting in a mean infiltration fraction of 89.24 ± 14.63 % (Yair, 1974; Yair, 1992b; Yair, 1999). For Avdat 37 rainfall-runoff events were measured at the catchment outlet by Evenari and other authors, resulting in a mean infiltration fraction of 90.33 ± 8.52 % (Evenari et al., 1964; Evenari et al., 1968). A linear regression analysis of precipitation quantity versus infiltration fraction was done, which resulted in a $R^2$ of 0.17 for Halluqim and a $R^2$ of 0.34 for Avdat. As apparently infiltration fraction was independent of precipitation quantity, one averaged infiltration fraction was used for all events and both catchments ($I_f$ of 0.90). Average pore volume of the soil was calculated using bulk density of oven dried soil samples of constant volume (100 $cm^3$) and the particle density (2.68 g $cm^{-3}$) based on local loess composition (Offer et al., 1992). The pore volume of Halluqim was 0.49 ± 0.01 (n = 4) and of Avdat 0.52 ± 0.03 (n = 4). For comparison between the catchments the pore volume of Halluqim and Avdat were averaged ($\phi$ = 0.50). For erosion calibration the parameters $K_{es}$, $P_{es}$, $m$ and $n$ were kept constant throughout the study. The values were based on previous calibration exercises (Table 3.2).

Table 3.2. Parameter setting as used in model exercises

| **Parameter** | **Unit** | **Value** | **Parameter** | **Unit** | **Value** |
|---|---|---|---|---|---|
| $K_{es}$ | $m^{-1}$ | 0.15 | $p$ | - | 1 |
| $P_{es}$ | $m^{-1}$ | 0.15 | $I_f$ | - | 0.90 |
| $m$ | - | 1.0 | $\phi$ | - | 0.5 |
| $n$ | - | 1.0 | | | |

First, a sensitivity analysis of the model to variations in parameter settings was done by varying the values of $p$ (1 – 9, steps of 1), $I_f$ (0.60 – 0.99, steps of 0.05) and $\phi$ (0.3 – 0.6, steps of 0.05) for a series of precipitation events ranging from 0.002 to 0.048 m. In the first exercise one parameter was varied while the others are kept constant following the standard scenario, in the second exercise all parameters were varied randomly (covering all possible combinations).
For comparisons the runoff receiving and runoff producing area ($m^2$) was used (mean ± standard deviation). Runoff receiving areas are defined as (groups of) grid cells which receive more runon

from higher neighbouring grid cells than they produce runoff to lower neighbouring grid cells (runon volume / runoff volume > 1). Runoff producing areas were defined as (groups of) grid cells which produce more runoff than that they receive runon (runon volume / runoff volume <1).

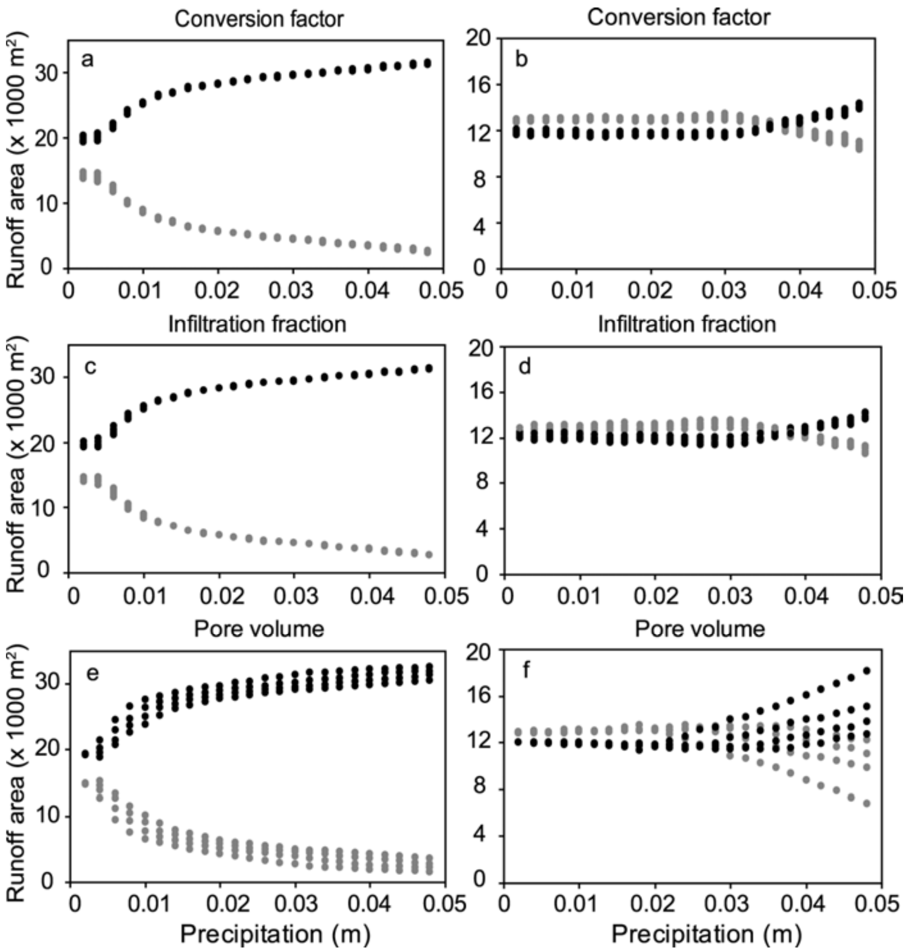


Fig. 3.3 Model sensitivity to variations in parameter values is given in runoff receiving area (grey dots) and runoff producing area (black dots) (x1000 $m^2$) for conversion factor p (a and b), infiltration fraction $I_f$ (c and d) and pore volume $\phi$ (e and f) for Halluqim (a, c and e) and Avdat (b, d and f) at different shower intensities (0.002 – 0.048 m).

In the third exercise a visual sensitivity analyses was done for Avdat by comparing infiltration maps of extreme values of $p$ (1 or 9), $I_f$ (0.60 or 0.99) and $\phi$ (0.3 or 0.6), while the other parameters were kept constant following the standard scenario at 0.048 m precipitation.

Second, the two catchments were compared for their hydrological response to various precipitation events. The maximum and average runoff and infiltration volumes were compared for seven precipitation events ranging between 0.002 and 0.040 m. Additionally the dependency of the catchment response of Halluqim to position of bedrock in the catchment is shown for two precipitation events (0.005 and 0.010 m). One simulation was made with the actual soil depth and one with reversed soil depth, whereby the actual shallow soils were transformed to deep soils and visa versa.
Third, visual comparisons were made between the simulated total infiltration pattern (m) for the rain seasons 2003/2004 and 2004/2005 and herbaceous plant coverage in percentage for both catchments. Additionally linear regressions were made between infiltration and vegetation coverage using input maps of different grid cell sizes (4x4, 8x8, 12x12, 16x16, 20x20, 25x25 m grid cells). To reduce spatial autocorrelation only 25% of the grid cells, equally distributed, were used for statistical comparisons.

## 3.3 Results

### *3.3.1 Sensitivity analyses*

The model sensitivity to variations in parameter values was firstly studied for each parameter separately, while the other parameters were kept constant following the standard scenario (Table 3.3). The runoff receiving and producing areas almost add up to the total catchment surface. In Halluqim only three neutral grid cells, covering 48 $m^2$, are formed in the model runs, while none are formed in Avdat. For Halluqim the maximum variation in runoff receiving and producing area is found at an event of 0.008 m precipitation, whereby the conversion factor ($p$) gives a standard deviation of 201 $m^2$, the infiltration fraction ($I_f$) a standard deviation of 460 $m^2$ and the pore volume ($\phi$) a standard deviation of 1490 $m^2$ (Table 3.3, Fig. 3.3). For Avdat the maximum variation in runoff receiving and producing area is found at an event of 0.048 m precipitation, whereby the conversion factor gives a standard deviation of 155 $m^2$, the infiltration fraction a standard deviation of 188 $m^2$ and the pore volume a standard deviation of 1917 $m^2$ (Table 3.3, Fig. 3.3). In both catchments the pore volume of the soil causes the largest variation in runoff receiving and producing area.

Table 3.3. Maximum model sensitivity for variation in parameter values described in average runoff receiving and producing area m$^2$ ± standard deviation for both catchments ($p$, 1 – 9; $I_f$, 0.60 – 0.99; $\phi$ , 0.3 – 0.6). For Halluqim maximum variation is at 0.008 m precipitation, for Avdat maximum variation is at 0.048 m precipitation

| | **Runoff receiving area (m$^2$)** | | **Runoff producing area (m$^2$)** | |
|---|---|---|---|---|
| | **Halluqim** | **Avdat** | **Halluqim** | **Avdat** |
| $p$ | 10037 ± 201 | 10466 ± 155 | 24075 ± 201 | 13950 ± 155 |
| $I_f$ | 10057 ± 460 | 10690 ± 188 | 24055 ± 460 | 13726 ± 188 |
| $\phi$ | 9695 ± 1490 | 9819 ± 1917 | 24417 ± 1490 | 14597 ± 1917 |

Second, sensitivity of the model to interacting parameter variations is studied by varying $p$, $I_f$ and $\phi$ for a total number of 566 runs per catchment covering all possible combinations (Fig. 3.4). The model variation in output decreases with precipitation in Halluqim, while it increases in Avdat. For both catchments the combined sensitivity graph resembles most closely the sensitivity graph of pore volume (compare Figures 3.3 and 3.4).

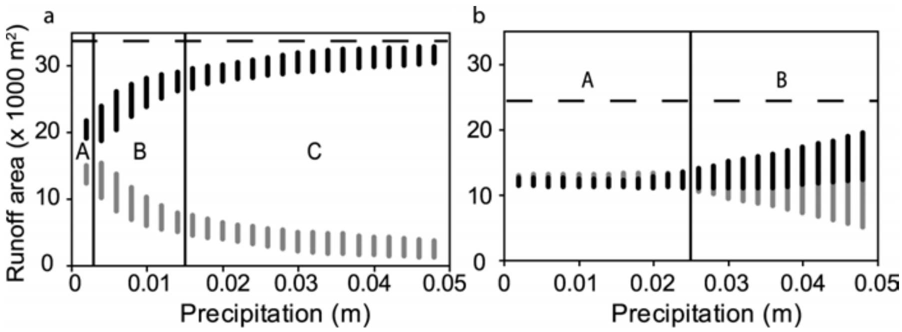


Fig. 3.4 Catchment response to parameter variation is given with runoff receiving area (grey dots) and runoff producing areas (black dots) (x 1000 m$^2$ for different shower intensities (0.002 – 0.048 m) for Halluqim (a) and Avdat (b). The dashed line indicates total catchment surface (x1000 m$^2$). The letters A, B and C indicate different catchment response types, whereby the black lines are the precipitation thresholds between them.

Third, the spatial sensitivity of the model to parameter variations is visualized for Avdat with infiltration maps (Fig. 3.5). The conversion factor has only a slight effect on runoff concentration (Fig. 3.5a and b, arrow). The infiltration fraction influences mainly the infiltration in the deeper soils (Fig. 3.5c and d, square). Again the pore volume appears to have a large effect on the model (Fig. 3.5e and f, circles).

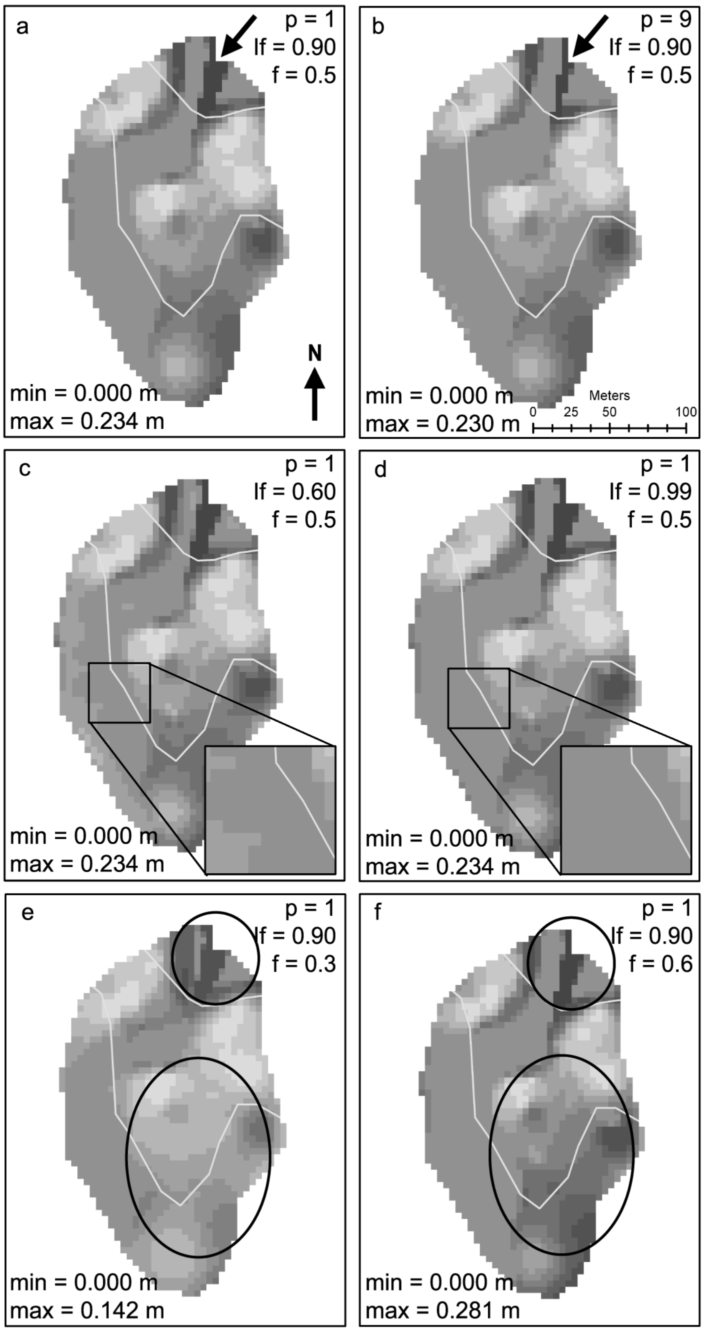


Fig. 3.5 Spatial model sensitivity to parameter variations for Avdat shown by infiltration (m). The variables vary between: $p$ = 1 (a) and $p$ = 9 (b), $I_f$ = 0.6 (c) and $I_f$ = 0.99 (d), $\phi$ = 0.3 (e) and $\phi$ = 0.6 (f). Precipitation = 0.048 m. Light grey colour indicates low infiltration and dark grey colour indicates high infiltration using similar scales for a and b, c and d, and for e and f. The white lines are five meter elevation lines. The squares, circles and arrows appoint specific areas discussed in the text.

Table 3.4. Hydrological comparison of Halluqim (HQ) and Avdat (AV) for seven precipitation events (0.002 – 0.040 m), whereby $p = 1$, $I_f = 0.9$ and $\phi = 0.5$

| **Event (m)** | **Average runoff (m)** | | **Maximum runoff (m)** | | **Average infiltration (m)** | | **Maximum infiltration (m)** | |
|---|---|---|---|---|---|---|---|---|
| | **HQ** | **AV** | **HQ** | **AV** | **HQ** | **AV** | **HQ** | **AV** |
| 0.002 | 0.001 | <0.001 | 0.013 | 0.003 | 0.002 | 0.002 | 0.011 | 0.004 |
| 0.005 | 0.009 | 0.001 | 0.084 | 0.011 | 0.005 | 0.005 | 0.056 | 0.010 |
| 0.010 | 0.044 | 0.002 | 0.721 | 0.032 | 0.008 | 0.010 | 0.123 | 0.027 |
| 0.015 | 0.148 | 0.006 | 3.371 | 0.072 | 0.012 | 0.015 | 0.542 | 0.066 |
| 0.020 | 0.286 | 0.012 | 6.413 | 0.276 | 0.014 | 0.021 | 0.574 | 0.112 |
| 0.030 | 0.590 | 0.036 | 13.256 | 1.316 | 0.015 | 0.032 | 0.574 | 0.230 |
| 0.040 | 0.899 | 0.101 | 21.108 | 3.648 | 0.016 | 0.042 | 0.689 | 0.230 |

### *3.3.2 Catchment response*

The hydrological response of both catchments on increasing precipitation events ranging between 0.002 and 0.040 m is shown in Fig. 3.4 (using all possible parameter combinations) and in Table 3.4 (using the standard scenario). Each catchment displays a typical response on increasing precipitation. In general, in Halluqim, the runoff producing area increases quickly with increasing precipitation (Fig. 3.4a). Consequently runoff receiving area decreases rapidly. In Avdat (Fig. 3.4b) a more gradual effect is shown.

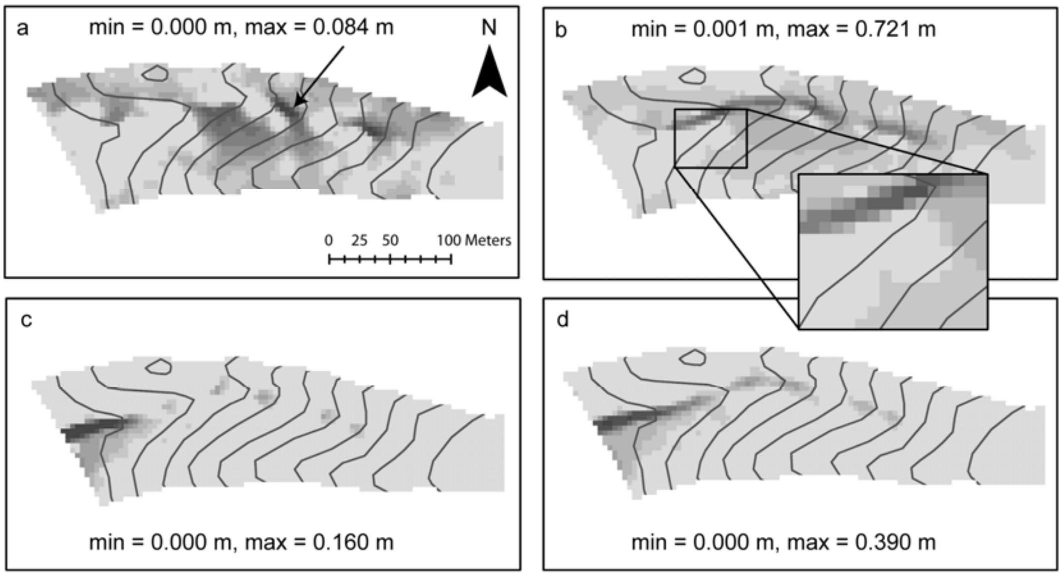


Fig. 3.6 Runoff patterns in Halluqim are shown for precipitation of 0.005 m (a and c) and 0.010 m (b and d), and for actual soil depth (a and b) and reversed soil depth (c and d). Light grey colour indicates low runoff amounts and dark grey colour indicates high runoff amounts.

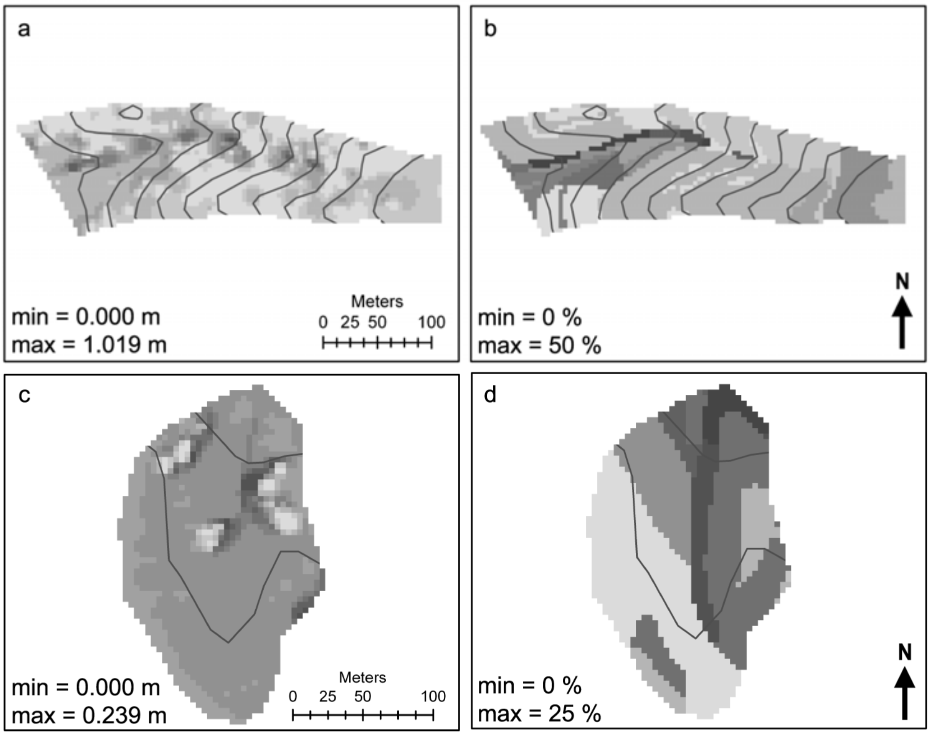


Fig. 3.7 Infiltration patterns for two rain seasons (2003/2004-2004/2005) for Halluqim (a) and Avdat (c) and herbaceous plant surface coverage (%) for Halluqim (b) and Avdat (d) are shown. Light grey colour indicates low infiltration amounts / surface coverage and dark grey colour indicates high infiltration amounts / surface coverage. The scales are not similar. The black lines are five meter elevation lines.

The reaction of the catchments on a precipitation event can be described in catchment response types. In total three catchment response types can be recognized, separated by precipitation thresholds (Fig. 3.4). Also in Table 3.4 it can be clearly seen that both catchments respond very differently to precipitation events. The maximum infiltration, maximum runoff and average runoff are higher in Halluqim than in Avdat. Average infiltration is higher in Avdat. Additionally the dependency of Halluqim on the position of bedrock in the catchment is shown. Therefore a simulation with actual soil depth is compared with a simulation with reversed soil depth (Fig. 3.6). Clear differences can be seen in position of the runoff formation.

### *3.3.3 Runoff and infiltration patterns compared to herbaceous plant coverage*

The hydrological response of both catchments on actual precipitation events of the rain seasons 2003/2004 and 2004/2005 is visualized for total infiltration (Fig. 3.7). In Halluqim a visual resemblance can be clearly seen between infiltration patterns and surface cover of herbaceous plants (Fig. 3.7a and b). In Avdat the agreement is clearly lower (Fig. 3.7c and d). Also statistically the relationship between infiltration and herbaceous plant coverage is generally stronger in Halluqim than in Avdat. In Halluqim the best results are achieved at 4x4, 12x12 or 25x25 m grid cell size ($R^2$ is respectively 0.27, 0.31 and 0.54), while at intermediate grid cell sizes results are less (Fig. 3.8). In Avdat the best result are achieved at intermediate grid cell sizes of 12x12 to 20x20 m ($R^2$ is respectively 0.15, 0.10 and 0.14).

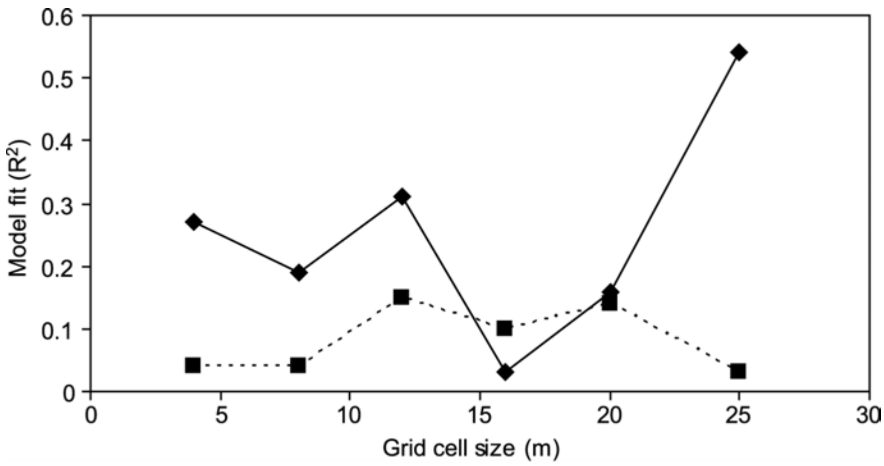


Fig. 3.8. The effect of grid cell size (m) on linear model fit ($R^2$) of modelled total infiltration (m) and herbaceous plant surface coverage (%) is given for two rain seasons (2003/2004-2004/2005) for Halluqim (solid line) and Avdat (dotted line).

## 3.4 Discussion

### *3.4.1 Sensitivity analyses*

The model sensitivity to parameter variations differs per catchment and per precipitation quantity. In Halluqim the highest variation in output is found at only 0.008 m precipitation, while in Avdat the maximum variation is not yet reached at the largest modelled event (Fig. 3.3). The model sensitivity to variations in conversion factor and infiltration fraction is limited, while the model is highly sensitive to variations in pore volume (Table 3.3 and Fig. 3.3). Consequently, when the combined effect of all parameters is considered, it is clear that the model is most sensitive for pore volume alone and no additional model sensitivity is caused by interacting parameters (Fig. 3.4).

The conversion factor barely influences the model sensitivity (Table 3.3 and Fig. 3.3a and b). It can however be seen that the runoff is more concentrated for higher conversion factors, when flow routing resembles the steepest descent principle instead of the multiple flow principle (Fig. 3.5a and b, arrows). The infiltration fraction appears to have slightly more effect than the conversion factor (Table 3.3). Using low infiltration fractions, less water will infiltrate and runoff volumes are larger, independent on soil depth. As such even on deeper soils redistribution patterns will be visible (Fig. 3.5c, square). When the infiltration factor is high, almost all precipitation will infiltrate, and water redistribution is limited to locations where water storage capacity is smaller than the available water (Fig. 3.5d). Variations in pore volume have the strongest effect on the model outputs of both catchments (Table 3.3 and Fig. 3.3e and f). When the pore volume is low relatively little water can be stored and more water runs off at a larger part of the surface (Fig. 3.5e). In case that the pore volume is doubled, twice as much water can be stored and infiltrated and water redistribution occurs mainly on locations where storage capacity is limited by shallow soils (Fig. 3.5f).

Maximum infiltration solely depends on soil depth and pore volume (storage capacity) and thus variations in the pore volume influence the maximum infiltration volume strongly, and by that runoff and water redistribution patterns (Fig. 3.5e and f, circle). In Halluqim the same effects are witnessed as for Avdat, only visually less clear due to the large runoff volumes. Therefore the results of this exercise are not visualized for Halluqim. There is a clear difference in sensitivity of both catchments to parameter variations. This is related to the large difference in surface and catchment characteristics and will be discussed below.

For models which rely strongly on saturation overland flow processes, like LAPSUS, using the correct pore volume is very important. However the pore volume varies per layer and location, depending e.g. on grain size, deposition type, crust occurrence and mechanic disturbances. Also vegetation influences pore volume strongly by rooting and stimulation of soil biota, forming biopores and reducing the occurrence of crusts (Puigdefabregas et al., 1999). Additionally antecedent soil moisture in the soil reduces available pore volume for infiltration and is especially important for continuous based modelling (Castillo et al., 2003; Cerda, 1997). As such pore volume and available storage capacity is difficult to model spatially.

### *3.4.2 Catchment response*

*Catchment response on precipitation events*. The two catchments respond very different on precipitation in the modelling results. In Halluqim more runoff is formed on a larger surface than in Avdat (Table 3.4 and Fig. 3.4). The higher part of Halluqim (almost half of the surface) is almost devoid of loess cover and has very shallow (or no) soils limiting infiltration capacity

(Table 3.1). The large bedrock surface stimulates runoff as even at precipitation events of one millimetre runoff is formed on bedrock (Yair, 1983; Yair, 1990). Therefore even at low precipitation events runoff forms and water is redistributed (Table 3.4). In Avdat almost the total surface is covered by (deeper) loess deposits and subsequently a much higher proportion of the precipitation will infiltrate instead of produce runoff. Also the daily precipitation threshold for runoff production is higher (3 to 5 mm for stony (colluvial) soils) (Yair, 1983; Yair, 1990). Although on average the infiltration is higher in Avdat than in Halluqim, maximum infiltration is lower in Avdat as it depends directly on the runoff volume (Table 3.4). The catchment response to precipitation is thus highly influenced by soil depth.

In addition, the model sensitivity to parameter variations differs per catchment. The model sensitivity to both conversion factor and infiltration fraction is higher in Halluqim than in Avdat (Table 3.3 and Fig. 3.3). The sensitivity of the conversion factor is influenced by the steepness of the slopes. In Halluqim slopes are steep and increasing the conversion factor will increase runoff concentration. Therefore the steepest descent flow routing is approached sooner than in the flatter Avdat. The infiltration factor is sensitive to both slope and soil depth. As a constant fraction of the runoff volume infiltrates, large concentrated flows (caused by steep slopes) are more affected by changes in infiltration fraction than smaller flows. Additionally changes in infiltration fraction only influence the water redistribution if the total storage capacity of the catchment is not yet filled. The model sensitivity to pore volume, however, is higher in Avdat than in Halluqim, as in Avdat a larger volume of soil can be influenced (Table 3.3 and Fig. 3.3).

The form of the graphs describing the runoff receiving or producing area differ strongly as well (Fig. 3.4). In Halluqim three different response types can be recognized. Up to an event of 0.003 m in Halluqim about half of the area produces runoff, while the other half receives runoff demonstrating local redistribution of water on the slopes (Fig. 3.4a, type A). Under these conditions no runoff is concentrated. When precipitation increases above 0.003 m, the catchment crosses a precipitation threshold. The runoff producing area will increase quickly, because the maximum infiltration capacity of the relatively shallow soils is reached and runoff is formed (Fig. 3.4a, type B). When events are larger than 0.015 m another precipitation threshold is crossed. The runoff producing area keeps increasing, but at smaller rate until eventually the total catchment of Halluqim produces runoff (Fig. 3.4a, type C). In Avdat the response to increased precipitation is much smaller than in Halluqim. Here the runoff producing and runoff receiving area is relatively stable up to an event of 0.025 m and water is only locally redistributed (Fig. 3.4b, type A). Remarkably, however, is that the runoff receiving area is higher than the runoff producing area. This appears contra intuitive, but is caused by the used multiple flow routing of runoff water. By using a low conversion factor ($p$ = 1) the runoff is redistributed to all lower grid cells and more grid cells receive water than there are higher neighbours producing runoff. When precipitation

events are larger than 0.025 m, the catchment crosses a precipitation threshold and more soils reach their maximum infiltration capacity producing runoff (Fig. 3.4b, type B). This precipitation threshold between catchment response type A and B is reached at a much later stage in Avdat than in Halluqim, because of the difference in surface characteristics. It is expected that in theory the catchment of Avdat could reach type C if precipitation is sufficiently increased to reach the maximum storage capacity of most soils. In reality it is not likely that this will happen, as in the last ten years no event larger than 0.040 m precipitation occurred (Fig. 3.2).
The differences in catchment response are not only caused by the differences in soil depth and slope of the catchments, but also by position of the shallow areas. The dependency of the catchment response on the position of bedrock areas is tested by comparing simulations using normal and reversed soil depth maps of Halluqim. In the simulation with normal soil depth continuous runoff patterns are formed on the rocky slopes even in small events (Fig. 3.6a, arrow), although the runoff formed on higher bedrock slopes infiltrates in soils below the bedrock (Fig. 3.6b - inset). For larger events runoff concentrates in the gully bed and infiltrates in the lower reach of the gully where deeper soils are found (Fig. 3.6b). In the simulation using the reversed soil depth map, runoff is principally formed in the lower gully bed (in this case bare rock) where no infiltration occurs (Fig. 3.6c). On the higher slopes, in this case all covered with a loess layer, no runoff is formed as all precipitation infiltrates. When precipitation increases, part of the higher gully with sufficient shallow soils, starts producing runoff (Fig. 3.6d). This exercise demonstrates that catchment response is indeed strongly dependent on the spatial distribution of the shallow areas in the catchment (Puigdefabregas et al., 1999). The length of the runoff flows is influenced by the surface area of bedrock and the precipitation quantity. As such every single precipitation event will generate a different pattern.

*Comparison of the catchments*. When comparing the simulation results of both catchments it is clear that significantly more water is redistributed and partly transported out of Halluqim than out of Avdat, although climate is similar. Halluqim has more water redistribution because of the large surface area and convenient position of the extensive bare slopes. As a consequence of the water redistribution and local infiltration of it, more moist positions can occur and a denser vegetation including species of wetter climates can be sustained. This is in agreement with the denser vegetation cover (corrected for available soil) of Halluqim (36%) compared to Avdat (20%). *Asphodelus ramosus*, a perennial Mediterranean geophyte, occurs in Halluqim, while it is absent in Avdat (Chapter 2) (Olsvig-Whittaker et al., 1983). The occurrence of Mediterranean species within Halluqim is a strong indication of locally improved water availability, spatially as well as temporally (Kadmon et al., 1989; Yair and Danin, 1980). Comparing daily precipitation for the last ten years with the catchment response, it is clear that in Halluqim every year water is redistributed, while in Avdat only in three out of ten years water is redistributed (Fig. 3.2 and 3.4). This explains the lack of *Asphodelus ramosus* in Avdat despite the similar precipitation quantities. The evidence from model and field results leads to the conclusion that Halluqim is locally “wetter” than Avdat. The dominant “wetness”-controls are thus soil depth and slope combined with the pattern of bedrock outcrops, together determining the efficiency of the rocky areas as runoff sources and the colluvial slopes as infiltration sinks.

### *3.4.3 Runoff and infiltration patterns compared to herbaceous plant coverage*

Vegetation density is positively related to water availability and subsequently infiltration volume (Olsvig-Whittaker et al., 1983; Schreiber et al., 1995). Especially herbaceous plants depend strongly on available water and respond directly to wet or dry years. As such it might be expected that the infiltration patterns in the catchments have a clear relationship with the observed vegetation patterns. Visually in Halluqim the high infiltration volume and the high herbaceous plant density in the gully bed agree well (Fig. 3.7a and b). In Avdat the agreement is less clear. Still resemblances are found in the gully bed (Fig. 3.7c and d). The relationship between modelled infiltration and herbaceous plant coverage at 4x4 m grid cells is clearly better in Halluqim ($R^2$ = 0.27, $P$ = 0.000) than in Avdat ($R^2$ = 0.04, $P$ = 0.001) (Fig. 3.8). This is in agreement with results obtained in chapter 2, which leaded to the conclusion that in Avdat herbaceous plants are only related to surface stone cover. This surface cover type is not incorporated in the model. In Halluqim herbaceous plants are related to bedrock and sedimentation zones. Both variables are incorporated in the model by soil depth (bedrock) and infiltration (sedimentation zones). As such modelling results are better.

For both catchments part of the exiting vegetation variation is not captured by LAPSUS. The model setup represents Hortonian overland flow only to a limited degree. Hortonian overland flow is an important runoff generation process in arid areas as soils often have low infiltration capacities caused by surface crusting and water repellence (Yair and Lavee, 1985). Additionally infiltration capacities vary tremendously over these slopes depending on soil – vegetation characteristics. As the model does not cope with this spatial variation in infiltration capacity, this variation is not represented in the model. By including differential infiltration fractions in the Hortonian overland flow model procedure spatial runoff patterns can be better simulated. Secondly, especially in Avdat, the input data used in the model is a source of spatial uncertainty (and lack of explained variance) because of the interpolation of the soil depth. Thirdly vegetation limiting processes, like severe erosion or sedimentation and salinization problems, explain non-optimal model results, as well as feedback mechanisms between vegetation and infiltration (Janeau et al., 1999; Ludwig et al., 2005; Nicolau et al., 1996; Schlesinger and Pilmanis, 1998).

Finally the impossibility to cover within grid cell variations partly explains the lack of explained variance, like crevices within the bedrock which have a favourable micro climate for vegetation. In future LAPSUS applications modifications can be made to potentially improve the results, with focus on Hortonian overland flow.

In Avdat $R^2$ improves when grid cell size increases up to grid cells of 20x20 m (Fig. 3.8). The surface characteristics of Avdat are relatively homogeneous. Therefore the variability is relatively small within the grid cells, and increasing the grid cell size averages the small scaled variability and improves the results. This is in agreement with previous observations that results tend to improve at coarser resolutions, as an increase in grid cell size causes a loss of local variance (Kok et al., 2001; Veldkamp et al., 2001a; Veldkamp et al., 2001b). When grid cell size increases above 20x20 m, the dominant surface cover type (loess) overrules the relatively small bedrock areas in Avdat and the landscape diversity is averaged out. Therefore the existing vegetation variation can not be captured by the model anymore and results are worse.

In Halluqim $R^2$ roughly increases up to 12x12 m grid cells, but deceases strongly if grid cell size increases up to 16x16 m grid cells (Fig. 3.8). For even larger grid cells the results improve again. This demonstrates the varying scales of the different surface cover patterns (O'Neill et al., 1991). In Halluqim the surface cover and infiltration capacity of the soil is patchy (crust – no crust), causing a large variation even at small distances. When grid cells become larger (up to 16x16 m grid cells) less of this small scale variation is represented in the model, with lower model fits as result. When grid cell size increases the effect of the patchy surface characteristics is overruled by the effect of the larger landscape elements, like the extensively bedrock covered slopes and the gully bed. By averaging these large landscape elements, small scale variation is averaged out and large scale pattern relationships emerge (Veldkamp et al., 2001a).

## 3.5 Conclusions

Surface characteristics strongly influence water redistribution and erosion, therefore simulating these patterns well is essential for water erosion models. LAPSUS is well equipped to simulate the difference in water redistribution volumes and patterns between the catchments. The model appears to be most sensitive to pore volume of the soil. A lower pore volume reduces the storage capacity of the soil and lowering of the runoff threshold of a catchment.

Catchments with different surface characteristics yield very different water redistribution patterns. The two catchments considered here differ strongly in surface characteristics and in resulting water redistribution quantity and patterns. This difference is clearly visible in the field as well as in the results of the model simulations. The dominantly bedrock-covered catchment of Halluqim redistributes more water than the dominantly loess-covered catchment of Avdat, while precipitation is practically the same. As a result, the Halluqim catchment is locally "wetter" than the catchment of Avdat, and allows the presence of a vegetation typical of Mediterranean climates.

The modelling results indicate that the water redistribution patterns correspond to a certain extent to the vegetation patterns. However a large part of the observed variation in vegetation cover can not yet be explained by the model. Modifications are proposed to incorporate interactions and feedbacks between water redistribution and vegetation and to improve the modelling results.

# 4 Modelling fluvial shrub mound formation and their stability on semi-arid slopes

*In semi-arid areas vegetation is scarce and often dominated by individual shrubs on raised mounds. The process of formation of these mounds is still debated. In this chapter I test the hypothesis that in the Negev Desert shrub mounds are formed by erosion and sedimentation. I studied shrub mounds in the loess-covered semi-arid catchment of Sayeret Shaked in the Northern Negev Desert. Height and diameter of shrub canopy and shrub mounds were measured and micro-morphological techniques were used to reconstruct the formation of the shrub mounds. The results suggest that shrub mounds are formed by accumulation of atmospheric dust and sedimentation of eroded material in the vicinity of the shrub, as well as by erosion of the surrounding crust. Model simulations for single events and longer time scales (100 years) suggest that mound formation is most prominent at low shrub density and large shrub canopy diameter. Positive and negative feedbacks between shrubs and resource redistribution results in a meta-stable landscape. Long-term model simulations of the current climate indicates that the rate of formation of shrub mounds is high initially, and later stabilizes at lower rates. In dryer and wetter climates mound formation is unlikely: resource redistribution is either too limited or too strong, causing either a stable or a highly erosive landscape. LAPSUS successfully simulates mounds similar to those observed at Sayeret Shaked, and may prove valuable for the modelling of ecohydrological landscape processes in semi-arid areas.*

Based on: E. Buis, A. Veldkamp, B. Boeken, A.G. Jongmans, J.M. Schoorl and N. van Breemen. Modelling shrub mound formation and their stability on semi-arid slopes in the Negev Desert of Israel. Submitted.

## 4.1 Introduction

Semi-arid landscapes are strongly influenced by complex interactions of ecohydrological and aeolian processes triggered by and resulting in patterns of vegetation surrounded by bare crusted soil (Breshears et al., 2003; Ludwig et al., 2005). Often these crusts, formed by physical and biological processes, tend to reduce infiltration and to stimulate runoff formation (Belnap, 2003; Eldridge et al., 2000; Shachak et al., 1998). The vegetation in such areas is often concentrated in distinct patches of shrubs, which tend to form islands of fertility by concentration of nutrients and litter below the shrubs themselves, enhancing biological activity and porosity as well as increasing infiltration capacity and water availability (Aguiar and Sala, 1999; Bhark and Small, 2003; Schlesinger and Pilmanis, 1998). In contrast the adjacent crusted surface often have a low infiltration capacity resulting in runoff of water, sediments and nutrients, which are trapped into the shrubs (Eldridge et al., 2000; Ludwig et al., 2005). Water, sediments and associated nutrients, concentrate below the shrubs where they enhance shrub growth, while crust surfaces tend to become depleted in water and nutrients, partly as a result of erosion (Calvo-Cases et al., 2003; Schlesinger and Pilmanis, 1998). Noteworthily, recent research in wind-dominated systems indicates that on sandy soils the infiltration rate below shrub canopies might be decreased by the deposition of fine sediments below shrub canopies (Ravi et al., 2007). The shrub – crust landscape is thus self-promoting and tends to reinforce the differences in water, sediments and nutrients in time (Schlesinger et al., 1990).

In the shrub – crust landscape the shrubs predominantly occur on mounds. The formation of these mounds is still debated, but appears to be caused by a combination of several processes depending on local climate circumstances, soil texture, vegetation type and occurrence of cyanobacteria (Bochet et al., 2000). According to Shachak and Lovett (1998) shrub mounds are sedimentary features formed by concentration of fine-grained atmospheric dust of rather local and of long-range origin and local organic matter below shrubs (Offer and Goossens, 2001). Rostagno (1988) stated that mounds are erosional features, caused by erosion of the surrounding crust surface, while the shrub covered surface is protected. Parsons et al (1992) demonstrated that mounds are both erosion and sedimentation features, formed by splash erosion whereby more soil particles are ejected towards shrubs than *visa versa*. This causes a relative rise of the soil surface covered by shrubs and lowering of the bare crust surface. Ravi et al. (2007) stated that shrub mounds are formed by aeolian processes of intercanopy wind erosion and sand deposition in the shrub canopy. Additionally, mound formation can be related to (lateral) root growth, which both causes upheaval of soil and increased porosity by bioturbation (Bochet et al., 2000; Fransen, 2004). Formed mounds increase micro-topography resulting in obstruction of runoff flow by reducing the flow velocity in the shrub-crust landscape, which in turn influences water and sediment redistribution (Ludwig et al., 2005). Little is known about the rate of formation of shrub mounds. Transition from grassland to shrub land occurred over the past 200 years in the south-western United States (Bhark and Small, 2003), while in Israel this transition may have occurred already more than 2000 years ago (Pers. Comm. B. Boeken). These transitions are often attributed to intense livestock grazing and drought stress (Bhark and Small, 2003; Schlesinger et al., 1990). For shrub mound development estimates of 60 or 70 years to several centuries are reported in the United States (Abrahams et al., 1994; Rostagno and Del Valle, 1988). However, such data does not provide a solid estimation of the time of shrub mound formation, as shrub mounds tend to stabilize once formed (Rostagno and Del Valle, 1988). Shachak and Lovett (1998) estimated that shrub mounds, in Sayeret Shaked, northern Negev Desert of Israel, form in 180 – 290 years, an underestimation of the real formation time according to both authors. Therefore, how fast shrub mounds form depends on local circumstances with respect to landscape position, dominant processes involved, soil texture, shrub species and architecture, and climate. Due to the large diversity of local circumstances, a concise time range is difficult to establish.

Model studies, which take in account erosional, hydrological and ecological aspects of a landscape may help to unravel the processes involved in shrub mound formation. However, suitable models are scarce. In general erosion models include hydrological processes, but often ignore the ecological aspects (e.g. De Roo and Jetten, 1999; Smith et al., 1999; Sun et al. 2002). In some hydrological models interactions between hydrology and ecology have been successfully made, but these models tend to ignore erosion and deposition processes or treat them only very basically (Howes et al., 2006; Mulligan, 1998). Ecological mathematical models that deal with self-organization of vegetation patterns on the other hand, often disregard erosion and sedimentation processes and do not describe topographical changes (e.g. Gilad et al., 2007; Rietkerk et al., 2002). A recent model study of Nield and Baas (2008) combines self-organizing vegetation patterns with geomorphological processes, but focussed on aeolian landscapes only, and is therefore unfit to model formation of shrub mounds in the Northern Negev Desert. Some more suited erosion models incorporate ecohydrological and geomorphological processes, however these focus on single precipitation events and are therefore inappropriate to study long-term processes of mound formation (e.g. Morgan et al., 1998; Siepel et al., 2002; Boer and Puigdefabregas, 2005; Istanbulluoglu and Bras, 2006). In this study ecohydrological processes are incorporated in LAPSUS, which enables us to simulate these processes at both short and longer time scales (Schoorl et al., 2000).

The objective of this study is to shed light on formation of shrub mounds in loess-covered catchments in the Northern Negev Desert, hypothesizing that here shrub mounds are formed under specific environmental conditions in a limited climate range in a process of water erosion and sedimentation. I will test my hypothesis by combining field data with model simulations of the shrub – crust landscape with LAPSUS focussing on water and soil redistribution and shrub mound formation at short and longer time scales. The bare surface in this region is dominantly covered by a biological crust, which protects the surface against erosion (both wind and water) and decreases infiltration (Eldridge et al., 2000). My study might help to bridge the gap between long-term ecohydrological processes and landscape process modelling and enables us to represent and reconstruct structure and function of semi-arid landscapes more realistically.

## 4.2 Material and Methods

### *4.2.1 Site conditions and field methods*

Individual shrub mounds were studied in the semi-arid catchment of Sayeret Shaked (Fig. 1.1 and §1.3.2). The landscape is covered with a thick layer of loess. The catchment has an annual precipitation of 200 mm (Stern et al., 1986). Livestock was excluded since 1987 (Boeken and Shachak, 1994). Bare soil surfaces are covered by cyanobacterial crusts consisting of *Microcoleus vaginatus*, interspersed with shrubs growing on a mound with an herbaceous understorey (Fig. 4.1) (Boeken and Shachak, 1994). Only mounds of the dominant shrub type, *Noaea mucronata* (n = 15), were considered. The relative height of the mound was measured by comparing the top of the mound with the surrounding crusted bare soil, as well as the average diameter of the shrub mounds. Undisturbed soil samples were taken in cardboard boxes (7 x 7 cm) along a transect through four shrub mounds and adjoining crust surface (0 – 7 cm depth). The samples were examined for colour, structure and consistence of the soil material with a stereo-microscope, using incident light.

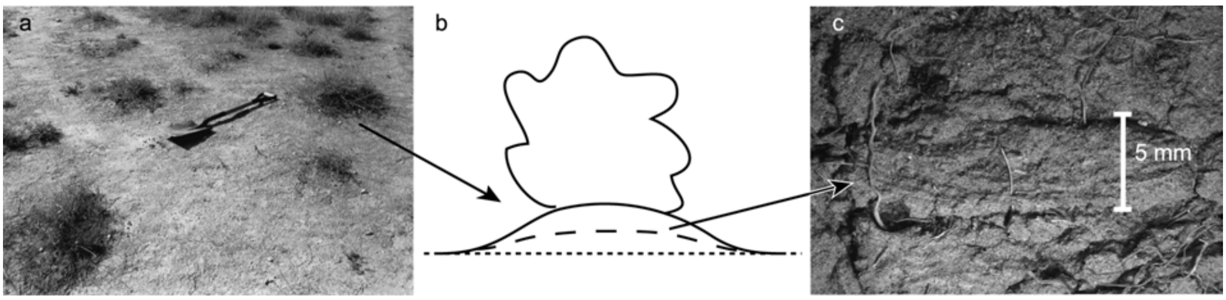


Fig. 4.1 a) An overview of shrub mounds in Sayeret Shaked, b) schematic drawing of shrub mound, whereby the solid line indicates actual mound surface, the dotted line indicates actual crust surface and the striped line indicates old crust surface in which mound formation started, c) close up of crust remnant which separates the upper soil layer and lower soil layer (mound M5).

### *4.2.2 The LAPSUS model*

In this study LAPSUS is further adapted to handle the influence of different surface covers on water redistribution. Infiltration $I$ (m time$^{-1}$) is therefore calculated based on the available water in a grid cell by the following formula (Chapter 3):

$$I = I_f \cdot Q \tag{3.1}$$

whereby the infiltration fraction $I_f$ (-) is dependent on vegetation cover $V$ (%), as follows:

$$I_f = I_v \cdot (V / 100) + I_c \cdot (1- (V / 100)) \tag{4.1}$$

whereby $I_v$ is the fraction of $Q$ infiltrating under shrubs and $I_c$ is the infiltration fraction for crust-covered surface. In this application a grid cell size of 0.125 m is used and grid cells are assumed to be either totally covered by vegetation or totally covered by crusts. This vegetation-dependent infiltration algorithm represents Hortonian overland flow processes in the model, as it differentiates between shrub covered areas with a high infiltration rate and crusted areas with a low infiltration rate. Infiltration is corrected for available storage capacity per grid cell, which equals soil depth times soil pore volume $\phi$ (m$^3$ m$^{-3}$), giving the maximum possible infiltration volume (m time$^{-1}$). This correction adds saturation overland flow processes in the model. The infiltration procedure has the advantage that it calculates infiltration only when total water on a grid cell (precipitation and runon) is known, which closely resembles the natural processes during a precipitation event. A disadvantage of this procedure is that at equal slopes, like the used test slope, infiltration and water flow tend to reach equilibrium, resulting in constant values for water flow and infiltration after only a few grid cells. This is not encountered in a natural catchment, where slope roughness causes more divergence and convergence of flows. For crust-covered surfaces an additional maximum infiltration depth is used to incorporate the low saturated hydraulic conductivity of a crusted surface in the model (Eldridge et al., 2000; Ludwig et al., 2005). Such a maximum infiltration depth helps to avert the limitations of the infiltration formula on the used test slope. After each run the DEM and soil depth map are corrected for net erosion or sedimentation (m time$^{-1}$) and dust deposition (m time$^{-1}$). Dust deposition is assumed similar over the whole catchment, following the conclusions of Shachak and Lovett (1998). Erosion and sedimentation are recalculated to kg ha$^{-1}$ using the average dry bulk density of the soil.

### *4.2.3 Model exercises*

*Test slope preparation*

To test the model a hypothetical test slope of 20 by 20 meter (400 $m^2$) was considered, which was divided in 0.125 x 0.125 m grid cells, with the surface characteristics and climate of Sayeret Shaked. The slope had a constant slope angle of 6° and no micro-relief (Fig. 4.2a). Soil depth was assumed constant (0.83 meter). The surface was divided into crust and shrub patches, by manually positioning individual shrubs over the area, first taking into account the shrub canopy diameter (0.125 – 0.875 m) and second the percentage of shrub canopy covering the test slope (0 – 100% surface cover). The shrubs were equally distributed over the test slope using a diagonal lattice, avoiding unrealistically long runoff lines (Fig. 4.2b).

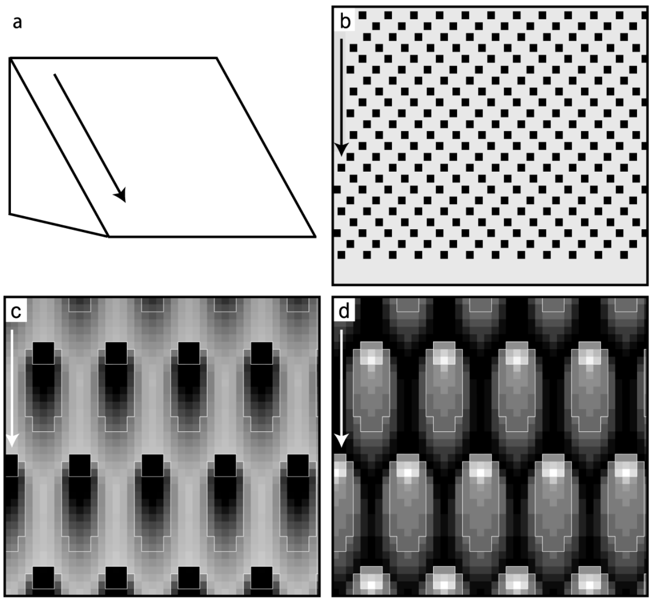


Fig. 4.2 a) DEM of the test slope (top 100.0 m asl, bottom 97.9 m asl), b) an example shrub cover map at shrub cover 21%, shrub diameter 0.625 m (grey – crust, black – shrub), c) spatial patterns of runoff (white – high and black – low) and of d) sedimentation (white) and erosion (black) for 6% shrub cover and 0.375 m shrub diameter. Black squares in c represent shrub surface area, white lines in c and d enclose sedimentation areas. The arrows indicate the downslope direction.

*Single precipitation event simulations*

First, the effect of shrub canopy cover (0 – 100% surface cover) and shrub canopy diameter (0.125 – 0.875 m) on runoff ($m^3$), erosion, sedimentation and sediment export (kg $ha^{-1}$) was studied during one single precipitation event of 30 mm. The effect of shrub cover were studied by varying shrub cover at a constant shrub diameter of 0.375 meter, while the effect of shrub diameter was studied by varying shrub diameter at 3, 12, 25 and 33% shrub cover. Parameter settings were, as much as possible, estimated with field data from Sayeret Shaked. The infiltration fraction of crust surface ($I_c$ = 0.64) and shrub surface ($I_v$ = 0.91) was based on rainfall-runoff experiments in the catchment of Sayeret Shaked at 0.5 $m^2$ plots (Shachak et al., 1998). Maximum infiltration depth for crusted surface was set at 0.03 meter, equal to the maximum crust depth (Eldridge et al., 2000; Eldridge et al., 2002). Average pore volume $\phi$ (0.46 ± s.d. 0.03, n = 7) was derived from bulk density (1442 ± 90 kg $m^{-3}$, n = 7) of oven-dried 100 $cm^3$ soil samples and particle density of the local loess (2.67 g $cm^{-3}$) (Offer and Goossens, 2001). Dust and organic matter deposition was set on 0.00216 mm/event for shrub surface and 0.00148 mm/event for crust surface based on previous studies (Shachak and Lovett, 1998). Obviously the difference in dust deposition between shrub and crust surface can be disregarded at this time scale. The parameters $p$, $K_{es}$, $P_{es}$, $m$ and $n$, were estimated according to Schoorl et al., 2000, and model calibration. The parameter $p$ was set to 2, and $m$ and $n$ to 1.5. For these short-term simulations, $K_{es}$ (erodibility) and $P_{es}$ (sedimentability), were assumed to be equal for crust and shrub surfaces to simplify comparison of results, and were estimated from model calibration based on a rainfall-erosion relationship established in a more arid part of the Negev Desert for a plot of 4 x 20 meter (Evenari et al., 1982a). No large scale erosion data are available in Sayeret Shaked. I estimated net slope erosion to be 232 kg $ha^{-1}$ for an event of 0.030 m precipitation at 6% shrub cover, resulting in $K_{es}$ of 0.030 $m^{-1}$ and $P_{es}$ of 0.003 $m^{-1}$.

*Long-term simulations*

Formation of shrub mounds, as reflected by an in increase of surface elevation, was studied over a 100-year period under different precipitation scenarios with LAPSUS. The initial DEM and soil depth map were similar to those used in the simulations of the single precipitation events. At t = 1 vegetation occurred as shrub seedlings on the slope (242 seedlings on 400 $m^2$). The seedlings grow during the model run following a simple growth curve, independent of precipitation, based on a growth curve of Chew and Eastlake Chew (1965). Competition and disturbances were not taken into account. Growth rates were assumed to be 1 cm $yr^{-1}$ during the first fifty years and to gradually decrease to produce a 21% surface cover with shrubs of 0.625 m diameter after 80 years (approximate curve: shrub canopy diameter = $-6*10^{-5}$ * shrub $age^2$ + 0.0126 * shrub age). Values for $I_v$, $I_c$, $\phi$, $p$, $m$, $n$ and dust deposition rate were similar to those in the simulations of single precipitation events. In contrast to the single-event simulations, I assume $K_{es}$ to be 0.0112 $m^{-1}$ for crusted surfaces and 0.0030 $m^{-1}$ for shrub surfaces, and $P_{es}$ to be 0.0050 $m^{-1}$ for crusted surfaces and 0.3000 $m^{-1}$ for shrub surfaces. Shrubs and crusts have a different sensitivity for erosion and sedimentation, which has a clear effect at longer time scales and were therefore included in the model (Bochet et al., 2000; Calvo-Cases et al., 2003; Schlesinger and Pilmanis, 1998). These values were obtained from model calibration with rates of shrub mound formation based on field results and literature.

Three different precipitation scenarios were considered. For the normal scenario I repeated ten 10-year daily precipitation events > 20 mm (21 events in ten years) measured at the Gilat Research Centre in the vicinity of Sayeret Shaked (1996/1997 – 2005/2006). In the dry scenario precipitation was decreased by dividing all used events of the normal series by two. For the wet scenario precipitation was increased by multiplying all used events of the normal series by two.

Table 4.1 Profile descriptions of shrub mound and neighbouring crusted surface

| **Mound number** | **Patch type** | **Height above surface** (cm) | **Depth** (cm) | **Layer description** |
|---|---|---|---|---|
| M1 | Mound | 3.0 | 0.0-1.7 | Darker colour, loosely packed, granular structure |
| | | | 1.7-6.5 | Lighter colour, densely packed, blocky structure |
| M4 | Mound | 6.0 | 0.0-2.2 | Darker colour, loosely packed, granular structure |
| | | | 2.2-2.4 | Small crust remnant 1.5 cm long |
| | | | 2.4-6.1 | Lighter colour, densely packed, blocky structure |
| | Crust | 0.0 | 0.0-0.2 | Crust with slightly darker colour |
| | | | 0.2-6.5 | Lighter colour, densely packed, blocky structure |
| M5 | Mound | 5.5 | 0.0-2.5 | Darker colour, loosely packed, granular structure |
| | | | 2.5-3.0 | Crust remnant of 4.0 cm long |
| | | | 3.0-6.0 | Lighter colour, densely packed, blocky structure |
| | Crust | 0.0 | 0.0-0.4 | Crust with slightly darker colour |
| | | | 0.4-6.5 | Lighter colour, densely packed, blocky structure |
| M6 | Mound | 5.0 | 0.0-1.7 | Darker colour, loosely packed, granular structure |
| | | | 1.7-2.0 | Crust remnant of 5.0 cm long |
| | | | 2.0-6.0 | Lighter colour, densely packed, blocky structure |
| | Crust | 0.0 | 0.0-0.2 | Crust with slightly darker colour |
| | | | 0.2-6.0 | Lighter colour, densely packed, blocky structure |

## 4.3 Results

### *4.3.1 Macro-morphological and micro-morphological shrub mound analyses*

The shrub mounds in Sayeret Shaked (n = 15) have an average diameter of 52.87 ± 14.24 cm (min. 28 cm, max. 80 cm) and an average height of 4.30 ± 1.96 cm (min. 1 cm, max. 9 cm). The diameter of the shrub canopy is 43.5 ± 12.26 cm (n = 8, min. 30 cm, max. 62 cm). Undisturbed soil samples in a subset (n = 4) of these shrub mounds (height 4.88 ± 1.31 cm) with surrounding crusted surface, were studied in detail with a stereo-microscope (Table 4.1). In each mound two different soil layers can be distinguished often separated by a discontinuous horizontally elongated and stratified crust (Fig. 4.1). The upper layer (2.03 ± 0.39 cm) has a darker colour due to the presence of soil organic matter and is loose-packed with a moderate granular structure and a friable consistence (Table 4.1). By contrast, the more densely packed lower layer lacks visible soil organic matter and has a massive structure with a hard consistence. It visually resembles the layer found below the crusted bare soil surfaces adjacent to the mounds, and is in average 2.85 ± 1.08 cm raised above the current crust surface (Fransen, 2004).

*4.3.2 Single precipitation event simulations*

I studied the effect of shrub canopy cover and diameter on water and sediment redistribution for single events by model simulation. Along a slope, runoff and runon are highest on the crusted surface, while infiltration is highest within the shrub patches (Fig. 4.2c). Erosion is highest upslope and at the sides of the shrubs, while sedimentation dominantly occurred in shrubs and immediately downslope (Fig. 4.2d). When shrub cover increases, by constant shrub diameter, runoff from the slope is strongly reduced, as well as total slope erosion and the sediment delivery ratio (Fig. 4.3). Under influence of increasing shrub cover total slope sedimentation initially increases and later decreases. I simulated the effect of shrub diameter on water and sediment redistribution for four different shrub covers keeping total cover constant. In general runoff of the slope increases with increasing shrub diameter, as does total slope erosion, total slope sedimentation and sediment export (Fig. 4.4).

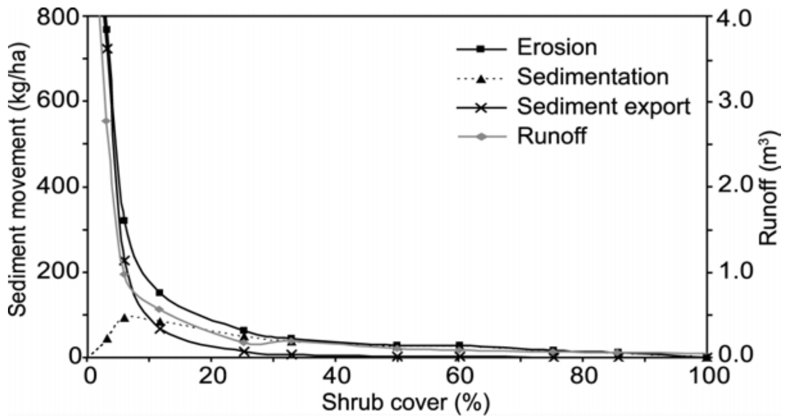


Fig. 4.3 Runoff ($m^3$), total slope erosion, sedimentation and sediment export (kg $ha^{-1}$) in relation to shrub cover (%).

### 4.3.3 Long-term simulations

Long-term (100 years) simulations with the current precipitation amount (normal precipitation scenario) result in formation of mounds by a surface rise of 1.32 centimetres of the shrub covered surface and a surface erosion of maximally 2.77 centimetres of the crusted soil (Fig. 4.5a). Bare surface is eroded while sedimentation only occurs below shrubs. Under a regime with low precipitation sums erosion is absent and little sedimentation (maximum 0.9 cm) occurs (Fig. 4.5b). By contrast, a high precipitation sum scenario demonstrates strong erosion (maximum 63.9 cm) and little sedimentation (maximum 0.7 cm) (Fig. 4.5c).

## 4.4 Discussion

### 4.4.1 Process of shrub mound formation

Shrub mounds can be formed by a combination of several processes, both sedimentary and erosive (Bochet et al., 2000; Parsons et al., 1992; Ravi et al., 2007; Shachak and Lovett, 1998). Shachak and Lovett (1998), studying mound formation in Sayeret Shaked, state that shrub mound formation in this loess covered catchment, is a sedimentary process caused by dust deposition and organic matter accumulation, assuming no erosion. The field and stereo-microscopy results of this chapter show that two soil layers with clearly different characteristics occur within the shrub mounds of this catchment, separated by a discontinuous horizontally elongated crust (Fig. 4.1). The lower layer of the shrub mounds is morphologically similar to the adjacent crust covered soils, while the top layer is darker coloured and displays a granular structure and loose packing (Fig. 4.1c). The similarity between the lower shrub mound soil and the surrounding crust soils, combined with the presence of intact crust remnants within the shrub mound, demonstrate that mound formation starts at the top of a crusted surface after shrub establishment (Fig. 4.1). In time mounds are raised by addition of aeolian dust and increased alluvial sedimentation by supply of material from the adjoining bare crust (including deposited aeolian dust), higher infiltration underneath the shrub and deposition of plant organic matter on top. As a result the top 2.03 ± 0.39 cm thick layer of the mounds is formed by sedimentation processes combined with higher biological activity and increasing porosity of the soil (Zaady et al., 1996). The established sedimentation activity agrees with that reported by Shachak and Lovett (1998) and Bochet et al. (2000). However, in my study the crust remnants between both soil layers are situated 2.85 ± 1.08 cm above the current surrounding crust surface. This observation strongly points to erosion of the surrounding crust surface (Table 4.1).

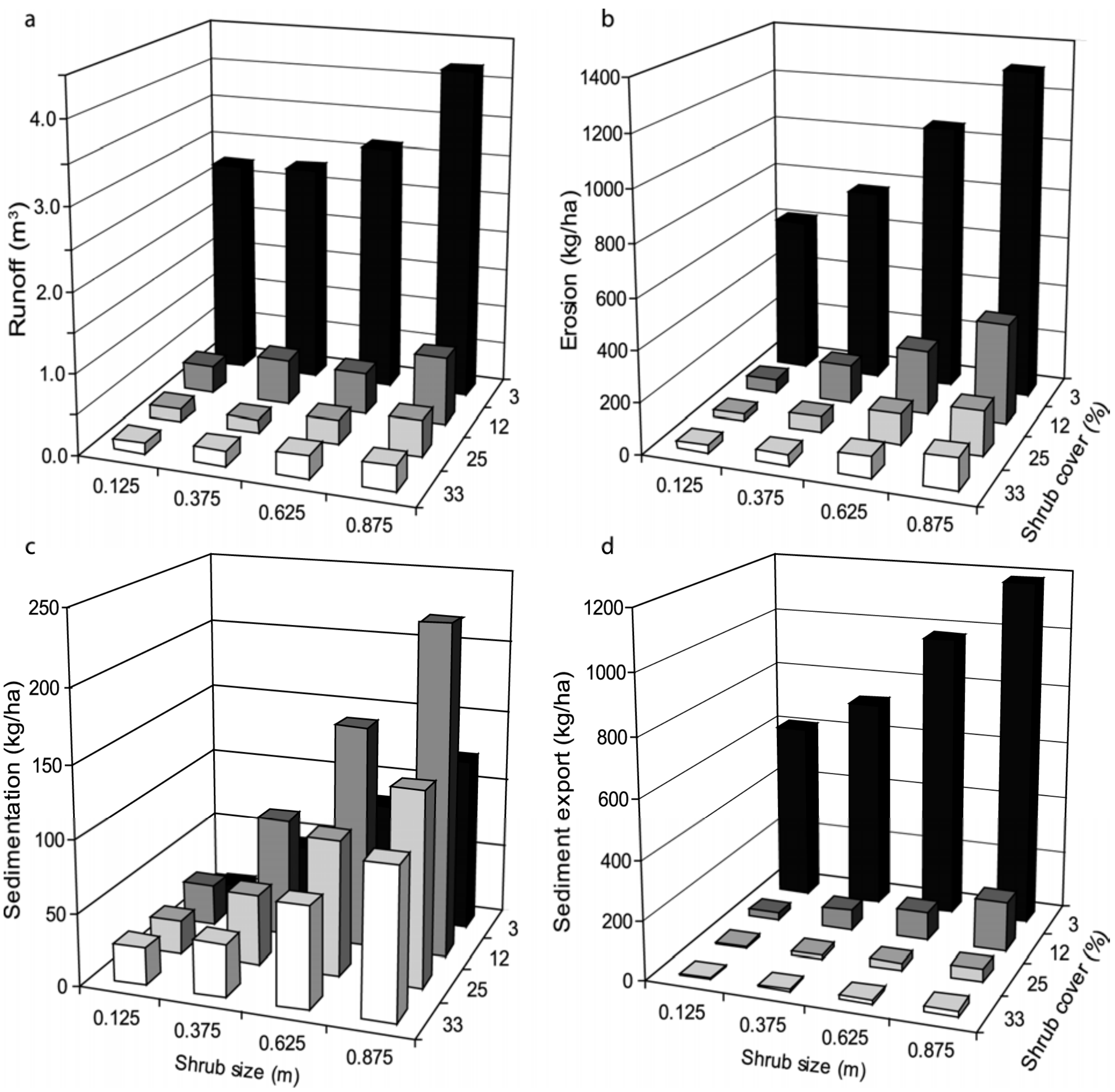


Fig. 4.4 Total slope a) runoff ($m^3$), b) erosion (kg $ha^{-1}$), c) sedimentation (kg $ha^{-1}$) and sediment export (kg $ha^{-1}$) in relation to shrub size for 3%, 12%, 25% and 33% shrub cover for one event.

Overall the crust surface will denudate in time, which is supported by the low, but continuous erosion rates in these areas in general (Shachak et al., 1998; Zaady et al., 2004).

The model simulations of single precipitation events also suggest spatial patterns of erosion and sedimentation. Sedimentation is highest within the shrub surface where infiltration and surface roughness is high, and decreases downslope from the shrub (Fig. 4.2c/d). Erosion is highest upslope and along the shrubs. Shrub surfaces are predominantly sedimentation zones while crust surfaces are predominantly erosion zones. The simulated spatial pattern of sedimentation diverges from field observations, as on real slopes shrub mounds tend to grow to the sides forming elongated mounds parallel to the elevation lines (Klausmeier, 1999). This phenomena is probably caused by the herbaceous understory growing on the upslope part of the mound. Here runoff water is redirected and slowed down, increasing water availability. Based on field observations and modelling exercises I conclude that shrub mounds, in Sayeret Shaked, are formed by a combination of sedimentation and erosion processes.

### *4.4.2 Conditions for mound formation*

Concerning the dominant processes and basic conditions, the model simulations indicate that runoff and erosion are highest on crusted slopes, and decrease strongly by increasing shrub cover, as does sediment export (Fig. 4.3). It confirms that densely shrub-covered slopes retain most water, sediment and nutrients within the slope itself. In contrast a less dense shrub-covered slope experiences high leakage of water and sediments as the few shrubs are ineffective in collecting and retaining the resources within the slope (Boer and Puigdefabregas, 2005; Cammeraat and Imeson, 1999; Ludwig et al., 1999; Wilcox et al., 2003). Although a densely covered slope retains more resources, vegetation cover is often limited by the low precipitation amounts in semi-arid areas. Established shrubs are favoured on less densely covered slopes where more water, sediment and nutrients are redistributed and available per shrub (Boeken et al., 1995; Schlesinger et al., 1989). This contrast is likely to result in slopes with higher resource leakage. Depending on local circumstances the feedbacks between shrubs and resource flows can result in self-organizing vegetation patterns of for instance strips, labyrinths or, like in Sayeret Shaked, spotted patterns (Rietkerk et al., 2002).

On a semi-arid slope with few shrubs in a spotted pattern both erosion and sedimentation are active, enabling shrub mound formation. In the model simulations shrub mounds form in a range of approximately 3 and 25% shrub cover. On a bare or almost bare slope, sedimentation is absent by lack of preferential infiltration areas (below shrubs), while at densely covered slopes sedimentation is reduced by availability of eroded sediment for later deposition (Fig. 4.3). Not only shrub cover but also shrub diameter strongly influences sediment redistribution and thus mound formation. Larger shrubs on a slope with constant shrub cover result in higher runoff, stronger erosion and more sediment export, as when shrubs get larger at a certain constant shrub cover the interspaces between shrubs get larger as well. This increases the distance that water can flow and increases the likelihood of continuous runoff lines directly to the outlet without interception by shrubs (Fig. 4.4). Meanwhile larger shrubs have a higher infiltration potential, higher sedimentation and a larger shrub mound. This positive feedback, provided that shrub cover remains constant, will stimulate shrub canopy growth and mound formation. Mound formation is therefore strongest at low shrub cover and large shrub canopy diameter (Fig. 4.4).

On a natural slope with dynamic shrub cover an increase in shrub cover by either shrub canopy growth or new shrub establishment results in a decrease in water and sediment redistribution and capture per shrub (Fig. 4.3). This negative feedback hampers a further increase in shrub cover. On the other hand, a decrease in shrub cover due to shrub mortality, can be counteracted by an increase in diameter of the remaining shrubs, because of the increase in resource capture per shrub and rate of mound formation and shrub growth. This negative feedbacks will push the shrub – crust landscape to the shrub cover with the highest resource capture per shrub. However, the shrub – crust landscape is unlikely to reach stability, due to the long response time of vegetation (especially in case of slow-growing shrubs) to external changes (for instance climate change). Therefore a shrub – crust landscape might follow other trajectories than discussed above.

### *4.4.3 Shrub mound formation at longer time scales*

Little is known about ages of shrub mounds and their rate of formation. According to a previous study in Sayeret Shaked shrub mounds are formed in 180 – 290 years by sedimentation only (Shachak and Lovett, 1998). Using the crude assumption that erosion and sedimentation are both as dominant, as resulted from the field study, I can half the formation time mentioned by Shachak and Lovett. I used a rounded formation time of 100 years, which fits well in the other estimations given (Abrahams et al., 1994; Rostagno and Del Valle, 1988).

Starting from a flat surface at t = 0, LAPSUS forms shrub mounds by using erosion and sedimentation, agreeing well with my field observations. In 100 years LAPSUS simulates maximally 2.77 centimetres erosion of the bare surface, while the shrub mound surface is raised with 1.3 centimetres by sediment and dust deposition (Fig. 4.5a). Erosion occurs on all bare surfaces, consistent with the continuous erosion rates in this catchment (Shachak et al., 1998; Zaady et al., 2004). The sides of the shrub mounds are most strongly eroded, as here continuous flow lines are formed over the whole test slope (Fig. 4.2b). Sedimentation only occurs below shrubs, which regulate lateral mound formation by increasing sedimentation positions with its canopy growth. In time formation rate of shrub mounds stabilizes. Once the shrub mound is raised above the zone of water influence and related sedimentation, only dust deposition will add sediments to the mound (Fig. 4.5a). Additionally the average crust surface will erode less, as runoff water concentrates in gullies, while the shrub mound itself will start eroding as well.

While erosion is simulated correctly, sedimentation is clearly underestimated by the model. This can be explained in several ways: first, the model simulates only sedimentation by water flow. Sedimentation caused by splash erosion is not taken into account, which can be important in mound formation (Parsons et al., 1992). Second, organic matter from plant detritus is deposited at higher rates on the mound than on the crust (Shachak and Lovett, 1998). This is not incorporated in the model as it only handles sediments. Third, during dust storms shrubs collect dust along the whole canopy, strongly increasing sedimentation on the surface compared to a bare surface. During precipitation events this dust is washed down adding to mound formation. Field results about this process are absent; therefore I could not take this in account in the model. Fourth, biological activity increased porosity of the mound. The model uses only one bulk density and ignores therefore the porosity increase and associated surface rise below shrubs in time.
Although LAPSUS does not incorporate all processes related to shrub mound formation, still mound simulation is successful and resembles the actual shrub mounds in Sayeret Shaked (Boeken and Orenstein, 2001; Shachak and Lovett, 1998). The model proves to be valuable for the modelling of ecohydrological landscape processes in semi-arid areas. The used multiple flow direction routing is essential to simulate mound formation, as it enables sediment deposition on raised grid cells, as long as they are not higher than the grid cell of origin. The steepest descent direction routing only routes water to the lowest neighbour, preventing mound formation. Consequently, only the use of the multiple flow direction routing in LAPSUS enables us to simulate mound formation.

### *4.4.4 Climate and management effect on shrub mound formation*

Climate change will affect the current semi-arid regions strongly (IPCC, 2001). For the Northern Negev Desert it is difficult to predict the future climate. This region has a high climate sensitivity because it is positioned at the border between Mediterranean and arid climate belts (Robinson et al., 2006). The semi-arid regions in Israel are expected to become more arid in future, because of higher temperatures and evapotranspiration, and lower precipitation (Guy and Safriel, 2000). The results of the scenario simulations should be seen as an indication of what might happen if annual precipitation sums change. For the low precipitation sum scenario the results indicate that redistribution of water and sediments will be strongly reduced. Shrub mound formation, starting from a bare surface, will be almost nil and the test slope very stable (Fig. 5b). In the scenario with low precipitation sums, it is unlikely that shrubs grow to a diameter of 0.63 m, as in these climates (100 mm precipitation per year) water redistribution is limited to slopes with bedrock outcrops where additional runoff is formed (Yair, 1994). Soil-covered slopes, as this test slope, barely redistribute water and are mostly too dry to sustain vegetation.

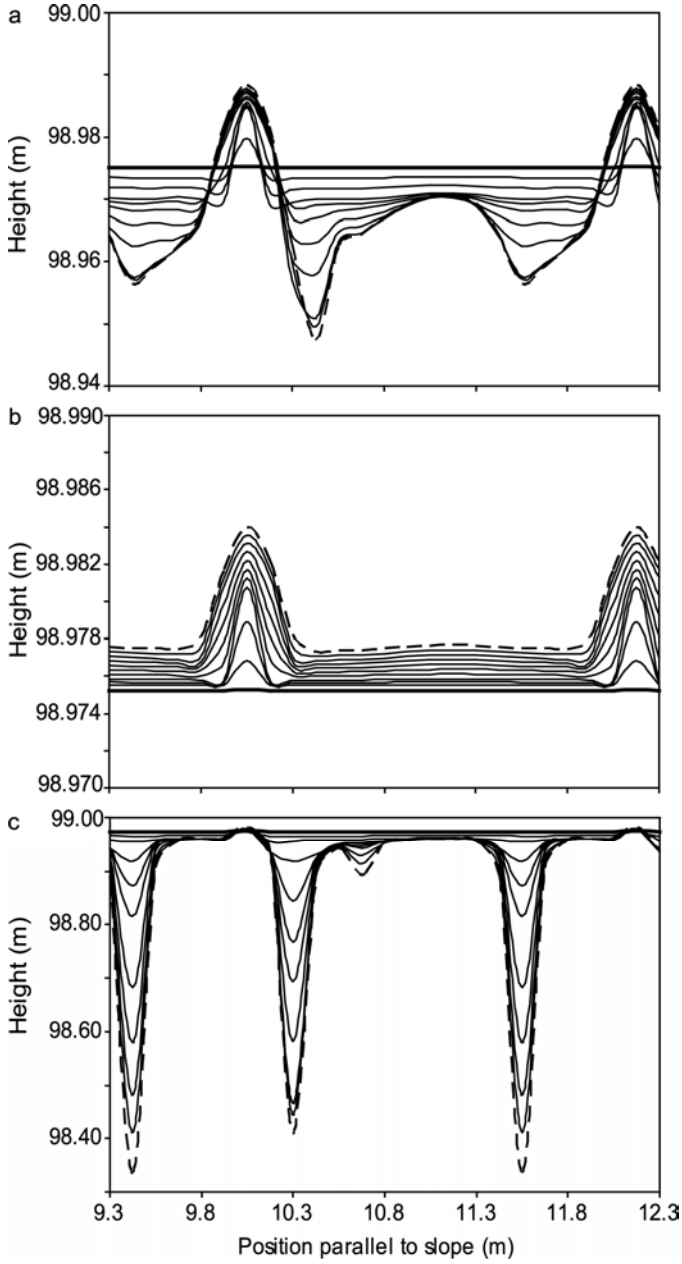


Fig. 4.5 Cross-sections parallel to the slope for 100 years of shrub mound simulation at a) current, b) low and c) high precipitation sum scenario. Year 1 is indicated by a solid line, year 100 is indicated by a dashed line, the intermediate lines represent approximately each 10th simulation year. Scaling of y-axis differs per graph.

In a high precipitation sum scenario erosion is much higher, resulting in erosion rates of almost 70 centimetres in 100 years forming deep gullies (Fig. 5c). The test slope is not stable at all. Under such conditions formation of shrub mounds results mainly from dust deposition on the shrub mound itself, as other sediments are routed around the mounds. Shrub seedlings will be damaged or removed by the strong water movement on the slope and will not have a chance to reduce runoff. In an existing shrub – crust landscape this gully formation might also occur when precipitation rapidly increases, as shrub cover will lag behind. In a landscape receiving annually 400 mm precipitation for a long time, it is expected that vegetation cover is complete. It is therefore unlikely that shrub mound formation occurs at all, except when long-term overgrazing reduces vegetation cover. Apparently only in a limited climate range these shrub – crust landscapes with shrub mounds can be formed.

## 4.5 Conclusions

In the semi-arid northern Negev Desert shrub – crust landscapes experience strong resource leakage, because the few shrubs are unable to retain the resources on the slope. Under these circumstances shrub mounds are formed, mainly by a combination of erosion by water and sedimentation. Aeolian processes are less important, at least in this region. Simulation studies with LAPSUS demonstrate that in this region the model is well able to simulate the dominant processes leading to the formation of shrub mounds. On bare slopes no sedimentation occurs for lack of shrub-related infiltration zones, while on strongly vegetated slopes sedimentation is limited for lack of eroded sediment. Therefore mound formation is strongest on slopes with a low shrub cover and large shrub diameters, where resource redistribution along the slope and resource capture near shrubs are highest. Shrub mounds, which represent the heterogeneity of the shrub – crust landscape in LAPSUS, form only in a limited climate range. Long-term simulation studies indicates that in both dryer and wetter climates mound formation under undisturbed circumstances is unlikely, because there resource redistribution is either too low or too high. What will happen to shrub – crust landscapes in future aridification phases depends strongly on the rate of climate change, the actual change and the ability of the vegetation to respond to climatic changes.


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# 5 History of a valley fill balancing between climate fluctuations and human occupation in the last 40 000 years

*The interactions between climate change, human occupation and semi-arid landscape dynamics are still poorly understood. In this study I aim to increase the insight in these interactions in a semi-arid environment. A Late Quaternary valley fill in the catchment of Sayeret Shaked is studied. The aggradation and incision history is reconstructed based on a transect study. The reconstructed valley fill is put in a temporal framework by correlation with local climate records and optically simulated luminescence and potsherd dates. Two Late Pleistocene and four Holocene aggradation and incision cycles are recognized, of which three occurred during the last 2000 years. Contradictory to the expected positive relation between amplitude of climate fluctuations and cycles of aggradation and incision, the Late Holocene cycles are stronger than those in the Late Pleistocene and Early to Middle Holocene. The most significant cycle coincides with the rise and fall of the Byzantine Empire and appears related to the higher pressure on the landscape due to human occupation during that time. Human activity appears to have had a strongly amplifying effect on aggradation and incision phases, which are initially triggered by climate fluctuations. This amplifying effect occurs only when human occupation crosses a threshold and triggers destabilization of the landscape. It causes collapse of the ecosystem and increases sediment redistribution.*

Based on: Buis, E., Veldkamp, A., Wallinga, J. and de Blécourt, M. History of a valley fill balancing between climate fluctuations and human occupation in the last 40 000 years, Northern Negev Desert, Israel. Under revision for Geomorphology.

## 5.1 Introduction

Land degradation is becoming an increasingly large problem throughout the arid and semi-arid regions of the world, among others causing increased incision of the gully bed and unwelcome deposition of sediments elsewhere (Roberts and Barker, 1993). These processes are often attributed to human activities on marginal lands (Bull, 1997). However, on a longer time scale it is clear that phases of aggradation and incision occurred well before human impact started (Avni et al., 2006). Already in the Pleistocene several aggradation and incision cycles were recognized all over the world (Avni et al., 2006; Botha et al., 1994; Bruins and Yaalon, 1993; Eriksson et al., 2006; Farabaugh and Rigsby, 2005; Temme et al., 2008; Thomas and Thorp, 1995). These cycles were mainly governed by trends of humidification and aridification. The biogeomorphic response model of Knox (1972) indicates that the interplay between precipitation and vegetation is the dominant factor influencing landscape dynamics (Botha, 1996; Bull, 1997; Eriksson et al., 2006; Roberts and Barker, 1993). In semi-arid regions even small changes in vegetation cover have a strong effect on landscape dynamics (Carson and Kirkby, 1972). A change from arid to semi-arid climate is expected to result in increased slope erosion and gully incision, as vegetation lags behind the increase in precipitation (Knox, 1972; Roberts and Barker, 1993). During transitions to arid climates the decrease in vegetation is more gradual and the landscape processes are less intense (Botha, 1996). The slopes erode, while the gully aggrades. Similarly during an arid phase sediments are redistributed from the slopes towards the gully, in some situations resulting in limited gully incision (Carson and Kirkby, 1972). During a semi-arid phase little sediment is redistributed, as vegetation cover is high and runoff low. The intensity and effect of landscape dynamics depends on the direction and rate of humidity change and on the position in the drainage network (Knox, 1972; Thomas and Thorp, 1995). This theory of climate driven landscape dynamics is widely accepted. Yet, the strong human influence which tends to accelerate the natural processes nowadays, can not be ignored (Avni et al., 2006; Foster et al., 2007; Rustomji and Pietsch, 2007; Viles and Goudie, 2003). Already since the first settlements in the Middle Bronze Age humans appear to have enforced landscape dynamics, most often increasing erosion and land degradation (Brown and Barber, 1985; Mieth and Bork, 2005; Schmitt et al., 2006; Vanwalleghem et al., 2006). A remaining question is whether human occupation, and related influence, is merely a resultant of long-term climate trends or if human occupation governed processes of incision and aggradation already in historical times. Reconstruction of former incision and aggradation cycles can help to unravel the combined effect of natural climate driven processes and human influence on landscape dynamics. Especially studies back to Pleistocene times are helpful to distinguish between the two processes (Roberts and Barker, 1993).

The Negev Desert in Israel has been occupied by humans already since Neolithic times and has a high climate sensitivity which makes this region very suited to study the interplay of climate, humans and landscape dynamics (Avni et al., 2006; Issar, 1998). In the history of the Negev a strong parallel can be seen between climate and human occupation, whereby peaks of human occupation appear closely related to wetter periods and Dead Sea high stands (Migowski et al., 2006; Robinson et al., 2006). Several societies seem to have collapsed because of aridification, suggesting climate as the main driver and human occupation as the resultant (Issar, 1998). Avni et al. (2006) even concluded that during the Holocene degradation was a natural process in the Negev Highlands and was counteracted by historical human activity.

This study aims to reconstruct the cycles of incision and aggradation in the small semi-arid catchment of Sayeret Shaked in the northern Negev Desert (Fig. 1.2 and §1.3.2). I aim to relate these cycles to known climate records, using optically stimulated luminescence dating and potsherd dates for age control on the sediments. This study adds to the study of Avni et al. (2006) as the selected catchments differ strongly in surface characteristics and in response to landscape driving factors (Chapter 2). Avni et al. (2006) studied rocky catchments, while I concentrate my interest on a loess-covered catchment. These catchments respond very differently to precipitation changes, because on rocky slopes runoff volumes are high, whereas on soil-covered slopes most runoff will infiltrate quickly (Yair and Raz-Yassif, 2004). As such a strong difference in runoff and erosion potential exist between rocky and soil-covered catchments. By unraveling the effect of climate change and human influence on land degradation, I aim to get better insight in the relevance and effect of climate change and human influence on landscape dynamics.

## 5.2 Material and Methods

### *5.2.1 Field methods*

A transect of 8 profiles was studied perpendicular to the current gully (Fig. 5.1). Additionally a ninth profile was studied, which was positioned near the outlet of the catchment. Elevation (meter above sea level) of the profiles was estimated in the field using topographical maps and GPS coordinates. Profile pits were excavated and layers were distinguished based on texture, colour, soil animal excrements, lithology and sedimentology, and described using the FAO terminology (De Blécourt, 2005; FAO, 1990). For each profile depth of the bedrock was determined, where needed by augering. Only where bedrock was found in profile an exact depth of the sediment layer could be given. Based on the soil profile descriptions, dated potsherds, optically stimulated luminescence (OSL) dates and local climate records, different phases of aggradation and incision were distinguished and placed in a temporal framework. The potsherds were dated by Dr. Y.

Yekutieli and Dr. P. Fabian of the Department of Bible and Ancient Near Eastern Studies, Ben Gurion University of the Negev, Israel. The potsherds found could give only a *terminus post quem* date which indicated that the layer could not be older than the date of the youngest potsherd, but younger was possible. As only body-sherds were found, the possible dating error of the potsherds is at least plus or minus one century. In this study geological and archeological disciplines were combined, and therefore the nomenclature and time indication common for these disciplines was used. Years ka (x 1000 years) and geological nomenclature was used for the time period before 6.0 ka. Archeological nomenclature and the BC/AD calendar was used for the period afterwards since the first settlements were found in the region of study (Grovin, 1998). Volumes ($m^3$) of aggradation and incision were calculated for a 1 meter segment at the position of the studied transect, by multiplying surface area ($m^2$) of a phase with segment length (m). The surface area was manually estimated using figure 3. Uncertainty ranges (s.e.) were estimated for the surface area of each phase, giving uncertainty volumes after multiplying with segment length. Deposition or incision rates were estimated based on the reconstructed time period of a phase ($dm^3\ yr^{-1}$).

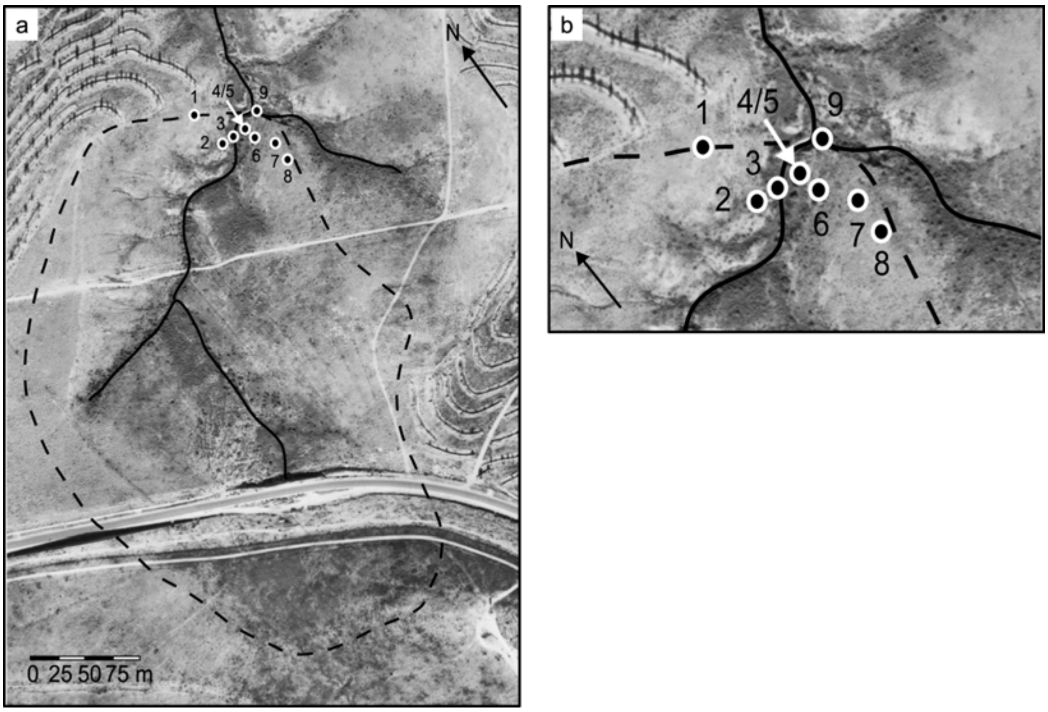



Fig. 5.1 a) Aerial photograph of Sayeret Shaked with positions of the profiles. The mottled line indicates approximate catchment border, solid lines indicate main gullies, b) close-up of position of the profiles.

### 5.2.2 Optically Stimulated Luminescence dating

We used Optically Stimulated Luminescence (OSL) dating of sand-sized quartz grains to determine the time of deposition and burial of deposits (Aitken, 1998; Duller, 2004; Murray and Olley, 2002; Wallinga et al., 2007). The OSL signal of quartz is reset by light exposure during transport and sedimentation of the mineral grains, and builds up after burial due to ionizing radiation from surrounding sediments and a small contribution from cosmic rays.

OSL ages are based on two measurements:

1) The amount of ionizing radiation absorbed by quartz grains since the 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 through the equation:

$$Age(ka) = \frac{D_e(Gy)}{\dot{D}(Gy/ka)} \tag{5.1}$$

Samples for OSL dating were taken in 7.5 cm diameter PVC tubes of 25-cm length in profile 4 and 9. The indicated height is the middle of the tube. Sediment from the outer, light-exposed ends of the tubes was removed under subdued orange light conditions and used for dose rate estimation. Dose rates were calculated based on radionuclide contents of the samples measured using high-resolution gamma-ray spectrometry (Murray et al., 1987). For equivalent-dose estimation quartz grains in a narrow size range (Table 5.1) 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. Table 5.1 lists what method was used for analysis of the $D_e$ distribution, and whether we expect that the OSL age is a reliable estimate of the time of deposition. For two samples (NCL-2105106 and NCL-2105107) the scatter between single aliquot $D_e$ estimates was so large that it was not possible to obtain a reliable estimate. Additional information on the OSL dating methods and age models used is provided in appendix 5.1 following this chapter.

Table 5.1 Summary of methods and age estimations of OSL dating sample. Stand. Stands for standard model, FMM for finite mixture model and MAM for minimum age model. + good validity, ? doubtful validity.

| Sample code | | | De determination | | | | | | |
|---|---|---|---|---|---|---|---|---|---|
| NCL | Profile | Depth | Grain size | Pre-heat | Method | Equivalent dose | Dose rate | Age | Validity |
| | | m | µm | ºC | | Gy (s.e.) | Gy $ka^{-1}$ (s.e.) | Years (s.e.) | |
| NCL-2105119 | 4 | 0.36 | 212-250 | 220 | Stand. | 0.13 (0.01) | 1.66 (0.05) | 1926 (6) AD | + |
| NCL-2105095 | 4 | 0.64 | 212-250 | 220 | Stand. | 0.11 (0.01) | 1.25 (0.05) | 1914 (8) AD | + |
| NCL-2105096 | 4 | 1.49 | 90-150 | 220 | FMM | 1.06 (0.05) | 2.01 (0.07) | 1477 (32) AD | + |
| NCL-2105107 | 9 | 0.61 | 90-150 | 220 | MAM | 2.8 (0.2) | 1.89 (0.06) | 537 (115) AD | ? |
| NCL-2105106 | 9 | 1.07 | 63-90 | 220 | MAM | 3.2 (0.2) | 1.95 (0.06) | 393 (127) AD | ? |
| NCL-2105100 | 9 | 1.87 | 90-150 | 270 | MAM | 5.4 (0.5) | 1.93 (0.06) | 806 (296) BC | + |
| NCL-2105105 | 9 | 2.98 | 90-151 | 270 | FMM | 59.8 (6.0) | 2.09 (0.08) | 28.7 (3.0) ka | + |
| NCL-2105103 | 9 | 3.06 | 90-150 | 270 | Stand. | 81.1 (5.3) | 2.16 (0.08) | 37.5 (2.8) ka | + |

# 5.3 Climate and human occupation record of the region

*5.3.1 Regional climate records*

In the Negev Desert climate ranges from Mediterranean in the north to hyper-arid in the south over a short range of 200 km. This strong gradient in aridity causes a high sensitivity to climatic changes (Robinson et al., 2006) (Fig. 5.1a). The palaeo-lake level record of the Dead Sea was used to reconstruct palaeoclimate of the region. The palaeo-lake level was dominantly controlled by climate and resulted from a balance between input water from precipitation in the source area and evaporation of the lake surface (Bartov et al., 2002; Bookman (Ken-Tor) et al., 2004; Robinson et al., 2006). Only by comparing the Dead Sea palaeo-lake level record with palaeo-temperature records an indication of humidity could be given (Fig. 5.2). We used a compilation of several Dead Sea palaeo-lake level curves (Bartov et al., 2002; Bookman (Ken-Tor) et al., 2004; Migowski et al., 2006; Robinson et al., 2006), and combined it with the more global $\delta^{18}O$ curve of the GRIP ice-core, which could be used as a relative proxy for global temperature (Dansgaard et al., 1993; Grootes et al., 1993; Johnsen et al., 1997).

During the Late Pleistocene the Dead Sea palaeo-lake level was high and temperature low, which reflected the relative wet climate during that time (Fig. 5.2) (Robinson et al., 2006). Both palaeo-lake level and temperature fluctuated, especially at the termination of the Pleistocene, and thus the humidity was expected to vary strongly as well. During the warm Bølling-Allerød period (± 14.6 – 12.9 ka), the palaeo-lake level was high, pointing to a very wet period.

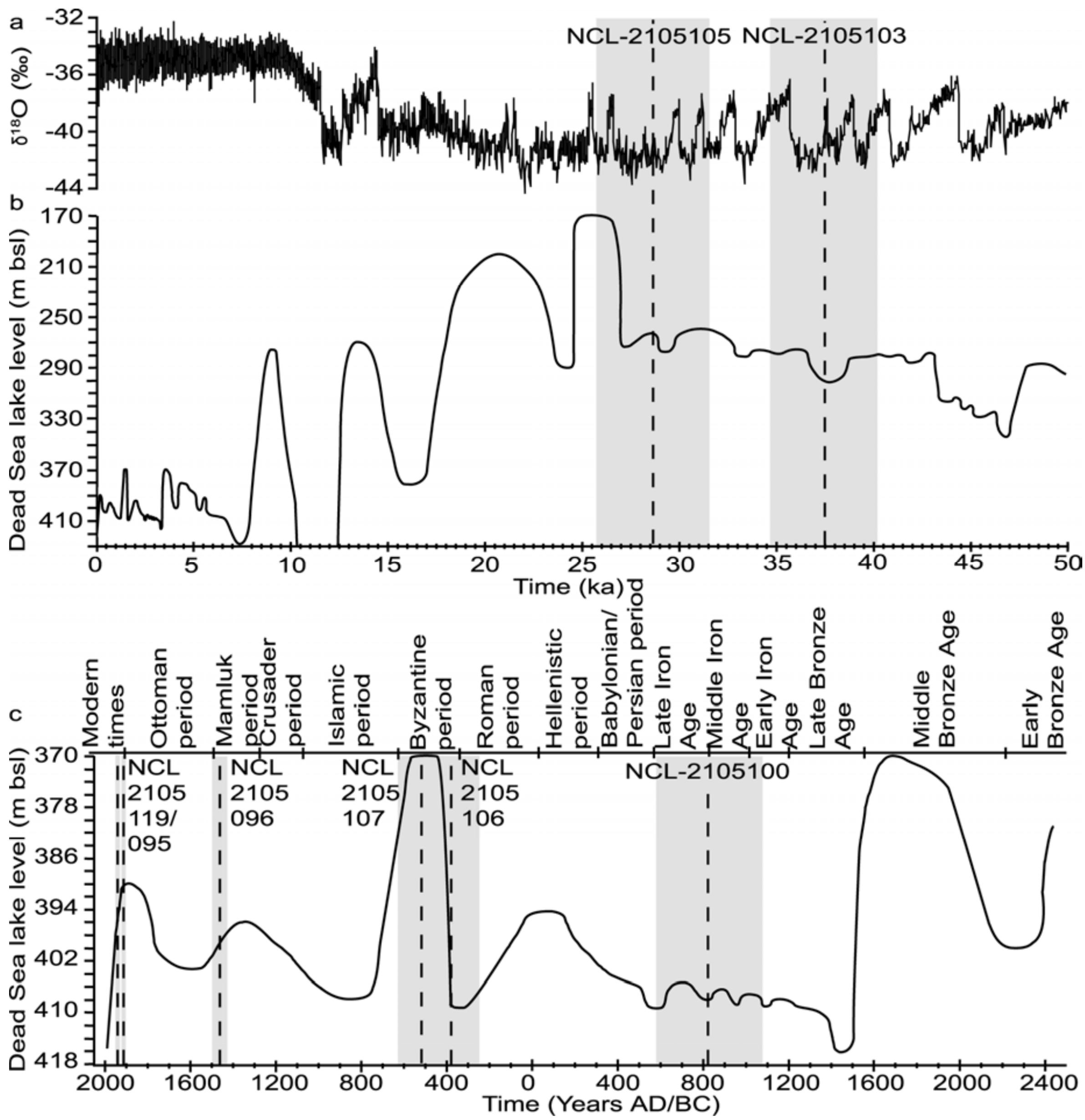



Fig. 5.2 a) $\delta^{18}O$ curve reconstructed from GRIP Ice-core (Dansgaard et al., 1993; Grootes et al., 1993; Johnsen et al., 1997), b) compilation of Dead Sea level curves: 0 – 7.5 ka (Migowski et al., 2006), 7.5 – 25 ka (Robinson et al., 2006) and 25 – 50 ka (Bartov et al., 2002), c) compiled Late Holocene Dead Sea level curve of Bookman (Ken-Tor) et al. (2004) and Migowski et al. (2006). Archaeological time periods according to Bruins (1986). OSL dates given with standard error margins.

The following cold Younger Dryas period (±12.7 – 11.5 ka) displays a very low lake level, possibly even down to 700 meter below average sea level. The Younger Dryas period was probably very dry (Neev and Emery, 1967).

The temperature in the Holocene was stable compared with the Late Pleistocene (Fig. 5.2) (Dansgaard et al., 1993). The resulting palaeo-lake level therefore mainly reflected changes in humidity. The Early Holocene (10 – 7.5 ka) had a high palaeo-lake level with a high temperature, and was therefore very wet. The remaining of the Holocene was considerably dryer, reflected in the low palaeo-lake levels (Goodfriend, 1990; Magaritz, 1986; Robinson et al., 2006). Relatively wet periods coincide with the archeological Chalcolithic period (6.2 – 5.2 ka, 4000 – 3200 BC) and the Early and Middle Bronze Age (5.2 – 3.5 ka, 3200 – 1550 BC), while the Neolithic B (7.5 – 6.2 ka) and the Late Bronze Age (3.5 – 3.2 ka, 1550 – 1200 BC) were drier (archaeological time periods after Bruins, 1986) (Issar, 1998).

The last 3500 years revealed several wetter and dryer periods (Fig. 5.2). Relatively wet periods occurred in the Hellenistic-Early Roman period, the Byzantine period, the Crusader-Mamluk period and the last part of the Ottoman period. Especially the Byzantine period was wet. The Late Bronze Age and Iron Age were dry, as was the transition between the Roman and Byzantine period and the Arab period (Bookman (Ken-Tor) et al., 2004; Migowski et al., 2006). The Dead Sea reached its final high stand at the end of the nineteenth century AD and declined strongly over the last decades because of human water use (Bookman (Ken-Tor) et al., 2004).

### *5.3.2 Regional human occupation record*

The Negev Desert has been used for pastoralism and agriculture since long (Bruins, 1986; Evenari et al., 1961). Already in the Epipaleolithic (ca. 10 – 15 ka) people lived in the Negev Highlands. In the Beer Sheva plain, close to the studied catchment, settlements existed since the Chalcolithic period. During the Early Bronze Age the number of settlements declined, which resulted in almost total abandonment of the settlements in the Middle Bronze Age. A new settlement phase started in the beginning of the Iron Age and increased strongly in the wetter Hellenistic-Roman Period. The number of settlements came to a maximum during the wet Byzantine period. The settlements were gradually abandoned, caused by a strong aridification at the end of the Byzantine period and political changes (Avni et al., 2006; Bruins, 1986; Migowski et al., 2006). It resulted in total abandonment after approximately 900 AD (Issar, 1990). Up to the twentieths century the Negev was mainly used for pastoralism by Bedouins (Bruins, 1986).

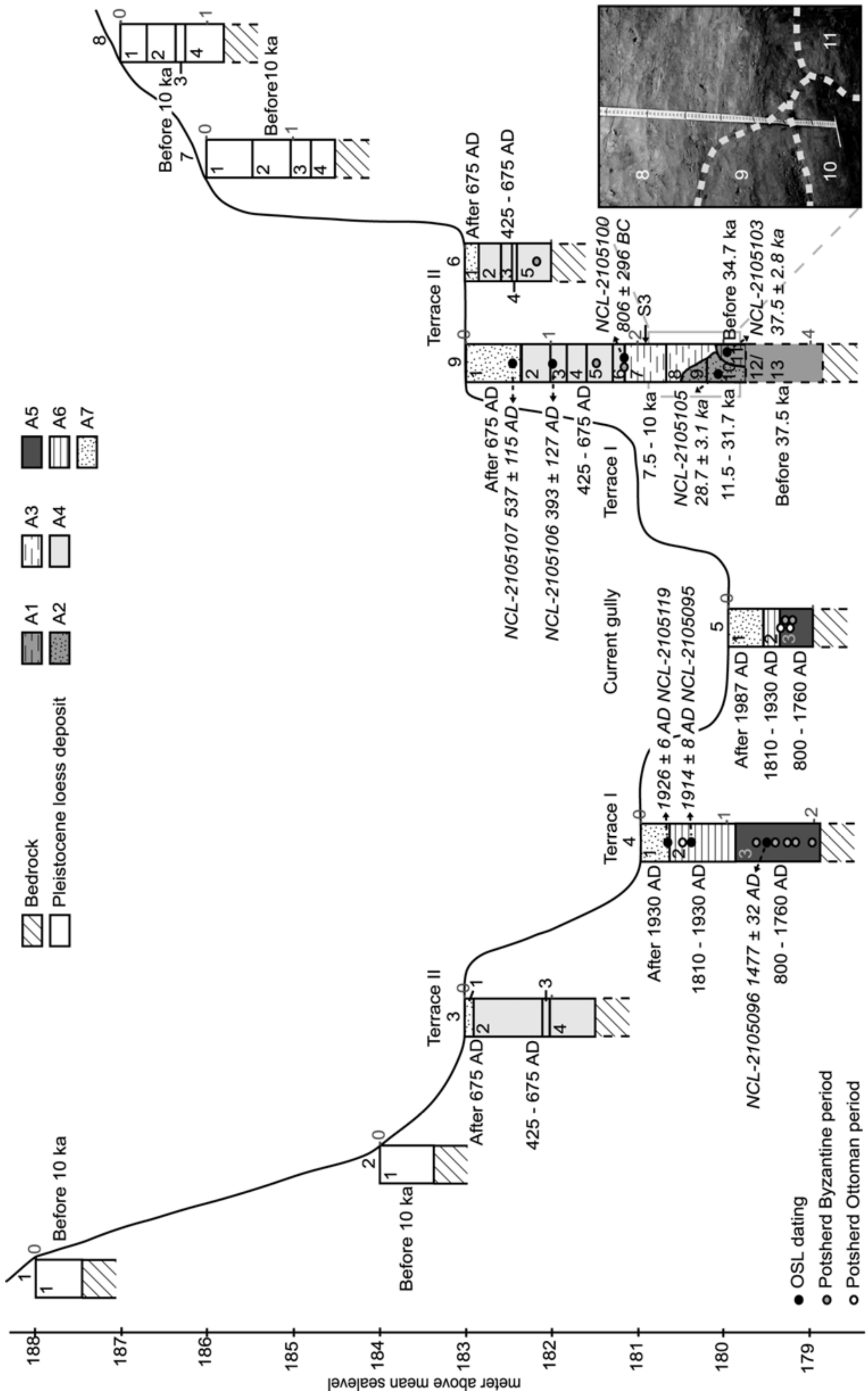



Fig. 5.3 Simplified profile descriptions, with indication of deposition phase and time of each layer. OSL dates given with standard error.

# 5.4 Results

*5.4.1 The higher slopes*

Profiles 1 and 2 are situated at the higher slopes (Fig. 5.3). The profiles exists of one layer of homogeneous loess, in which $CaCO_3$ precipitates resembling mycelia can be seen (Table 5.2). Several blocky stones are found within the profiles. Profiles 7 and 8, at similar position on the other side of the gully, exists of homogeneous loess deposits with layers rich in hard calcium carbonate nodules. In profile 7 these layers also have a high percentage of soil animal excrements. Some layers of profile 8 have a coarser texture.

*5.4.2 The second terrace*

Profiles 3, 6 and 9 are positioned on the second terrace (Fig. 5.1b). Profile 9 is situated near the outlet of the catchment. Profile 3 has three layers of a loamy texture and one layer of coarse sand (Table 5.2 and Fig. 5.3). The layers vary in consistency, percentage of soil animal excrements and amount of crust fragments. One blocky limestone is found.

In profile 6 four layers with loamy texture can be distinguished, which differ only in occurrence and frequency of crust (fragments), percentage of soil animal excrements and calcium carbonate nodules. The fifth layer of silt loam texture has a higher consistency and more calcium carbonate nodules than the layers above. In this layer potsherds of the Byzantine-Islamic transition phase are found ($5^{th}$ – $8^{th}$ century, 400 – 800 AD).

Profile 9 is the deepest profile with thirteen layers. Layer 1 has a homogenous sandy loam texture, with crust fragments and soil animal excrements. Layer 2 has a loamy texture and internal layering which varied in percentage of soil animal excrements and occurrence of crust (fragments). Layer 3 exists of balls of thick waving crusts positioned at similar depth within sandy loam deposits. The balls resemble part of layer 4. This layer exists of sandy loam deposits with many crust fragments and thin continuous crusts, combined with piles of thick waving undisturbed crusts. Layer 5 is composed of homogeneous sandy loam alternated with discontinuous layers of rounded micro-aggregates. Potsherds of the Byzantine-Islamic transition phase are found in this layer. Layer 6 has a loamy texture and some soil animal excrements. Also here potsherds are found of the Byzantine-Islamic transition phase.

Table 5.2 Profile descriptions ($CaCO_3$ as nodules. Excr. stands for soil animal excrements)

| **Profile** layer | **Depth** Cm | **Texture** | **$CaCO_3$** % | **Excr.** % | **Remarks** |
|---|---|---|---|---|---|
| | | | | 1 | 188 m asl |
| 1 | 0-52 | Loam | - | - | Poorly sorted material, many blocky limestones and flint (2-18 cm) |
| | >52 | - | - | - | Saprolite |
| | | | | 2 | 184 m asl |
| 1 | 0-63 | Loam | - | - | Poorly sorted material, many blocky limestones and flint (5-10 cm). $CaCO_3$ precipitates resembling mycelia |
| | >63 | - | - | - | Saprolite |
| | | | | 3 | 183 m asl |
| 1 | 0-10 | Loam | - | - | Few crust fragments, some disturbed by biological activity |
| 2a | 10-44 | Loam | - | 25 | High consistency, many crust fragments |
| 2b | 44-95 | Loam | - | 25 | Many crust fragments, a blocky limestone (5 cm) at 60 cm depth |
| 3 | 95-99 | 420-600 µm | - | - | |
| 4 | 99-150 | Loam | - | 25 | Many crust fragments, >107 cm higher consistency |
| | | | | 4 | 181 m asl |
| 1 | 0-36 | Sandy Loam | - | 5-15 | Few crust fragments |
| 2a | 36-38 | Silt Loam | - | - | Crust layer |
| 2b | 38-48 | 200-400 µm | - | - | Thin dark organic layer at 42 cm depth |
| 2c | 48-49 | Silt Loam | - | - | Crust layer |
| 2d | 49-52 | Sandy Loam | - | 2 | - |
| 2e | 52-53 | Silt Loam | - | - | Crust layer |
| 2f | 53-56 | Sandy Loam | - | 2 | - |
| 2g | 56-58 | 75-105 µm | - | - | Potsherds of Late Ottoman period at 57 cm depth |
| 2h | 58-61 | Sandy Loam | - | 2 | - |
| 2i | 61-69 | 300-350 µm | - | - | - |
| 2j | 69-79 | Sandy Loam | - | 2 | Thin dark organic layer at 71 cm depth |
| 2k | 79-80 | Loamy Sand | - | - | - |
| 2l | 80-90 | Loam | - | - | Many crust fragments |
| 2m | 90-93 | Sandy Loam | - | 2 | - |
| 2n | 93-95 | 300-350 µm | - | - | - |
| 2o | 95-99 | Loamy Sand | - | - | Thin continuous crusts alternate with fine sand (75 µm) |
| 2p | 99-103 | Sandy Loam | - | 2 | - |
| 2q | 103-105 | 150-210 µm | - | - | - |
| 2r | 105-107 | Loamy Sand | - | - | Thin continuous crusts alternate with fine sand (75 µm) |
| 2s | 107-110 | 105-150µm | - | - | - |
| 3a | 110-122 | Sandy Loam | - | 30 | Crust fragments |
| 3b | 122-210 | Sandy Loam | - | 60 | Few blocky limestones and flint (5-10 cm) at 170-175 cm depth. Potsherds of the Byzantine-Islamic transition period at 135, 153, 175, 176 and 200 cm depth |

Table 5.2 continued. Profile descriptions ($CaCO_3$ as nodules. Excr. stands for soil animal excrements)

| **Profile layer** | **Depth** Cm | **Texture** | **$CaCO_3$** % | **Excr.** % | **Remarks** |
|---|---|---|---|---|---|
| | | | | 5 | 180 m asl |
| 1 | 0-43 | Loamy Sand | - | - | Dark organic layer at 22 cm depth |
| 2a | 43-45 | Sandy Loam | - | - | - |
| 2b | 45-47 | >2000 | - | - | Poorly sorted gravels: limestone, flint and calcrete fragments |
| 2c | 47-62 | 420-500 | - | - | Poorly sorted sediments: limestone, flint and calcrete fragments. |
| 3 | 62-100 | Sandy Loam | - | 60 | Potsherds of the Byzantine-Islamic transition period at 65 and 70 cm, of the Late Ottoman period at 62 and 70 cm. |
| | | | | 6 | 183 m asl |
| 1 | 0-16 | Loam | 1 | - | Few crust fragments |
| 2 | 16-42 | Loam | 1 | 35 | Horizontal crust fragment at 37 cm depth |
| 3 | 42-55 | Loam | 1 | 10 | |
| 4 | 55-61 | Loam | - | 40 | Many crust fragments |
| 5 | 61-100 | Silt Loam | 4 | - | High consistency. Potsherds of the Byzantine-Islamic transition period at 83 cm depth |
| | | | | 7 | 186 m asl |
| 1 | 0-54 | Loam | 3 | 25 | 2% $CaCO_3$ precipitates resembling mycelia at 17 - 36 cm |
| 2a | 54-73 | Loam | 30 | 25 | |
| 2b | 73-82 | Loam | 3 | - | |
| 2c | 82-88 | Loam | 30 | 30 | |
| 2d | 88-96 | Loam | 3 | - | |
| 3 | 96-119 | Loam | 60 | 55 | 25% solid calcium carbonate nodules |
| 4 | 119-150 | Loam | 0 | - | |
| | | | | 8 | 187 m asl |
| 1 | 0-30 | Sandy Loam | 10-15 | - | - |
| 2a | 30-50 | Loam | 20-25 | - | Few organic matter mottles of 2 mm diameter |
| 2b | 50-68 | Loam | 5 | - | - |
| 3 | 68-76 | Sandy Loam | 30 | - | - |
| 4a | 76-83 | Loam | - | - | - |
| 4b | 83-98 | Loam | 30 | - | - |
| 4c | 89-100 | Loam | - | - | - |
| 4d | 100-120 | Loam | 30 | - | Many solid calcium nodules |
| | >120 | - | - | - | High concentration of hard calcium carbonate nodules |

In the lower layers often laminated deposits are found, existing of well sorted 1 mm thick layers of grey to black material alternated with lighter sediments. The laminae are approximately horizontally deposited. In layer 7 only fragments of laminae are found. The layer has a loamy texture, a higher consistency than the surrounding layers and several crust fragments. At the top of the layer potsherds of the Byzantine-Islamic transition phase are found.

Table 5.2 continued. Profile descriptions ($CaCO_3$ as nodules. Excr. stands for soil animal excrements)

| **Profile** layer | **Depth** Cm | **Texture** | **$CaCO_3$** % | **Excr.** % | **Remarks** |
|---|---|---|---|---|---|
| | | | | 9 | 183 m asl |
| 1 | 0-67 | Sandy Loam | - | 5-20 | Few crust fragments |
| 2a | 67-73 | Loam | - | 35 | Crust fragments are common |
| 2b | 73-94 | Loam | - | 25 | Many crust fragments, concentrated in 2-5 cm layers |
| 2c | 94-98 | Loam | - | - | Thin continuous crusts at 94 and 98 cm depth |
| 3 | 98-117 | Sandy Loam | - | - | Several rounded blocks of different lithology (4 - 6 cm) are positioned at 113 cm depth (see 4-I) |
| 3-I | | Silt Loam | - | - | Blocks exist of waved thick crusts and show pseudo gley |
| 4a | 117-121 | Sandy Loam | - | - | Crust fragments are common |
| 4b | 121-139 | Silt Loam | - | - | Very thick waving crust |
| 4c | 139-141 | Sandy Loam | - | - | Thin continuous crusts at 139 cm and 141 cm depth |
| 5 | 141-169 | Sandy Loam | - | - | Layers of micro-aggregates (see 6-I) are alternated with layers without micro-aggregates. Potsherds of the Byzantine-Islamic transition period at 153 cm depth |
| 5-I | | Loam | - | 100 | Layer consists of accumulation of rounded micro-aggregates |
| 6 | 169-186 | Loam | - | 10-15 | Crust fragments are common. Potsherds of Byzantine-Islamic transition phase at 182 cm depth. |
| 7 | 186-232 | Loam | - | - | Higher consistency. Darker than surrounding layers. Crust fragments are common. Fragments of laminae. Potsherds of the Byzantine-Islamic transition period at 188 cm depth. |
| 8 | 232-290 | Silt Loam | - | - | Laminated deposit (see 9-I) alternated with loessial deposit |
| 8-I | | Silt Loam | - | - | Fine (1 mm) layers of dark grey to black material alternate with lighter sediment layers |
| 9 | 255-283 | Loam | - | - | Loess deposit alternated with coarse material (see 9-I). Fragments of laminae. |
| 9-I | | Loamy Sand | - | - | Contains gravels (<3 mm) |
| 10 | 283->320 | Silt Loam | - | 5 | Fine layering (<1 mm) |
| 11 | 290->320 | Silt Loam | - | - | Laminated deposit (see 12-I) alternated with loessial deposit |
| 11-I | | Silt Loam | - | - | Fine (1 mm) layers of grey material alternate with lighter sediment layers |
| 12 | 320-375 | Loam | - | - | Sampled by use of hand auger |
| 13 | 375-415 | Silt Loam | - | - | Sampled by use of hand auger |

The laminae of layer 8 are deposited as local infillings surrounded by mixed loessial deposits of silt loam texture. In layer 9 loamy deposits alternate with loamy sand layers with small gravels (< 3 mm). Fragments of laminae are visible. The border between layer 9 and 10 is very gradual. Layer 10 has a silt loam texture and few soil animal excrements. No laminae can be distinguished. Layer 11 has a silt loam texture as well and showed several local infillings with laminae of a lighter color than the laminae of layer 8. Layer 12 has a loamy texture and layer 13 a silt loam texture. Five OSL samples are taken in the profile ranging in age from 38 ± 3 ka to 537 ± 115 AD (Table 5.1 and Fig. 5.2, 5.3).

### *5.4.3 The first terrace*

Profile 4 is situated on the first terrace (Fig. 5.3). Three different layers can be recognized (Table 5.2). The upper layer exists of a homogeneous sandy loam deposit in which some crust fragments are found. The middle layer has a fine internal layering with textures varying between silt loam and coarse sand. Potsherds of the Late Ottoman period are found in this layer (18$^{th}$ to 20$^{th}$ century, 1700 – 2000 AD). The lowest layer has a sandy loam texture with a high percentage of soil animal excrements and contained some blocky limestones and potsherds of the Byzantine-Islamic transition period. Three OSL samples are taken in the profile ranging in age from 1926 ± 6 to 1477 ± 32 AD (Table 5.1 and Fig. 5.2, 5.3).

### *5.4.4 The current gully*

Profile 5 is positioned in the current gully bed in the same profile pit as profile 4 (Fig. 5.1). Three different layers are distinguished (Table 5.2 and Fig. 5.3). The top layer has a loamy sand texture, with halfway a continuous dark organic layer. The middle layer is composed of sub-layers of varying texture (sandy loam, coarse sand and gravels). The lowest layer has a sandy loam texture and high percentage of soil animal excrements. In this layer potsherds of the Late Ottoman and of the Byzantine-Islamic transition period are found.

## 5.5 Discussion

### *5.5.1 Correlation and timing of the phases*

*The Pleistocene*

The oldest deposits are found on the slopes (profile 1, 2, 7 and 8) and typically existed of homogeneous loamy loess (Table 5.2 and Fig. 5.3). They resemble Late Pleistocene loess deposits near Netivot, in the vicinity of Sayeret Shaked (Bruins and Yaalon, 1979). In the humid climate of the Late Pleistocene loess accumulated from dust loaded rainstorms (Fig. 5.2) (Issar et al., 1987). During loess deposition several stable stages of soil formation occurred, represented in the profiles by layers rich in calcium carbonate nodules. Several aggradation and incision cycles occurred as well, of which two were recognized in profile 9 (Fig. 5.3).

Table 5.3. Estimated time period, volumes and accumulation (or incision) rate per phase

| Phase | **Estimated time period** Years | **Volume** $m^3$ (s.e.) | **Accumulation rate** $dm^3$ $year^{-1}$ |
|---|---|---|---|
| A1 | 43 – 35 ka | 12.0 (6.0) | 1.4 |
| I1 | 35 – 32 ka | -5.8 (4.8) | -1.9 |
| A2 | 32 – 11.5 ka | 14.5 (6.0) | 0.7 |
| I2 | 11.5 – 10.0 ka | -9.0 (4.9) | -6.0 |
| A3 | 10 – 7.5 ka | 14.5 (5.7) | 5.8 |
| S3 | 7.5 ka BP – 360 AD | 1.36 (0.5) | 0.2 |
| I3 | 360 – 425 AD | -4.3 (4.1) | -66.2 |
| A4 | 425 – 675 AD | 39.5 (7.5) | 158.0 |
| I4 | 675 – 800 AD | -52.0 (9.0) | -416.0 |
| A5 | 800 – 1760 AD | 8.8 (3.0) | 9.2 |
| I5 | 1760 – 1810 AD | -1.0 (0.4) | -20.0 |
| A6 | 1810 – 1930 AD | 9.3 (3.3) | 77.5 |
| I6 | 1930 – 1987 AD | -1.6 (0.6) | -28.5 |
| A7 | 1987 – 2005 AD | 0.8 (0.4) | 41.7 |

The first aggradation phase (A1), visible in layer 9.11 (profile 9, layer 11), was formed in a process of infilling of an older gully below the current level (Fig. 5.3, 5.4). Well sorted laminated deposits were formed under wet circumstances in a connected slope-gully system (Table 5.2). In this wet climate vegetation cover was high and slope erosion low. During an event coarser sediments were transported out of the catchment, while finer sediments and organic matter settled out of the sediment loaded water left behind in small ponds and gullies. Simultaneously loess accumulated (Issar et al., 1987). The gully slowly aggraded 12.0 ± 6.0 $m^3$ of sediments, though several smaller incision phases occurred as well (Table 5.3). Layer 9.11 was OSL dated to 38 ± 3 ka (NCL-2105103, Fig. 5.2, 5.3).

A hiatus between layer 9.11 and layers 9.9 and 9.10 suggested a new incision phase (I1) (Fig. 5.4). This incision phase eroded 5.8 ± 4.8 $m^3$ (Table 5.3). Afterwards layer 9.10 and 9.9 were deposited (14.5 ± 6.0 $m^3$) during the second aggradation phase (A2) (Table 5.3 and Fig. 5.3, 5.4). The homogeneous loamy deposits and fine layering of layer 9.10 indicted that this layer was formed by loess accumulation from loess loaded rainstorms combined with local redistribution of slope sediments. Layer 9.10 was OSL dated to 29 ± 3 ka (NCL-2105105, Fig. 5.2, 5.3). The gravels and laminae of layer 9.9 were formed by an active gully in a connected slope-gully system combined with loess deposition. These two layers were formed in an increasingly active gully in an increasingly wet climate, while catchment wide fluvial processes dominated more and more over local sediment redistribution along the slopes.

The temperature and Dead Sea level curves revealed several shifts in humidity between the phases A1 and A2 as dated by OSL (Fig. 5.2). Following the biogeomorphic response model of Knox (1972) these shifts could have triggered aggradation and incision phases, of which only one incision phase (I1) was visible in the profile (Botha, 1996; Eriksson et al., 2006). Correct timing of phase A1, I1 and A2 is difficult. Phase A1 could have started after the previous incision phase ended, which could be triggered by the humidity increase at 43 ka. Phase A1 could have lasted to ~35 ka (NCL-2105103 plus standard error). Phase A2 could have started around 32 ka (NCL-2105105 minus standard error), leaving ~3 ka for incision phase I1 (Table 5.3). The termination of phase A2 is unclear, as possible younger Late Pleistocene deposits were not preserved. A final age of 11.5 ka is assumed applying the biogeomorphic response model of Knox (1972) on the initiation of incision phase I2 (see §6.1.2.).

*The Late Pleistocene to Roman era*

Incision phase 2 is the strongest incision phase of the Late Pleistocene in this transect (11.5 ± 4.9 $m^3$) (Table 5.3 and Fig. 5.4). It is likely to date from the termination of the very dry Younger Dryas between 10 – 11.5 ka and was recognized throughout the Negev Desert (Avni et al., 2006). The incision was triggered by the sharp humidification at the start of the Holocene, when precipitation increased rapidly and eroded the bare surface (Fig. 5.2) (Eriksson et al., 2000; Knox, 1972; Roberts and Barker, 1993).

The following aggradation phase A3 (layer 9.8) is of Holocene age, even though the deposit resembled the Pleistocene laminae of layer 9.11 (Table 5.2 and Fig. 5.3, 5.4). We have three reasons for this interpretation. Firstly the hiatus between layer 9.8 and 9.9 indicated the most intense incision phase up to this height in the profile, which was linked to incision phase 2 attributed to 10 – 11.5 ka. Secondly layer 9.7 and 9.8 appeared to be formed in one continuous phase. Layer 9.7 formed in layer 9.8 in a process of soil formation, recognized by the higher organic matter content and fragmented laminae-remnants left behind by biological activity. Additionally the top of layer 9.7 was OSL dated to 806 ± 296 BC (NCL-2105100, Fig. 5.2, 5.3). Thirdly the conditions for laminae formation were met in the Early Holocene as well, after which during the relatively humid Middle Holocene soil formation could occur (Fig. 5.2). Therefore we expect that aggradation phase A3 (12.5 ± 7.9 $m^3$) took place during the Early Holocene wet period between 10 – 7.5 ka in an active gully in a connected slope-gully system, with additional loess deposition (Layer 9.8) (Fig. 5.2, 5.4). Afterwards soil formation (S1) occurred in the stabilized sediments during the wetter periods between 7.5 ka and 360 AD (layer 9.7), combined with slow dust deposition (Eriksson et al., 2000).

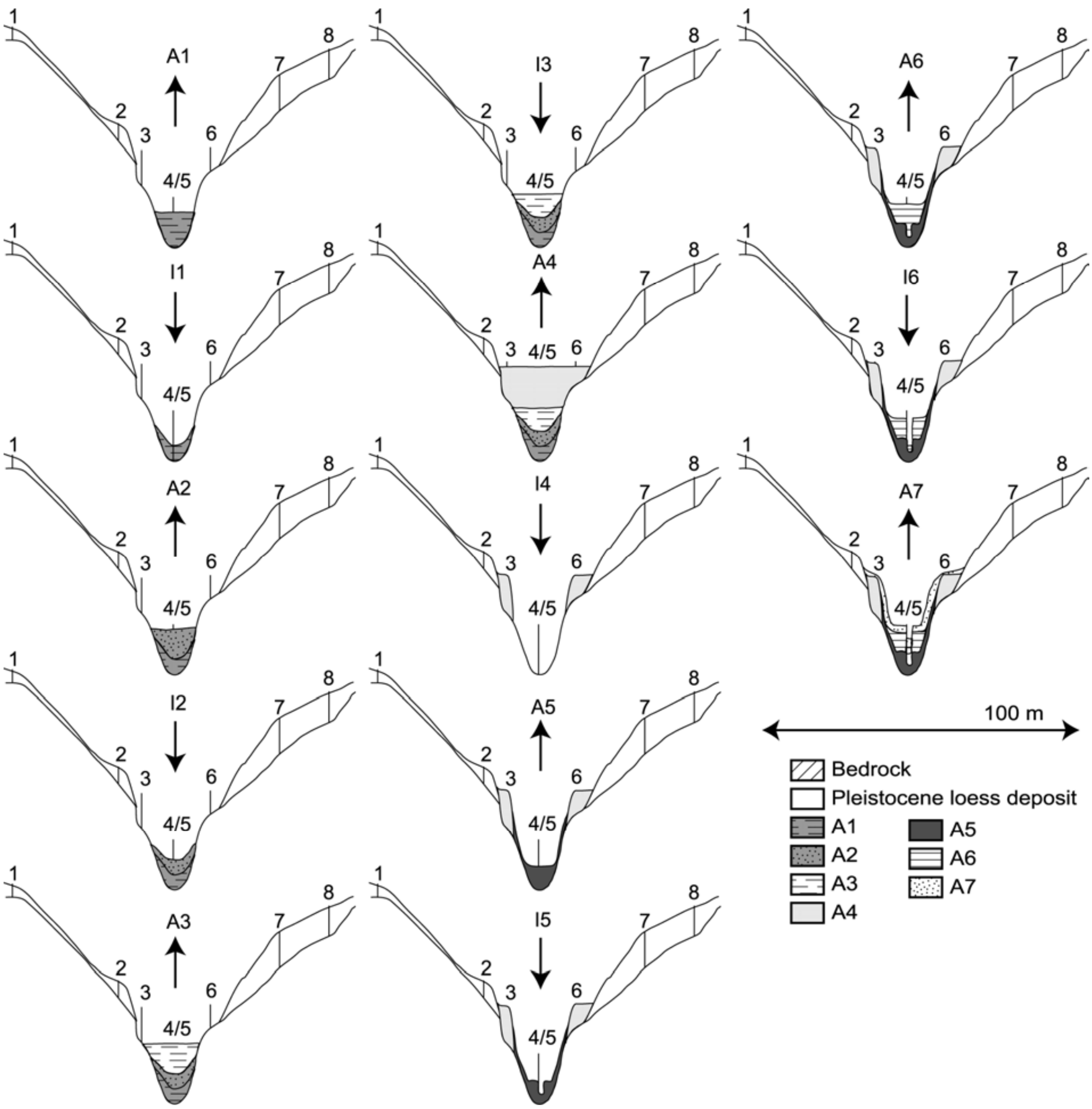



Fig. 5.4 Reconstruction of aggradation and incision phases of Sayeret Shaked

*The Byzantine era*

The following phases I3, A4 and I4 were recognized in layers 3.2-3.4, 6.2-6.5 and 9.2-9.6 (Fig. 5.3, 5.4). Incision phase I3 left a hiatus between layers 9.7 and 9.6 and eroded 4.3 ± 4.1 $m^3$ of sediments (Table 5.3). This phase was confined between the OSL date of 806 ± 296 BC and a potsherd of the Byzantine-Islamic transition phase of 400 – 800 AD, both positioned at the border between the layers (Table 5.2 and Fig. 5.3). Following the theoretical framework of Kirkby (1972), this incision phase could be related to the sharp increase in precipitation at the beginning of the Byzantine period between ± 360 and 425 AD.

During the initial stage of aggradation phase A4 sediments were redistributed along the slopes and down to the gully. In layer 6.5 reworked calcium carbonate nodules were found which originated from higher on the slope. In the gully bed crusts were formed, which were broken and mixed by biological activity (layer 9.6) (Table 5.2). The redistribution of sediments along the slopes points to a low vegetation cover and active slope erosion (Carson and Kirkby, 1972). The crust formation in the gully bed demonstrated that the gully was locally bare, while the lack of fluvial deposits and occurrence of soil animal excrements pointed to an inactive, but humid gully bed. Under these humid circumstances a full vegetation cover would have been expected with little or no sediment redistribution (Carson and Kirkby, 1972; Knox, 1972). In this period in history human occupation of the area was very likely, as the amount of settlements in the Beer Sheva basin reached it maximum (Fig. 5.5) (Issar, 1990). The related livestock grazing might have lowered vegetation cover and by that increased slope erosion (Foster et al., 2007). Later, in layer 9.5, featureless loess was deposited alternating with longitudinal elongated heaps of rounded micro-aggregates. The high amount of micro-aggregates, probably formed by ants, indicated a high biological activity, while the featureless loess layers indicated redeposition of sediments and aggregates along the slope. On top of these layers piles of thick waving crusts were formed, similar to deposits found in the much dryer Negev Highlands nowadays (layer 9.4). Obviously these thick loess deposits were formed in a much wetter climate than would be expected based on current field evidence. These thick crusts were formed by runoff flows with high sediment loads. In layer 9.3 evidence was found of lateral movement and undermining of the gully walls: thick balls of waving crusts were found in between sandy loam deposits (Vanwalleghem et al., 2005). Layer 9.3 was OSL dated to 393 ± 127 AD (NCL-2105106, Fig. 5.2, 5.3). Upstream in profile 3 a coarse sand layer was deposited (layer 3.3). These layers all indicate fluvial activity. On top of and below these layers deposits were found with high soil animal excrements (up to 40%) and many crust fragments (layers 3.2, 3.4, 6.2-6.4 and 9.2). The high soil animal excrements indicated a humid environment, while the lack of fluvial deposits demonstrated an inactive gully. The wide gully bed (± 25 m wide) could have been used for agricultural activities by humans at this time (Issar, 1990). The tillage activity resulted in bare soil surfaces subject to crusting and inclusion of plant remains in the soil increasing soil animal activity. The blocky limestone in layer 3.2 emphasizes this hypothesis as it is unlikely to be left there by natural gravitational processes as no bedrock outcrops are positioned upslope. The agricultural activities made the gully bed vulnerable for erosion, while the livestock decreased vegetation cover on the slopes, increasing crust cover and runoff. It resulted in rapid formation and infilling of an ephemeral gully in the agricultural field (layers 3.3, 9.3 and 9.4). In croplands on loess soils these gullies rapidly form, often by a combination of intensive agricultural land use and heavy rainfall (Dotterweich et al., 2003). Most gullies are ephemeral and fill rapidly by tillage, undermining of gully walls (like in layer 9.4) and sediment redistribution by runoff water (Vanwalleghem et al., 2005). Several potsherds of the Byzantine-Islamic transition period were found throughout the layers and confined aggradation phase 4 between 400 and 800 AD (Fig. 5.3). The deposition started at the end of incision phase I3 at ±425 AD and continued throughout the wettest part of the Byzantine era and during the first part of the aridification phase to ± 675 AD (Fig. 5.2). The OSL date of layer 9.3 confirmed this timing (393 ± 127 AD, NCL-2105106, Fig. 5.2, 5.3). In total 39.5 ± 7.5 $m^3$ of sediment was deposited in this phase, much more than would have been expected in an undisturbed catchment during a wet period and a transition to a dryer climate (Table 5.3 and Fig. 5.4) (Knox, 1972).

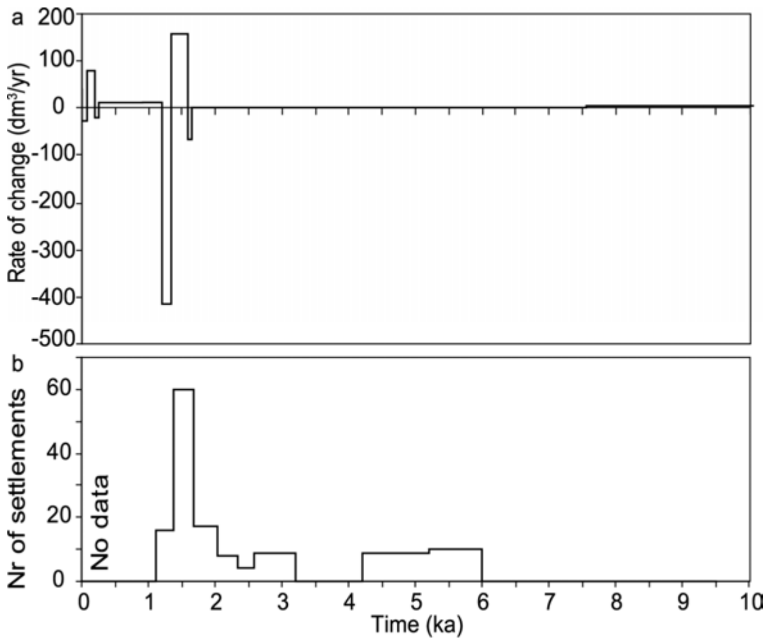



Fig. 5.5 a) Estimated rate of volume change ($dm^3\ yr^{-1}$) at the transect and b) number of archaeological settlements in the Beer Sheva basin after Issar (1990).

In the following incision phase I4 human influence was still too high for the carrying capacity of the catchment. The strongest incision phase (I4) recognized in the history of the catchment, eroded up to 52.0 ± 9.0 $m^3$ (Table 5.3 and Fig. 5.5). It is related to the strong aridification at the end of the Byzantine era (Fig. 5.2). The human occupation in a drying climate caused an increasing pressure on the land (Fig. 5.5). The bare slopes, heavily degraded by overgrazing, were covered by crusts, increasing runoff volume and rate. The runoff eroded the bare gully bed, which possibly incised up to the bedrock. This occurred between ± 675 – 800 years AD, a period during which the Byzantine society collapsed and the Islamic period started in the Negev (Enzel et al., 2003).

*The Islamic, Crusader and Mamluk era* After the Byzantine period the amount of settlements declined strongly in the Beer Sheva plain (Issar, 1990). In the dry climate of the Islamic era (800 – 1100 AD), with little of no human influence, the landscape was relatively stable. Some sediment redistribution from slope to gully bed was likely. The deposits of the Islamic era could not be separated from the deposits of subsequent aggradation phase 5 (layers 4.3 and 5.3), as the high activity of the soil animals (60% of excrements) removed earlier layering in the profile (Table 5.2). The deposits of aggradation phase 5 were further characterized by several potsherds of the Byzantine-Islamic transition period and blocky stones of 5 to 10 cm in diameter. Layer 4.3 was dated with OSL to 1477 ± 32 AD (NCL-2105096, Fig. 5.2, 5.3). The high biological activity indicated a wet climate. The occurrence of potsherds and blocky stones throughout the profile, without any indication of river activity, points to an artificial deposit by humans. During the wetter Crusader-Mamluk period human occupation was likely as a cistern is located close by, which enabled additional water collection (Evenari et al., 1982b). Tillage and livestock trampling deposited slope sediments in the gully (Fig. 5.3, 5.4). In total 8.8 ± 3.0 $m^3$ of sediments were deposited in this phase (Table 5.3). In layer 5.3 two potsherds of the succeeding Ottoman period were found (1700 – 2000 AD); one on the border with the upper layer and one eight centimeter lower. These Ottoman potsherds dropped in the gully during incision phase 5 and were left on the surface. The lowest potsherd intruded the older layer by external force. It confines aggradation phase 5 between 800 and 1760 AD, using the Ottoman potsherds and incision phase 5 as upper boundary.

*The Ottoman and modern times* Incision phase 5 could be recognized by a hiatus between layers 4.3 and 4.2 and between 5.3 and 5.2 and removed 1.0 ± 0.4 $m^3$ of sediment (Fig. 5.3). We can confine incision phase I5 between 1760 and 1800, assuming a relationship with the increase in humidity at that time (Fig. 5.2) (Knox, 1972). The following aggradation phase 6 (layers 4.2 and 5.2) existed of layers of small grained and coarser grained deposits, with even some gravelly layers (Table 5.2). It indicated an active gully system, where sediment transport and sorting occurred in a wet climate. Probably the slopes were covered by vegetation and slope erosion was low. The gully incised upstream in its own sediments to fulfill the sediment need of the runoff water and aggraded downstream (Fig. 5.1). Layer 4.2 was dated with OSL to 1914 ± 8 AD (NCL-2105095, Fig. 5.2, 5.3). Additionally potsherds of the Late Ottoman period were found (Fig. 5.3).

On the border between layer 4.1 and 4.2 another OSL sample was dated at 1926 ± 6 AD (NCL-2105119). In total 9.3 ± 3.3 $m^3$ sediments were deposited. Aggradation phase A6 was confined between the wettest period of the Late Ottoman and the beginning of the Modern times (1810 and 1930 AD).

Afterwards a final incision phase occurred (I6), which was probably triggered by grazing by Bedouin herds and an increase of precipitation between 1930 – 1940 AD destabilizing the landscape and increasing runoff and incision (Table 5.3 and Fig. 5.4) (Foster et al., 2007; Heim et al., 1997). A second increase in precipitation between 1975 – 1984 AD possibly renewed the incision process (Heim et al., 1997). Approximately 1.6 ± 0.6 $m^3$ of sediments were removed (Table 5.3 and Fig. 5.4). We expect that aggradation phase 7 (layer 5.1) was triggered by a change in management in 1987 AD, when grazing was banned in the catchment (Boeken and Shachak, 1998). In the re-vegetated gully bed 0.8 ± 0.4 $m^3$ of sediments were deposited. Nowadays the slopes in the catchment are almost stable. Although runoff can be formed on the crusted soil, it will infiltrate quickly in the spread vegetation patches downslope (Shachak et al., 1998). Water and sediment redistribution are therefore only local slope processes and the gully inactive.

On the higher slopes aggradation phase 7 started after gully influence had ceased, in general representing local redistribution of slope sediments in the top layers. After precipitation events crusts were formed, which were disturbed by biological activity and possible moved further along the slope. Timing of the profiles depends on the position in the catchment (Fig. 5.3).

### *5.5.2 Environmental implications of climate change and human occupation*

The valley fill of Sayeret Shaked was formed in several cycles of aggradation and incision (Fig. 5.4). Especially the large increase in humidity at the termination of the Younger Dryas (I2) resulted in high incision rates in the Pleistocene (Table 5.3 and Fig. 5.2). Smaller humidity fluctuations in the Late Pleistocene and Early to Middle Holocene resulted in much lower rates (Table 5.3). The intensity of the cycles seemed to depend on the rate of change in humidity (Knox, 1972). Also in the Late Holocene stronger changes in humidity tended to be related to larger aggradation and incision cycles (Table 5.3 and Fig. 5.2). Especially the period between 360 and 800 AD experienced strong humidity fluctuations and high aggradation and incision rates.

The cycles in the Late Pleistocene and Early to Middle Holocene were markedly smaller in volume and rate than in the Late Holocene (Table 5.3). The humidity fluctuations, on the other hand, were much stronger during the Late Pleistocene and Early Holocene than later on, when both temperature and Dead Sea lake levels were relatively stable (Fig. 5.2). Following the biogeomorphic response model of Knox (1972) the aggradation and incision cycles of the Late

Pleistocene should have been much stronger than those of the Holocene. Although this appeared applicable in several other studies, in our catchment this relationship appeared to be invalid (Avni et al., 2006; Benvenuti et al., 2005; Eriksson et al., 2006; Roberts and Barker, 1993). Interestingly the strongest aggradation and incision cycles in volume and rate (I3, A4 and I4) coincided in time with the rise and fall of the Byzantine Empire and the period with the highest settlement rate in the Beer Sheva plain (Table 5.3 and Fig. 5.5) (Issar, 1990). During the strongest human occupation in the Byzantine era the gully aggraded. The gully incised only in the period afterwards, when human occupation declined because of the aridifying climate. Also in the eighteenth to twentieth century (I5, A6 and I6), the rates of incision and aggradation were high compared with a non-human influenced situation in the Late Pleistocene and Early Holocene (Table 5.3 and Fig. 5.5). It demonstrated that the amplitude of aggradation and incision cycles could be strongly amplified by human occupation. However, when examining figure 5 more closely it became clear that human occupation amplified the cycles only when human occupation pressure crossed a certain threshold. Above this threshold the connected agricultural land use destabilized the landscape by strong vegetation reduction, causing the system to collapse and large scale redistribution of sediments to occur (Rietkerk and van de Koppel, 1997; Van de Koppel et al., 1997). When human occupation pressure stayed below this threshold, the amplitude of the cycles was governed by climate fluctuations only. The interplay between human activity and climate fluctuations dominated landscape dynamics more than climate fluctuations alone in this semi-arid environment (Bull, 1997). In several other studies worldwide similar conclusions were achieved, demonstrating a distinct increase in widespread erosion and degradation after large scale human occupation and arable land use started (Foster et al., 2007; Mieth and Bork, 2005; Rustomji and Pietsch, 2007; Schmitt et al., 2006; Vanwalleghem et al., 2006). Contrary to these results Avni et al (2006) concluded that humans even counteracted the natural process of degradation in the rocky Negev Highlands, by taking measurements to slow down runoff and increase sediment storage. The difference is caused by the difference in surface characteristics of the studied catchments (Chapter 2). In the loess covered catchments of the northern Negev Desert the runoff infiltrates quickly, unless human activity decreased vegetation cover and increased area and strength of surface crusts. In that case erosion potential is increased and the area is degraded. This is very different from rocky catchments with a natural high runoff rate and erosion potential, where only human influence could reduce natural erosion and land degradation processes (Avni et al., 2006; Bruins, 1986).

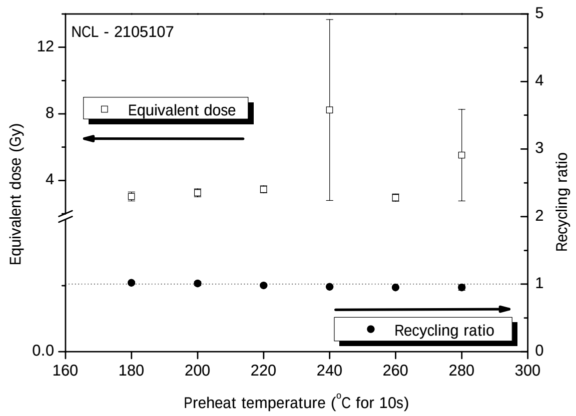
In former times an increase in human occupation appeared to be a resultant of improved climate (Migowski et al., 2006; Robinson et al., 2006). A following collapse of a society, however, seemed more related to an intense degradation of the land caused by human overpressure and mismanagement in a drying climate, than to the initial aridification itself. Apparently an inadequate response, or impossibility to respond in time, caused the ecosystem to move over the threshold and collapse (Van de Koppel et al., 1997).

## 5.6 Conclusions

In Sayeret Shaked two Late Pleistocene and four Holocene aggradation and incision cycles were recognized. The aggradation and incision cycles appeared stronger in the Late Holocene than before, even though the amplitude of climate fluctuations reduced since the Pleistocene. The strongest incision and aggradation phases in the Late Holocene coincided in time with the rise and fall of the Byzantine Empire and seemed related to the high human pressure on the landscape during that period. It demonstrated that although the phases of aggradation and incision were initiated by changes in humidity, the climate driven phases were strongly amplified by human influence. The interplay between human activity and climate fluctuations had therefore a much stronger effect on the landscape than climate fluctuations alone. Although increasing human occupation was a resultant of improving climate, the collapse of society and landscape degradation appeared mainly caused by an inadequate response of the society to changes in climate and resulting carrying capacity of the ecosystem.

# Appendix chapter 5

All luminescence measurements were made using a Risoe TL/DA 15 TL/OSL reader (Bøtter-Jensen et al., 2000). Based on an investigation of the dependence of the equivalent dose on the preheat temperature used (Fig. A5.1), a 10s preheat of 220 or 270°C was selected (Table 5.1).



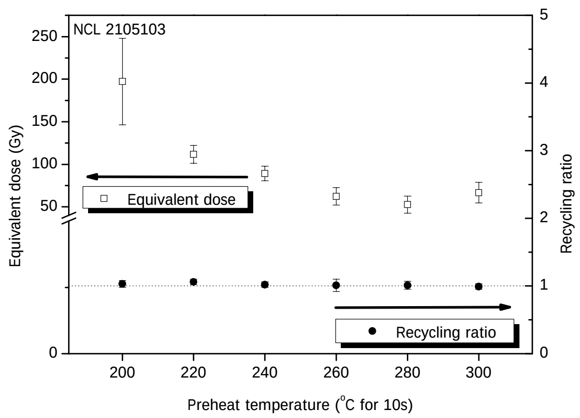




Fig. A5.1 Typical preheat plateaus for a Holocene (NCL-2105107) and Pleistocene (NCL-2105103) sample. Based on these results, and those on other samples, a preheat plateau of 220°C was selected for the younger samples, and 270°C for the older samples.

Tests using infrared (IR) stimulation showed that some feldspar contamination remained after the HF treatment. To minimise the contribution of feldspar minerals to the OSL signal used for equivalent dose determination, an IR exposure prior to each OSL measurement was applied (Wallinga et al., 2002). With the adopted procedure we could successfully determine a dose given in the laboratory to samples that had their natural OSL signal removed by exposure to blue light at ambient temperature (average dose recovery ratio 1.01 ± 0.01; Fig. A5.2).

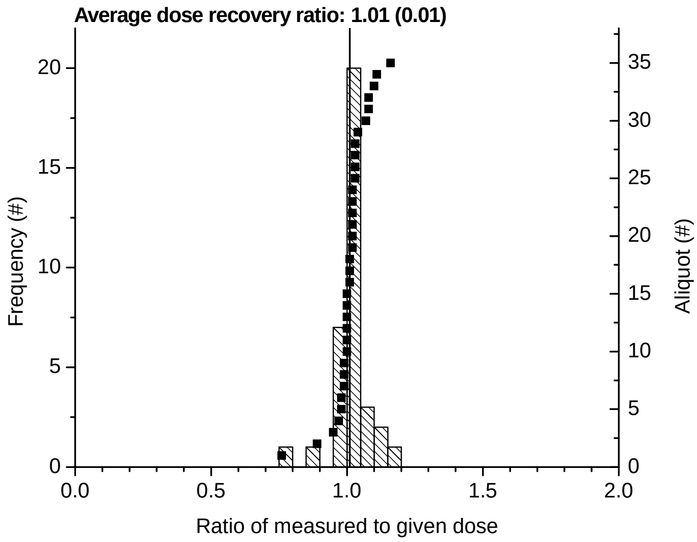



Fig. A5.2 Histogram of results of the dose recovery test, showing a tight distribution around unity.

For each sample at least 25 subsamples (aliquots) were measured, each containing ~ 1 mg of quartz. Results showed a wide spread in single-aliquot equivalent doses, indicating that for some grains the OSL signal was not completely reset prior to deposition and burial. Ignoring this information and taking a simple average of the $D_e$ estimates would lead to an overestimation of the burial age. Through visual inspection of the $D_e$ distribution plotted in radial plots (Galbraith et al., 1999) we adopted a suitable method to obtain the best estimate of the burial dose following three different methods (Fig. A5.3):

1. For samples where the $D_e$ distribution was relatively tight with a few outliers giving greater $D_e$ estimates, we iteratively removed points that had values more than two standard deviations from the sample mean. The average of the remaining estimates is expected to be a good indication of the burial dose.
2. For samples showing a wide scatter in single aliquot $D_e$'s but with a well-defined group of data near the lower tail of the distribution, we adopted the finite mixture model (FMM; (Roberts et al., 2000)).

3. For samples showing a wide scatter in single aliquot $D_e$'s without a well-defined group of datapoints near the lower tail of the distribution, we adopted the minimum age model (MAM; (Galbraith et al., 1999)).

Below fig. A5.3a-h Radial plots showing the equivalent dose estimations on individual aliquots, and the sample equivalent dose adopted for OSL age calculation. These plots were preferred over standard histograms as they include information on the precision of equivalent dose estimates obtained on individual aliquots. The grey bands indicate the $D_e$ used for age calculation; single aliquot results that agree within their individual uncertainty with this estimate are filled. For samples were the FMM or MAM was used, an additional line indicates the $D_e$ that would be obtained using the standard method.

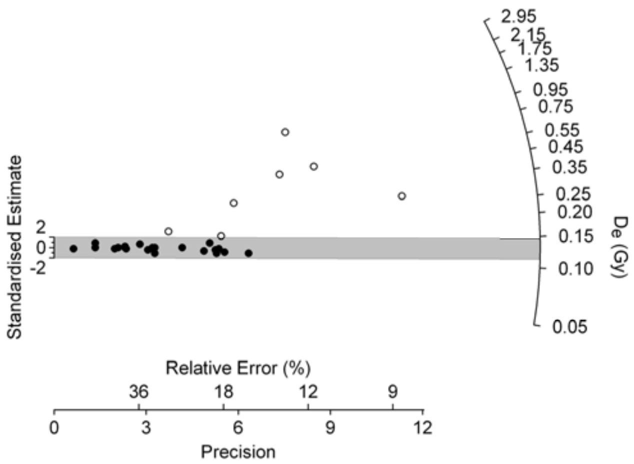



Fig. A5.3a NCL-2105119 (standard; $D_e$ = 0.13 ± 0.01)

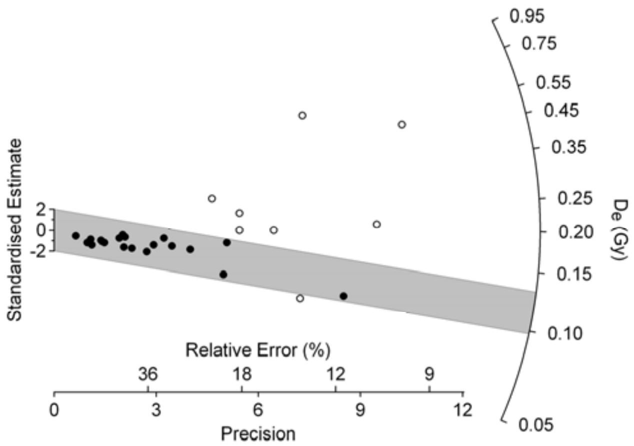



Fig. A5.3b NCL-2105095 (standard; $D_e$ = 0.11 ± 0.01)

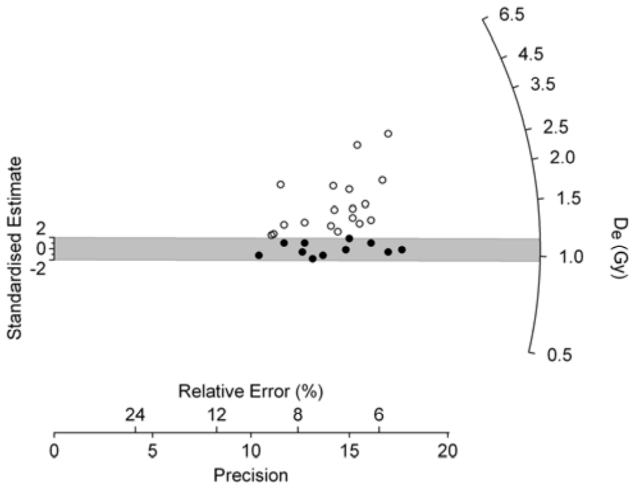



Fig. A5.3c NCL-2105096 (FMM; $D_e$ = 1.06 ± 0.05)

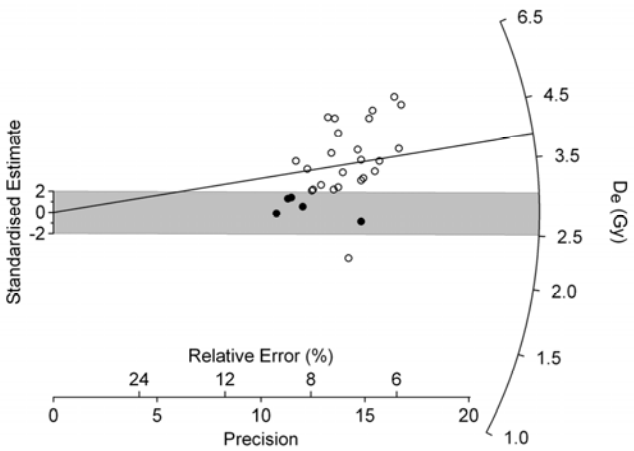



Fig. A5.3d NCL-2105107 (MAM; $D_e$ = 2.77 ± 0.20; validity questionable)

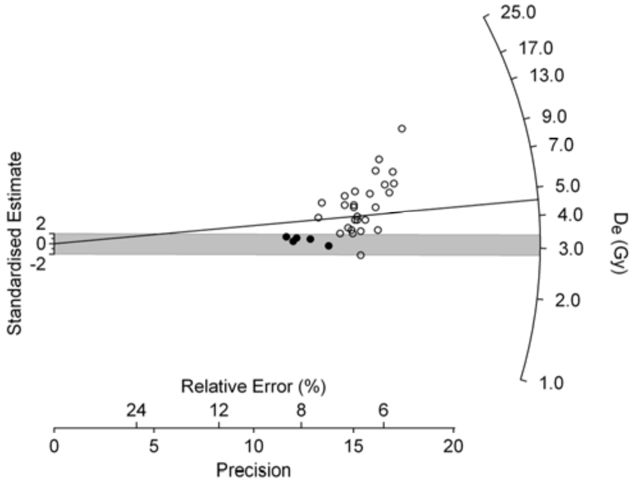



Fig. A5.3e NCL-2105106 (MAM; $D_e$ = 3.15 ± 0.23 ; validity questionable)

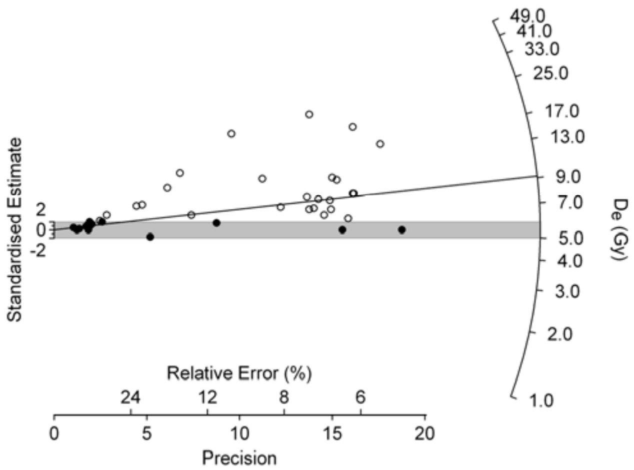



Fig. A5.3f NCL-2105100 (MAM; $D_e$ = 5.42 ± 1.93)

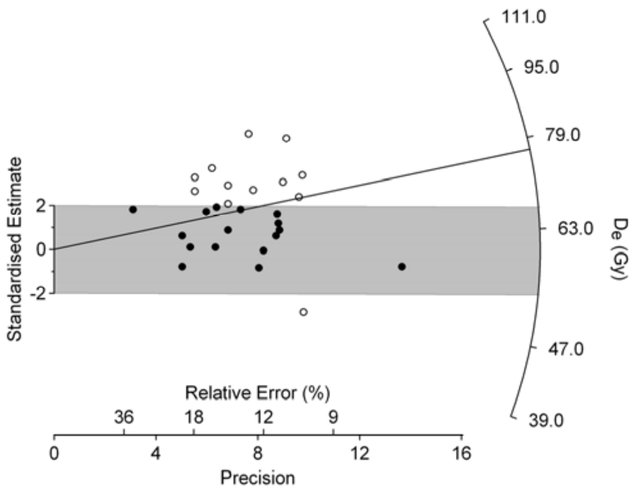



Fig. A5.3g NCL-2105105 (FMM; $D_e$ = 60 ± 6)

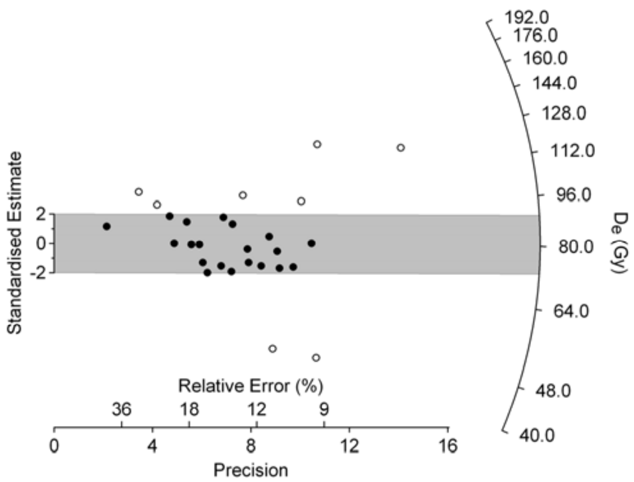



Fig. A5.3h NCL-2105103 (standard; $D_e$ = 81 ± 5)

# 6 Quantifying the effect of historical land use on landscape dynamics: a simulation study

*Landscapes are formed in time by interacting processes, both natural and human influenced. Only few attempts have been made to quantify the effect of humans. This study aims to fill this gap, by reconstructing the infill history of a small catchment in the Northern Negev Desert of Israel using the landscape evolution model LAPSUS. Firstly the infill history of the Sayeret Shaked catchment between about 800 BC and 800 AD is reconstructed. Secondly three land use scenarios are tested to quantify the effect of extensive grazing, more intensive grazing and intensive grazing combined with rainfed agriculture. Especially intensive grazing combined with rainfed agriculture leads to strong landscape dynamics, due to tillage-induced sediment transport. Extensive grazing causes almost no landscape dynamics, resulting in an almost stable landscape. The results seem to indicate that this catchment is formed by co-evolution of human and natural induced processes. Rainfed agriculture leads to valley aggradation by tillage-induced sediment transport, whereas intensive livestock grazing causes gully incision. Humans appear to be the main driven factor of landscape dynamics in this semi-arid catchment, much more than climate fluctuations. Only a short time period of strong human land use can irreversibly alter the development trajectory of a catchment. It is thus of high importance to manage the land sustainable, both in the present and future, to avoid further degradation of drylands.*

Based on: E. Buis, A. Temme and A. Veldkamp. Quantifying the effect of historical land use on landscape dynamics in the Northern Negev Desert of Israel: a simulation study. Submitted.

## 6.1 Introduction

Landscapes are formed in time by interacting processes. The interplay between climate and vegetation strongly influences landscape dynamics on geological timescales (Roberts and Barker, 1993; Temme et al., in press; Thomas, 2004). In addition, humans strongly affect landscapes on historical timescales and seem to have increased erosion and sediment redistribution already since the Neolithic (Chester and James, 1991; Fuchs, 2007; Lespez, 2003).

The Negev Desert of Israel, a dryland region and focus of this study, has been used by humans since the Neolithic (Issar, 1998). Here land use was restricted to pastoralism (nomadic, sedentary or a mixture of the two) and rainfed agriculture (often with use of rainwater harvesting techniques), depending on political, economical, environmental and climatological conditions (Avni et al., 2006; Bruins, 1986).

Livestock grazing reduces infiltration by trampling and reduction of vegetation cover, leading to more runoff and higher erosion rates. Rainfed agriculture has an even bigger effect, because it requires clearing of the land and tillage. In both situations humans increase rates of landscape dynamics and enlarge the sediment fluxes through the landscape. A relatively short period of human influence, might therefore, by its strong effect, dominate long-term landscape dynamics (Fuchs et al., 2004; Lespez, 2003).

Although most scientists agree nowadays on the amplifying effect of humans, only few attempts have been made to quantify their impact (Coulthard et al., 2000). In addition to more traditional geomorphological field studies of landscape reconstruction, landscape evolution models can be very valuable for this purpose (Coulthard, 2001). These models, developed to explore the formation and dynamics of landscapes, vary strongly in spatial and temporal extent studied, ranging from hillslopes to mountain ranges and from historical to geological time scales (Braun and Sambridge, 1997; Favis-Mortlock et al., 1997; Peeters et al., 2006; Schoorl et al., 2000; Tucker and Slingerland, 1997).

In historical landscape evolution models the strong human influence on landscape dynamics can not be ignored. Often, human influence is translated into tillage and accordingly included in the model, thus focusing on rainfed agriculture (Favis-Mortlock et al., 1997; Peeters et al., 2006). However, in semi-arid regions as the Negev Desert, pastoralism is relevant as well (Avni et al., 2006; Bruins, 1986). Livestock grazing reduces vegetation cover, and by that infiltration. Incorporation of vegetation cover in landscape evolution models can therefore be very useful, but is only scarcely done up to now (Favis-Mortlock et al., 1997).

In this study the LAPSUS model is used, which calculates aggradation and incision at catchment scale based on water redistribution and tillage-induced sediment transport (Buis and Veldkamp, 2008; Schoorl et al., 2000). The model is adapted to incorporate vegetation cover and effect of livestock grazing. It thus includes several of the most relevant landscape dynamics processes operating in semi-arid areas, in contrast to most other landscape evolution models, which focus on one or two processes mainly. LAPSUS approaches complete landscape dynamics during simulation and is able to study the interactions among different landscape evolution processes. LAPSUS is thus very suited for simulation studies in semi-arid areas.

I hypothesize that humans dominantly controlled the historical landscape dynamics of the catchment of Sayeret Shaked in the Northern Negev Desert, resulting in strong amplification of aggradation and incision rates and volumes in periods with high human occupation density. Additionally I aim to quantify to what extend humans influenced landscape dynamics, both in volumes and time. The hypothesis is tested by simulating the infill history of Sayeret Shaked with LAPSUS, based on climate and land use records. The results of chapter 5 give strong indications that this catchment has been used for rainfed agriculture twice during the wetter phases of the Holocene. During the Byzantine period (360 – 800 AD) and the Crusader – Mamluk period (1100 – 1700 AD) several observations in the deposits point to tillage activity. The duration of the agricultural activities is less clear. Traditionally these lands have been used for livestock grazing as well, next to rainfed agriculture.

Furthermore the importance of human land use on landscape dynamics is assessed by simulating three scenarios with different land use types. In the first scenario land use is restricted to extensive grazing, in the second scenario to more intensive grazing, while in the third scenario intensive grazing and rainfed agriculture are combined. The scenario setup enables quantification of the effect of tillage and grazing intensity on landscape dynamics. In this chapter I focus on a 1600 years time span between about 800 BC and 800 AD, because human occupation density varied strongly and a good sedimentation record is available supported by optically stimulated luminescence (OSL) dates and dated potsherds.

## 6.2 Study site

### *6.2.1 Regional setting*

The catchment of Sayeret Shaked is situated in the loess region of the Northern Negev Desert (Fig. 6.1 and §1.3.2). Between 800 BC and 800 AD climate fluctuated (Bookman (Ken-Tor) et al., 2004; Migowski et al., 2006). Especially the Byzantine period (324 – 634 AD) was wet. In the Beer Sheva plain settlements were built during the Iron Age (1200 – 587 BC) (Issar, 1990). The number of settlements increased strongly in the Hellenistic Period (332 – 37 BC) and Roman Period (37 BC – 324 AD) and reached a maximum during the Byzantine period. The settlements

were gradually abandoned, which resulted in total abandonment after approximately 900 AD (Issar, 1990).
Currently the catchment receives approximately 200 mm precipitation annually and has a semi-arid climate (Stern et al., 1986). Bare rock crops out at only 1% of the area, while vegetation (69%) and cyanobacterial crusts (30%) cover the remaining soil covered area (Chapter 2).

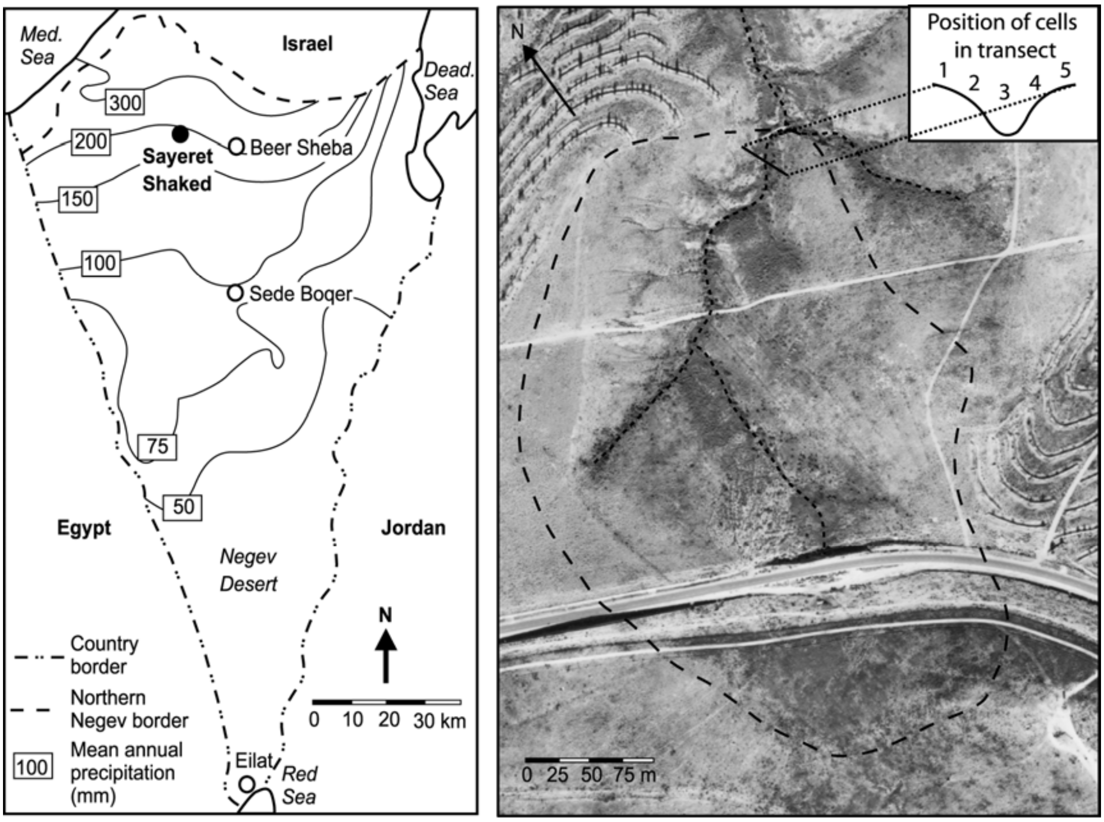



Fig. 6.1 Location of Sayeret Shaked in the Negev Desert of Israel, with close up of studied catchment. The mottled line indicates gully bed, the striped line indicates the catchment border and the solid line indicates the studied transect.

*6.2.2 Geomorphological history of the study site between about 800 BC to 800 AD*

The aggradation and incision history of Sayeret Shaked has been reconstructed in a transect study (Chapter 5). The transect is approximately 100 meter long (Fig. 6.1). Volumes are calculated over a 1 meter wide strip at the position of the transect. Several phases of aggradation and incision were recognized since the Late Pleistocene, four of which occurred between 800 BC and 800 AD. The first aggradation phase A1, between 806 BC and 360 AD, was a stable period with soil formation and slow dust deposition (Table 6.1). The lower border was dated 806 ± 296 BC with OSL. Succeeding incision phase I1 eroded 4.3 ± s.e. 4.1 $m^3$ of sediments at the position of the transect. This phase was confined between ~360 and 425 AD. Aggradation phase A2 (39.5 ± 7.5 $m^3$) was deposited between ~425 and 675 AD in a period with (over)grazing on the higher slopes and tillage in the gully bed. Two OSL dates indicate ages of 393 ± 127 AD and 537 ± 115 AD. At the end of the Byzantine era the catchment experienced strong incision during phase I2, triggered by decreasing carrying capacity caused by a strong aridification and still high human occupation. Between ~675 and 800 AD, 52.0 ± 9.0 $m^3$ of sediments was eroded and incision locally reached bedrock. During only 5% of the time (phase A2 and I2) 95% of the sediments were redistributed.

Table 6.1 Estimated time period (yr), volumes ($m^3$) and accumulation or incision rate per phase ($dm^3$ $year^{-1}$) at the position of the transect (Chapter 5).

| Phase | **Estimated time period** Years | **Volume** $m^3$ (s.e.) | **Accumulation rate** $dm^3$ $year^{-1}$ |
|---|---|---|---|
| A1 | 800 BC – 360 AD | 1.36 (0.5) | 0.2 |
| I1 | 360 – 425 AD | -4.3 (4.1) | -66.2 |
| A2 | 425 – 675 AD | 39.5 (7.5) | 158.0 |
| I2 | 675 – 800 AD | -52.0 (9.0) | -416.0 |

# 6.3 Material and Methods

### *6.3.1 LAPSUS*

*Water incision and aggradation* LAPSUS was used here as well, whereby the water redistribution model developed in chapter 3 (§3.2.2) and chapter 4 (§4.2.2) was used. In this study the temporal resolution is ten years. $Q$ is therefore a ten-year summation per grid cell of precipitation plus runon minus infiltration. Infiltration is corrected for available storage capacity $SC$ (m $time^{-1}$) per grid cell per ten years giving the maximum possible infiltration volume:

$$SC = h \cdot \phi \cdot 10 \tag{6.1}$$

Where $h$ is the soil depth (m) and $\phi$ soil pore volume ($m^3$ $m^{-3}$). The infiltration fraction $I_f$ (-) is dependent on the actual vegetation fraction $V_{act}$ (-) (Collins et al., 2004):

$$I_f = I_v \cdot V_{act} + I_c \cdot (1- V_{act}) \tag{6.2}$$

where $I_v$ is the infiltration fraction for vegetated surface and $I_c$ is the infiltration fraction for crusted surface (Chapter 4). Actual vegetation cover $V_{act}$ is corrected for livestock grazing:

$$V_{act} = V_{pot} \cdot (1 - H) \tag{6.3}$$

Where $V_{pot}$ is the undisturbed vegetation fraction (-) and $H$ is human occupation density (-). Higher human occupation therefore results in reduced vegetation cover and reduced infiltration. This increases runoff and erosion.
After calculating the water balance of a grid cell, runoff towards all lower neighbouring grid cells is calculated following the multiple flow principle (Holmgren, 1994; Quinn et al., 1991). After calculating runoff, the capacity for transport of sediments between cells is compared with the amount of sediment in transport. Portions instead of totals of the surplus or deficit in capacity are satisfied within every grid cell, depending on grid cell seize and erosion or sedimentation characteristics. For larger cells and easier erosion and sedimentation, a larger portion of surplus or deficit is satisfied (Schoorl et al., 2000).

*Tillage-induced sediment transport* Transport of sediments due to tillage is included as well following §1.2.4. In this LAPSUS application tillage is only active if human occupation density is larger than 0.5.

### *6.3.2 Input data*

*DEM and soil depth map* A current 2x2 m DEM is made by interpolation of hand measured elevation points following the method of Hutchinson, surveyed at a ~20 m grid. Because only little information of the 800 BC topography is available, the current DEM is used as model input. A current soil depth map is made by interpolating field measured soil depth points (n = 129), using the exponential Kriging method (Chapter 2). A palaeo-soil depth map is made by increasing the current map with 0.9 m soil to correct for the gully incision since 800 BC.

*Palaeo-precipitation record* The flowchart in Fig. 6.2 describes the method used to reconstruct the palaeo-precipitation record shown in Fig. 6.3. Holocene temperature was relatively stable (Dansgaard et al., 1993). As evaporation of a deep lake as the Dead Sea appears nearly constant from year to year in this climate (Klein and Flohn, 1987), fluctuations in palaeo-lake level can be positively related to precipitation in the source area (Enzel et al., 2003; Klein, 1981). According to Enzel et al. (2003) temporal variations of precipitation between northern Israel and Beer Sheva are largely synchronous and in phase. This implies that, although Sayeret Shaked is actually part of the Mediterranean drainage basin, we can use the Dead Sea lake level as a precipitation proxy. To establish the relationship between changes in palaeo-lake level and precipitation, first, the Dead Sea level record (m bsl) between 1854 and 1965 is averaged over 9 years (Enzel et al., 2003) and translated to volume ($km^3$) following Neev and Emery (1967) (Fig. 6.2: 1-2). After that, the annual change of the Dead Sea volume ($km^3$ $yr^{-1}$) is derived (Fig. 6.2: 3). A linear regression of the annual change in Dead Sea volume ($km^3$ $yr^{-1}$) with a nine-year averaged Jerusalem precipitation record (m $yr^{-1}$) between 1854 and 1965 (Heim et al., 1997), results in a $R^2$ of 0.60 ($P$ = 0.000) (Fig. 6.2: 4-5):

Precipitation = 0.416 * annual volume change + 0.602 (6.4)

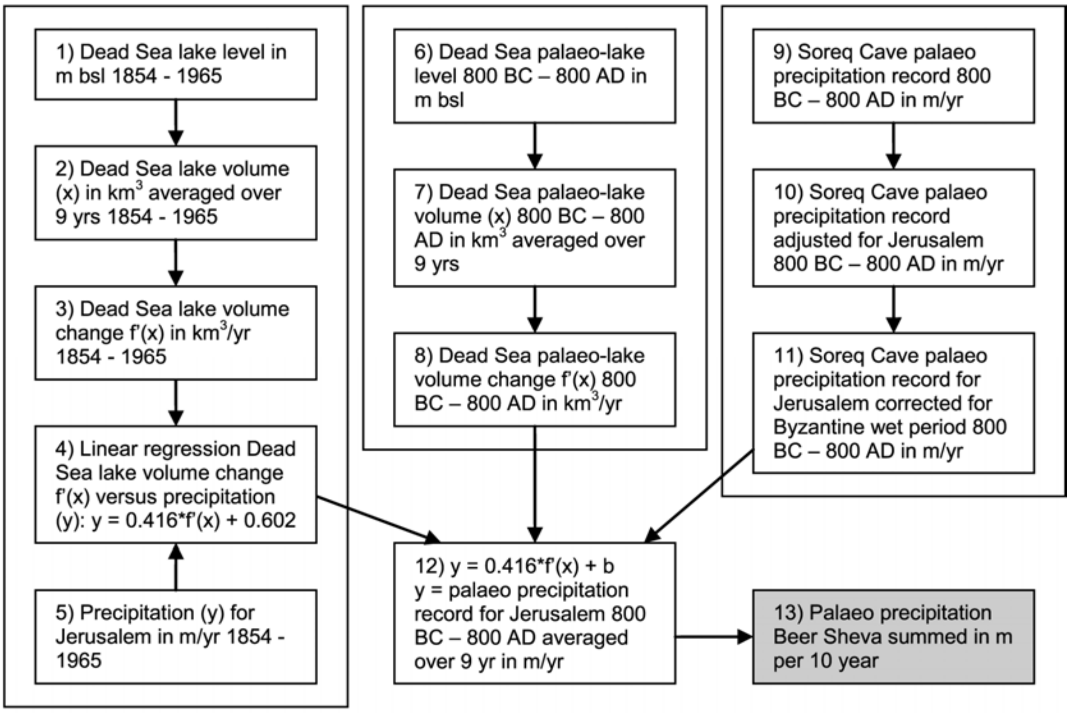



Fig. 6.2 Flowchart of method of palaeo-precipitation reconstruction.

Second, annual Dead Sea volume change between 800 BC to 800 AD is derived of a palaeo-lake level record of Migowski et al. (2006) (Fig. 6.2: 6-8). This annual volume change is used as input of the previously established regression formula (Fig. 6.2: 12). A consequence of this method is that precipitation fluctuates around the average precipitation of Jerusalem between 1854 and 1965 and therefore assumes relatively stable precipitation since 800 BC. Because this assumption appears unlikely, average precipitation (variable b in the y = ax + b equation) is replaced with the palaeo-precipitation curve of the Soreq Cave in the Judean Mountains, Israel (Bar-Matthews et al., 2003) (Fig. 6.2: 9-12). We do not use the palaeo-precipitation curve of Bar-Matthews et al. (2003) directly because its temporal resolution is too low for our modelling exercises. The curve is corrected for the difference in average annual precipitation between Soreq Cave and Jerusalem (Fig. 6.2: 10). Additionally this curve is increased with 70 mm in the Byzantine period, known to have been relatively wet (Bookman (Ken-Tor) et al., 2004; Issar, 1990; Migowski et al., 2006), as this short wet period is not visible in the coarser grained curve of Bar-Matthews et al. (2003) (Fig. 6.2: 11). Finally the resulting palaeo-precipitation record for Jerusalem (Fig. 6.2: 12) is corrected for the difference in average annual precipitation between Jerusalem and Beer Sheva and summed per 10 years to enable 10 years model runs (Fig. 6.2: 13 and Fig. 6.3).

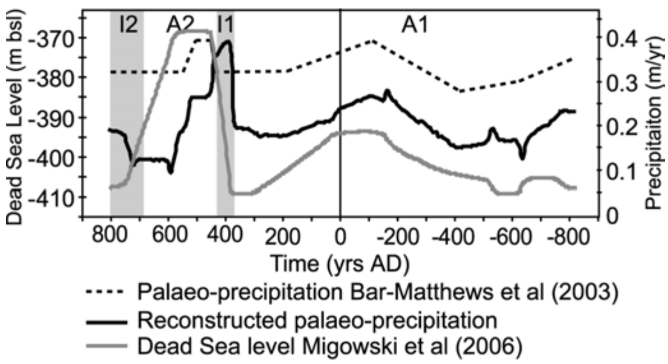



Fig. 6.3 Dead Sea lake level record of Migowski et al (2006) (m bsl) at left axis, palaeo-precipitation of Bar-Matthews et al (2003) (corrected for Byzantine period) and reconstructed palaeo-precipitation (m $yr^{-1}$) at right axis. Time in years AD at x-axis. Phase A1 and A2 are aggradation phases, I1 and I2 are incision phases.

*Palaeo-vegetation cover* Palaeo-vegetation cover is reconstructed based on chapter 2 (Fig. 6.4). In this study three groups of vegetation were observed in four sites on a climate gradient in the Northern Negev Desert: herbaceous plants, *Asphodelus ramosus* and shrubs. Biological and physical soil crusts make up the remaining surface. Surface cover of these vegetation croups had a strong relationship with precipitation. Over an annual precipitation gradient from 93 to 328 mm per fraction of soil on the surface (excluding positions with bedrock at the surface), it resulted in linear regression curves of:

| | | | |
|---|---|---|---|
| Herbaceous plants: | $y = 0.95x + 0.12$ | ($R^2 = 0.68$, $P = 0.176$) | (6.5) |
| *Asphodelus ramosus*: | $y = 0.69x – 0.07$ | ($R^2 = 0.93$, $P = 0.037$) | (6.6) |
| Shrubs: | $y = -0.24x + 0.28$ | ($R^2 = 0.73$, $P = 0.147$) | (6.7) |

where x was the precipitation per fraction of soil (m $yr^{-1}$) and y was vegetation cover per fraction of soil (-). Because in Sayeret Shaked less than 1% of the surface is covered by bedrock, precipitation per fraction of soil was set equal to precipitation. The vegetation groups respond differently to changes in precipitation. Herbaceous plants respond directly to changes in precipitation. For *Asphodelus ramosus*, which can live up to 9 years, response is slower. I assumed that an increase in precipitation resulted in a 10-year delayed increase in surface cover. A decrease in precipitation directly influenced Asphodelus ramosus negatively. As shrubs grow slowly and can reach ages of a few hundred years, response to precipitation changes was expected to be slow as well (Evenari et al., 1982b). For shrubs an increase in precipitation resulted in a decrease in shrub cover with a delay of 10 years, and a decrease in precipitation caused an increase in cover with a delay of 50 years. The resulting reconstructed total vegetation cover for 800 BC to 800 AD is shown in Fig. 6.4. Palaeo-vegetation cover is assumed homogenous over the catchment.

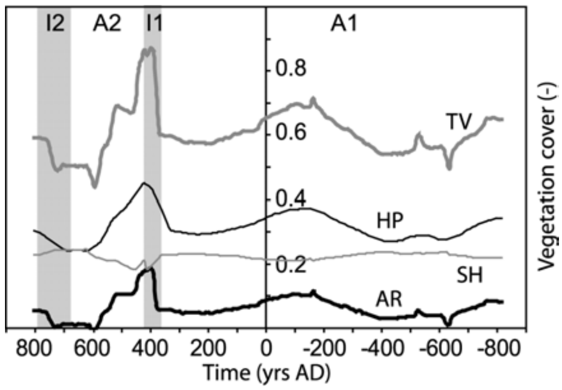



Fig. 6.4 Palaeo vegetation cover (-). Total vegetation (TV), herbaceous plants (HP), shrubs (SH) and Asphodelus ramosus (AR). Phase A1 and A2 are aggradation phases, I1 and I2 are incision phases.

*Human occupation record* The human occupation record was reconstructed based on a settlement record of the Beer Sheva plain between 8000 BC and 900 AD (Grovin, 1992; Issar, 1990). The maximum amount of settlements (~60) reached in the Byzantine era got a value of human occupation density $H$ = 1. Accordingly human occupation density of the other periods were calculated ($H$ = settlement density / maximum settlement density). The record was smoothed to a 30 year average to avoid unrealistically sharp transitions (Fig. 6.5).

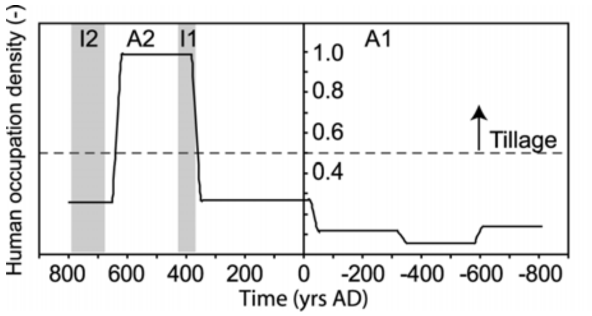



Fig. 6.5 Human occupation density (-). The broken line indicates human occupation density above which the model simulates tillage. Phase A1 and A2 are aggradation phases, I1 and I2 are incision phases.

### *6.3.3. Model calibration*

First, LAPSUS is calibrated between 800 BC to 800 AD per phase based on the results of chapter 5 (Table 6.2). Second, LAPSUS is tested for three alternative land use scenarios. The following land use types are used depending on human occupation density: 1) extensive grazing ($H \leq 0.2$), 2) intensive grazing ($0.2 < H \leq 0.5$) and 3) intensive grazing and rainfed agriculture ($H > 0.5$). For the extensive grazing scenario the parameter values of phase A1 are used, which has an average human occupation density of 0.17 (Table 6.2). For the intensive grazing scenario two simulations are done to estimate a range of sediment redistribution. The parameter values of aggradation phase A2 and incision phase I2 are used, both with the average human occupation density of phase I2 ($H = 0.27$). For the intensive grazing and rainfed agriculture scenario two simulations are done with the parameter values of incision phase I1 and aggradation phase A2, whereby an average human occupation density of 0.89 is used (the average of phase I1 and A2).

During model calibration pore volume $\phi$, infiltration fractions $I_c$ and $I_v$, dust deposition rate, conversion factor $p$ and plough depth $PL$ are kept constant in time and space. The infiltration fraction of crust surface ($I_c = 0.64$) and shrub surface ($I_v = 0.91$) is based on rainfall-runoff experiments in the catchment of Sayeret Shaked (Shachak et al., 1998). Average pore volume $\phi$ ($0.46 \pm 0.01$, n = 7) is derived from bulk density ($1442 \pm 90$ kg m$^{-3}$, n = 7) of oven-dried 100 cm$^3$ soil samples and particle density of the local loess (2.67 g cm$^{-3}$) (Offer and Goossens, 2001). Dust deposition is set at 0.0000213 m yr$^{-1}$ for the total surface based on Shachak and Lovett (1998). The parameter $p$ determines the water redistribution routing ($p = 1$: multiple flow, $p = \infty$: steepest descent) and is set to 2 (Schoorl et al., 2002). Depth of the plough layer is set on 0.16 m (Schoorl et al., 2004).

Parameters $m$, $n$, $K_{es}$, $P_{es}$ and $k_{td}$ are calibrated. The parameters $m$ and $n$ give an indication of the system studied: $m = 0$ and $n = 1$ suggest soil creep, while $m = n = 3$ suggests large rivers (Kirkby, 1971). As vegetation has a different sensitivity to erosion and deposition as crusted surface,

different values for erodibility $K_{es}$ and sedimentability $P_{es}$ are used for crusted and vegetated surfaces (Calvo-Cases et al., 2003). $K_{es}$ for vegetation is set equal to $K_{es}$ for crusted surfaces times 10, as the soil surface below vegetation is not, or less, covered by surface protecting (biological) surface crusts. $P_{es}$ for vegetation is set equal to $P_{es}$ for a crusted surface times 100, as under vegetation water flow is reduced and sedimentation is higher.
For calibration the net aggradation and incision volume ($m^3$) of a phase is calculated for a 1 meter wide transect (Fig. 6.1). The simulated volumes are compared with the observed volumes of a dated stratigraphic sequence (Table 6.1). Based on the difference between the predicted and observed volumes Root Mean Squared Errors (RMSE) are calculated. Additionally a comparison is made with net height change at five grid cells in the transect (Fig. 6.1).

## 6.4 Results

### *6.4.1 Reconstructing the valley fill*

The model calibration results in very different parameter settings per phase, reflecting the variability in human occupation, land use and precipitation among the phases (Table 6.2).

Table 6.2 Parameter sets resulting from calibration

| Phase | $m$<br>- | $n$<br>- | $K_{es}$<br>$m^{-1}$ | $P_{es}$<br>$m^{-1}$ | $k_{td}$ | **Av. human occ. density** |
|---|---|---|---|---|---|---|
| A1 | 1.0 | 0.5 | 0.00001 | 0.0001 | - | 0.17 |
| I1 | 1.1 | 1.1 | 0.01 | 0.000001 | 0.0001 | 0.90 |
| A2 | 0.1 | 0.4 | 0.1 | 0.01 | 1.0 | 0.88 |
| I2 | 1.1 | 0.1 | 1.0 | 0.0000001 | - | 0.27 |

The calibrated LAPSUS model approaches the field results closely, incising during incision phases and aggrading during aggradation phases (Table 6.3 and Fig. 6.6). The RMSE is lowest here. The simulated height difference of five grid cells compared to their height at about 800 BC, resembles the field results, though the final simulated incision is smaller (Fig. 6.1 and Fig. 6.7). The different phases result in different spatial patterns of incision and aggradation (Fig. 6.8a/b). During phase A1 aggradation is homogenous over the catchment. During phase I1 incision is concentrated in the main gully and on the slopes with shallow soils. In phase A2 incision dominates on the areas downslope of shallow soils, while the gully aggrades. In phase I2 incision concentrates on the aggradation – incision boundary of the previous phase. At the end of phase I2 soil depth is strongly reduced over the whole catchment (Fig. 6.8c).

Table 6.3 Volume in transect ($m^3$) for field results ± s.e. and for simulation results, and resulting RMSE per scenario.

| | Volume ($m^3$) | | | | |
|---|---|---|---|---|---|
| **Phase** | **A1** | **I1** | **A2** | **I2** | **RMSE** |
| Field results | 1.36 ± 0.5 | -4.30 ± 4.1 | 39.5 ± 7.5 | -52.00 ± 9.0 | - |
| | | Scenario | | | |
| Field based | 1.40 | -2.87 | 47.84 | -25.83 | 9.00 |
| Extensive grazing | 1.40 | -0.71 | 0.13 | 0.13 | 23.78 |
| Intensive grazing | 85.80 / -76.20 | -2.77 / -0.07 | -1.37 / -0.24 | -0.30 / -0.12 | 44.63 / 43.35 |
| Intensive grazing + agriculture | 166.32 / -34.33 | 4.38 / -4.67 | 10.84 / -6.71 | 8.22 / -1.81 | 65.63 / 33.12 |

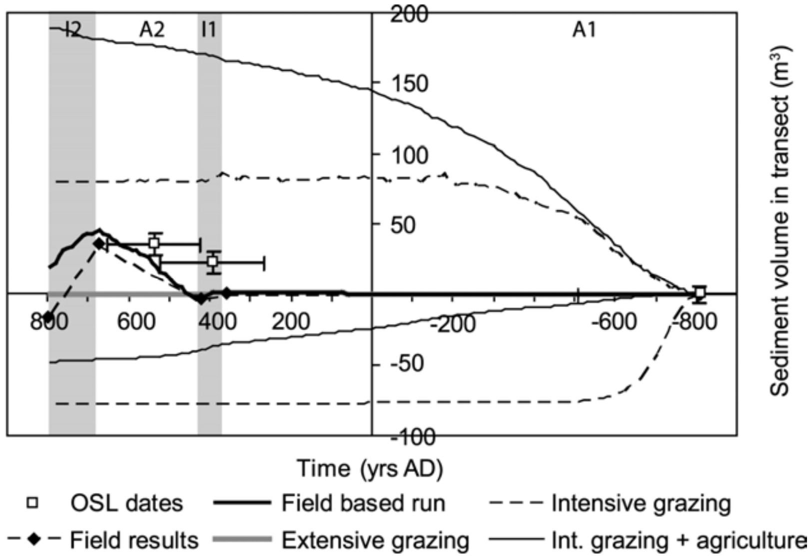



Fig. 6.6 Volume of sediment in transect ($m^3$) in time (yrs AD) for four scenarios and field results. OSL dates are given as well, with indication of error bars. Phase A1 and A2 are aggradation phases, I1 and I2 are incision phases.

### *6.4.2 Land use scenarios*

The land use scenarios diverge further from the field results than the field based simulation, reflected in higher RMSE values (Table 6.3 and Fig. 6.6). At the extensive grazing scenario in total 2.37 $m^3$ sediment is redistributed, while in the more intensive grazing scenario and the intensive grazing and rainfed agriculture scenario a range of in total 76.63 to 90.24 $m^3$ and 47.52 to 189.76 $m^3$ respectively are replaced.

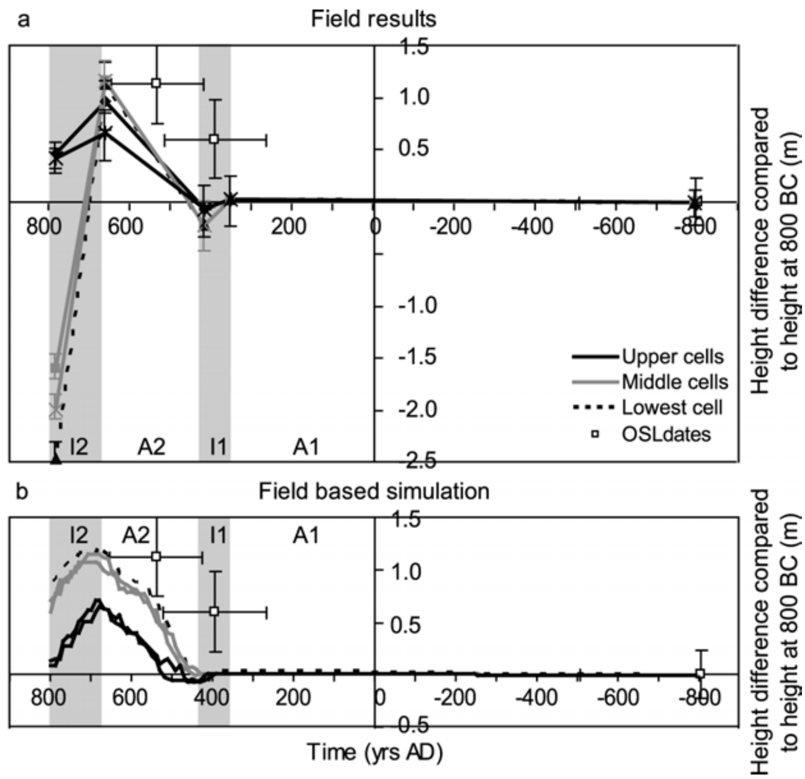



Fig. 6.7 Height difference (m) of five grid cells at position of the transect compared with height at 800 BC, a) field results, including error bars indicating estimated height error and b) field based scenario. Phase A1 and A2 are aggradation phases, I1 and I2 are incision phases.

When focussing on five grid cells in the transect, similar results are visible (Fig. 6.1 and Fig. 6.9). In the extensive grazing scenario only the centre cell (cell 3) incises (Fig. 6.9a). In the more intensive grazing scenario all grid cells experience aggradation or incision depending whether the aggradation or incision parameter set is used (Fig. 6.9b). In the intensive grazing and rainfed agriculture scenario sediment redistribution is high for all grid cells, especially during the simulation with the aggradation parameter set (Fig. 6.9c).

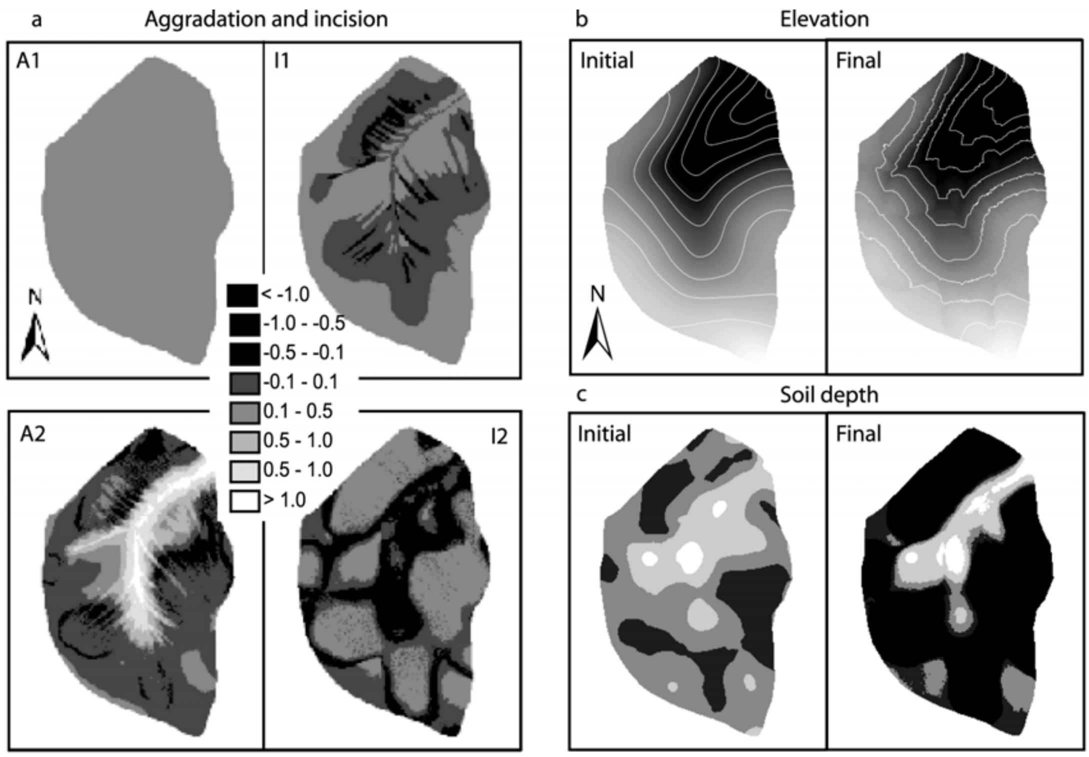



Fig. 6.8 a) Spatial patterns of aggradation (black) and incision (white) in Sayeret Shaked for the field based scenario. Initial and final digital elevation (b) and soil depth (c) (black is low/shallow and white is high/deep).

## 6.5 Discussion

### *6.5.1 Pitfalls of long-term simulation studies*

Longer-term simulation studies of human influence on catchment-wide landscape evolution are scarce (Coulthard, 2001). This is firstly caused by lack of accurate input data and secondly by a high process variability in time. Particularly at longer time scales these problems become more pressing.

Firstly accurate input data records and palaeo-input maps are hard to obtain. Especially reconstruction of palaeo-input maps is complex, as often only low-resolution spot data is available. Non-ambiguous interpolation of these data is hardly possible (Rommens et al., 2005). Also in this study a correct, error-free palaeo-DEM and soil depth map could not be obtained. To avoid uncertainty propagation, we used a more accurate current DEM and corrected current soil depth map instead.

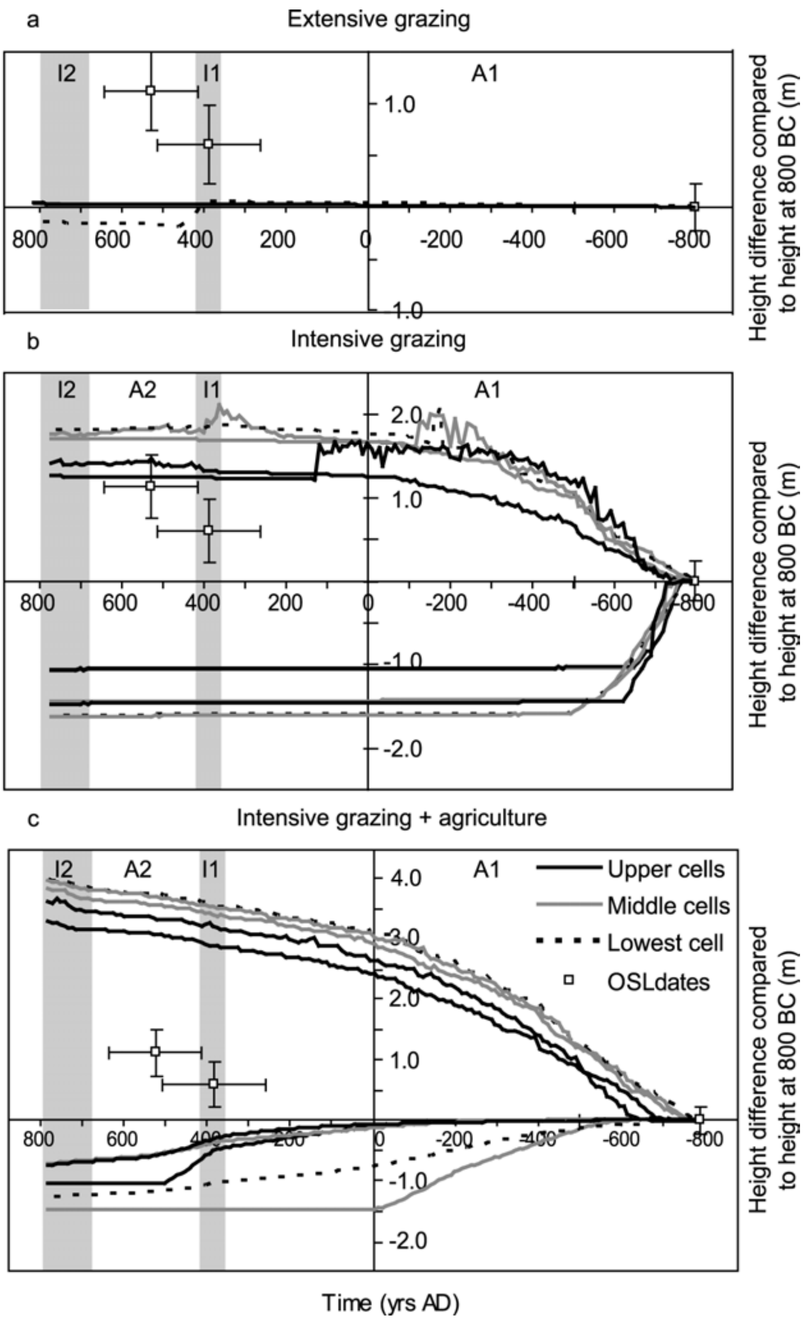



Fig. 6.9 Height difference of five grid cells in the transect compared with height at about 800 BC (m). For a) extensive grazing scenario, b) intensive grazing scenario and c) intensive grazing and rainfed agriculture scenario (different scaling of y-axis!). Phase A1 and A2 are aggradation phases, I1 and I2 are incision phases.

Even though the results of this study have no high spatial precision, the differences in volume and incision depth among the scenarios at the position of the transect are clearly different and beyond the error margins (Table 6.3 and Fig. 6.7). The results demonstrate a range of possible sediment redistribution intensities, outlining the extremes under aggrading or incising circumstances.

Secondly the driving factors of landscape evolution differ in time, causing landscape evolution processes to vary in relevance as well. Most landscape evolution models focus merely on one or few of the possibly relevant landscape evolution processes. This type of models is therefore likely to be incapable of handling alternating driving factors through time. Additionally it is difficult to make a model which, based on a single set of parameter values and input records, can handle the variations in dominant processes in time. As LAPSUS incorporates several of the most relevant landscape evolution processes, different landscape evolution processes can be emphasized and their interactions studied. To enable accentuation of different landscape evolution processes per period, the time period is split in four parts, whereby different parameter settings are used (Table 6.2).

During phase A1 mainly small-scale slope processes are simulated. The parameter values of phase A1 are in range with other studies and LAPSUS applications (Follain et al., 2006; Schoorl et al., 2004; Schoorl and Veldkamp, 2001). During the other phases the slope and gully are more connected. Erodibility $K_{es}$ of the other phases is rather high (Schoorl et al., 2000), as a result of human land use and associated increase in erosion. The values of sedimentability $P_{es}$ are in range with other applications, though slightly low. This can be explained by the reduction of surface roughness and vegetation cover by livestock. The strong tillage activity in phase A2 is reflected in a relatively high $P_{es}$ value, caused by the increase in surface roughness by tillage and high tillage transport coefficient $k_{td}$.

### *6.5.2 Reconstructing the valley fill*

The results demonstrated that LAPSUS, given its process description, is able to reproduce the history of the valley fill of Sayeret Shaked at the position of the transect (Table 6.3, Fig. 6.6 and Fig. 6.7). This is reflected in a low RMSE value. Additionally all phases are simulated in the correct direction of change: the aggradation phases experience aggradation, while the incision phases experience incision. Also the OSL samples, taking the error margins of the dating in account, fit within the simulated sediment deposits and thus verify the simulated aggradation and incision at the position of the transect (Fig. 6.6 and Fig. 6.7). Especially in the phases A1 and A2, the field based volumes are closely approximated, overestimating only 3% and 21% respectively (Table 6.3). The volumes of incision phases I1 and I2 are underestimated by LAPSUS, resulting in 43% and 50% underestimation respectively. Though the volumes of incision deviate rather strongly from the field results, the overall trends are evident.

The dominant processes vary in time. During phase A1 almost no sediment is eroded in the catchment (Fig. 6.8). The main process is dust deposition. The stability of the catchment was confirmed by the palaeo-soil formed in that period (Chapter 5). During phase I1 incision dominantly occurs within the main gully bed and on the slopes with shallow soils. On these shallow soils saturation overland flow is quickly formed, initiating erosion. Although human occupation is high, the dominant driving factor of landscape dynamics during this time seems to be water, forming typical water erosion patterns (Fig. 6.8a). Tillage is less intense and can not balance gully incision. During phase A2, at the high stand of the Byzantine Empire, human occupation is high as well. Large volumes of sediment are redeposited in the catchment mainly by tillage-induced sediment transport, filling the gully and flattening the valley relief (Fig. 6.8a). The simulation of aggradation phase A2 shows alteration of dominant aggradation phases with small periods of incision due to water erosion (Fig. 6.6 and Fig. 6.7). These fluctuations are reflected in the field results as well, where several sub-layers were distinguished in the deposits of phase A2. It points to the ability of LAPSUS to handle non-linearity in time, resulting in temporal incision during periods of dominant aggradation. The field results indicate that during incision phase I2 large volumes of sediment have been removed out of the catchment (Table 6.3 and Fig. 6.6). Strong water erosion leaded to gully incision (Fig. 6.7). The model underestimates this incision. This is mainly due to an inability of LAPSUS to simulate the event based, extremely high rate of incision (Table 6.1 and Fig. 6.6). This high rate is possibly caused by ephemeral gully formation, a process frequently occurring in loess soils under rainfed agriculture (Poesen et al., 2003). These ephemeral gullies have a smaller spatial scale than can be captured in the 2x2 m DEM used here and are therefore not taken in account in the simulation. Additionally LAPSUS approaches event based modelling in its process description, but is not truly able to represent the variation during events.

### *6.5.3 Land use scenarios*

The land use scenarios diverge strongly from the field results (Table 6.1 and Fig. 6.6). At the extensive grazing scenario in total 2.37 $m^3$ sediment is redistributed, much less than in the intensive grazing scenario (76.63 – 90.24 $m^3$) and the intensive grazing and rainfed agriculture scenario (47.52 – 189.76 $m^3$) (Table 6.3).

In the extensive grazing scenario the catchment is thus almost stable and infilling results mainly from dust deposition (maximum 0.05 m aggradation in total). Only after ~430 AD some incision of maximal 0.18 m is apparent in the lowest grid cell of the transect (Fig. 6.9). In contrast to the

extensive grazing scenario, large volumes of sediment are redistributed in the more intensive grazing scenario and the intensive grazing and rainfed agriculture scenario, directly after 800 BC (Fig. 6.6 and Table 6.3). For both scenarios incision is dominant when the incision parameter set is used. The transect is stronger incised in the more intensive grazing scenario than in the intensive grazing and rainfed agriculture scenario, with maximum incision depths of 1.66 m and 1.45 m respectively. During the more intensive grazing scenario incision is solely caused by water erosion resulting in gully incision, whereas in the intensive grazing and rainfed agriculture scenario tillage-induced sediment transport is active as well, flattening the relief in the valley and filling ephemeral gullies (Vanwalleghem et al., 2005). Analogously, the simulation based on the aggradation parameter set results in stronger aggradation in the intensive grazing and rainfed agriculture scenario (maximal 3.94 m) than in the intensive grazing scenario (maximal 2.18 m).
In Fig. 6.9 a stepwise incision can be seen for the intensive grazing scenario. This phenomenon is likely caused by backwards gully retreat, whereby several pulses of incision passed the transect at different periods in time. This process can nowadays be seen in the more arid regions of the Negev Desert, where gullies actively retreat (Avni, 2005). In the intensive grazing and rainfed agriculture scenario these pulses are visible as well, but less distinct. Here translocation of sediments by tillage causes a rapid infilling of ephemeral gullies, counteracting incision (Vanwalleghem et al., 2005).
Different land use types have different effects, though both intensive grazing and rainfed agriculture strongly increase landscape process rates (Fig. 6.6). Rainfed agriculture increases slope erosion and gully aggradation by tillage-induced sediment transport. Meanwhile, the reduced soil depth on the slopes increases runoff towards the gully bed, thereby contributing to the available water for crops making rainfed agriculture more feasible in the flattened gully bed (Bruins, 1986). Additionally this runoff initiates water erosion, leading to interactions of tillage and water related processes. Intensive grazing of livestock leads to increased runoff rates, due to vegetation reduction and crust formation by trampling. As a result gully erosion increases and gully patterns become more pronounced. Whereas rainfed agriculture reduces relief in a catchment, livestock grazing increases the relief. Under an extensive grazing regime the catchment seems stable, caused by the high water storage capacity of the deep loessic soils, high infiltration rates under vegetation and rapid formation of protecting biological crusts on bare soils (Shachak et al., 1998). The effect of various land use types on landscape dynamics are thus distinctly different and each land use type will create a specific path of landscape development. Alternation of land use types will therefore result in complex landscapes.

### *6.5.4 Driving factors of long-term landscape dynamics*

The strong changes in precipitation, fluctuating between ~100 mm $yr^{-1}$ and ~380 mm $yr^{-1}$, are barely visible in the results (Fig. 6.3 and Fig. 6.6). Only in the intensive grazing scenario a weak response to precipitation fluctuations can be seen (Fig. 6.9). Land use, on the other hand, has a distinct effect in rate and patterns of landscape dynamics, especially rainfed agriculture. Thus, fluctuations in precipitation appear much less relevant than the effect of land use in Sayeret Shaked. However, indirectly precipitation fluctuations might be influential by its driving capacity on land use and human occupation.

Taking this observation a step further, it seems that the only way this valley fill could have developed, is by an alternating sequence of different land use types with varying intensity (Fig. 6.5 and Fig. 6.6). Especially tillage activities seem to have been important for the aggradation of the valley fill. The period of strong incision seem more related to intense livestock grazing, increasing runoff and erosion. In both situations human land use destabilized the landscape. These results confirm our hypothesis that in Sayeret Shaked humans control landscape dynamics, resulting in strong amplification of aggradation and incision rates and volumes in periods with high human occupation density and intense land use. It agrees with several studies that name humans as a main driving factor of landscape dynamics in the Mediterranean, which demonstrate a distinct increase in sediment redistribution after human land use started and not because of precipitation fluctuations (e.g. Chester and James, 1991, Lespez, 2003, Fuchs et al., 2004, and Fuchs, 2007). The combination of human and natural induced processes lead to a co-evolutional trajectory of landscape development, forming typical landscapes which would otherwise not have formed (Bruins and Jongmans, 2004). This co-evolution is recognized in other regions as well and seems to have put a clear mark on landscape evolution world wide (Chester and James, 1991; Mieth and Bork, 2005; Pape, 1970).

In Sayeret Shaked the most prominent periods of landscape change dynamics since the Late Pleistocene, are concentrated during the few hundred years of the rise and fall of the Byzantine Empire. During only 5% of the time 95% of the sediments were redistributed. This strong effect on landscape dynamics during the Byzantine Era is recognized in other settings in the Eastern Mediterranean as well (Lespez, 2003). Humans probably influenced large regions, as they influenced Sayeret Shaked. Even during a short time period, the intense effect of humans can alter the geomorphology of a catchment and its development path into the future. Clearly the influence of humans is not only strong today, but was so already further back in time.

## 6.6 Conclusion

The valley fill in Sayeret Shaked is formed in an alternation of phases of incision and aggradation between about 800 BC and 800 AD. Most sediments are redistributed through the catchment during the short time period of the Byzantine Era, a period with high human occupation density. The intensive land use during that time caused aggradation during periods with dominantly rainfed agriculture and strong tillage activity and incision during periods with dominantly intensive livestock grazing. The LAPSUS model demonstrates its ability to reconstruct the valley fill of Sayeret Shaked, whereby several landscape evolution processes are integrated and combined. The land use scenarios demonstrate that especially during periods with more intensive grazing and tillage activity sediments are redistributed in Sayeret Shaked. Intensive grazing on itself mainly causes incision of the gully, whereas tillage activity leads to infilling. Under extensive, low-pressure grazing the catchment is almost stable and only little sediment is replaced. The valley fill is formed by co-evolution between human and natural induced processes. Human influence have been essential for formation of this valley fill. Humans appear in this semi-arid catchment the main driver of land dynamics, much more than precipitation fluctuations. Only a short time period of strong human land use can irreversibly alter the development trajectory of a catchment. It emphasizes the importance of sustainable land management in the present and future in order to combat further dryland degradation.

# 7 General synthesis

## 7.1 Interactions and feedbacks among landscape structure, organisms and flows of water and sediment

### *7.1.1 Temporal and spatial scale of landscape dynamics*

Landscape dynamics reflects the formation of a landscape by the interactions among landscape structure, resource flows and organisms (§1.1) (Fig. 7.1). Landscape dynamics operate at multiple temporal and spatial scales. The temporal scale varies between single events to millennia. Processes forming the landscape structure, the physical basis on which a landscape is formed, act predominantly at long time scales, and involve tectonics and rock weathering. These processes often result in typical landscape structures that cover larger spatial regions. At smaller spatial scales local heterogeneity in bedrock outcrops and micro-topography influence landscape dynamics. Resource flows can operate at short time scales, e.g. single precipitation events, but at long timescales as well, e.g. slowly aggrading dust deposits (Shachak and Lovett, 1998). The spatial scale of resource flows is very flexible, ranging from microscopic, as when dust is collected by sticky polysaccharide sheaths of biological soil crusts, to thousands of kilometres for dust exported from the Sahara (Belnap, 2003; Offer and Goossens, 2001). The timescale of organisms is often rather limited, from a year for annual vegetation to centuries for shrubs (Evenari et al., 1982b). Similarly, the spatial scale of organisms is limited, although e.g. biological surface crusts can cover large areas. The temporal and spatial scale of the interactions and feedbacks of landscape dynamics thus depend on the temporal and spatial scale involved, and ranges therefore from short to long and from small to large.

### *7.1.2 Landscape structure and flows of water and sediment*

In the Northern Negev Desert of Israel the most relevant interactions and feedbacks among the three parts of a landscape are related to water (Fig. 7.1 and 7.2). The simulation results described in chapter 3 indicate that water redistribution and availability is most strongly influenced by the landscape structure. Bedrock outcrops are practically impermeable for water and produce runoff even at very low precipitation rates, causing runoff to soil-covered patches down slope (Yair and Kossovsky, 2002). On soil-covered patches infiltration rate is much higher and runoff infiltrates quickly (Yair and Raz-Yassif, 2004). Soil-covered areas produce less runoff and have, beyond the reach of bedrock outcrops, less water available for plants than near bedrock outcrops (Chapter

3). Patterns of runoff and runon depend thus strongly on position and extent of bedrock outcrops (Calvo-Cases et al., 2003). Model simulations illustrate that catchments with different surface characteristics yield very different water redistribution patterns and quantities, leading to different vegetation types and patterns (Chapter 3). The positive feedback mechanism between runoff generating bedrock outcrops and erosion of soil patches, causes a continuous decrease in soil/rock ratio and increase in runoff generation (Yair, 1992a).

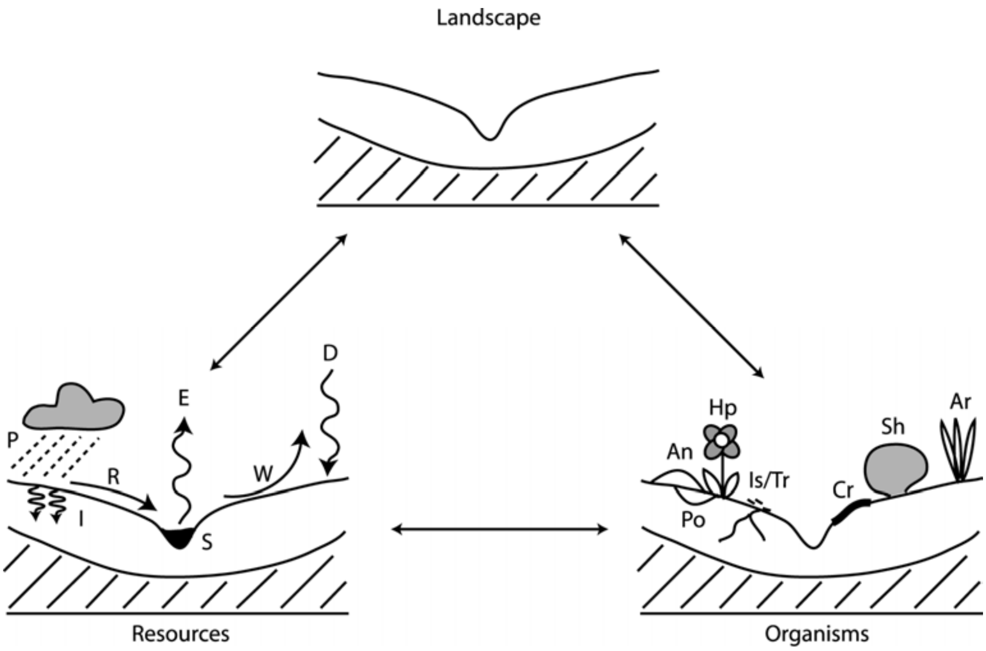



Fig. 7.1. Schematic drawing of the Interactions and feedbacks between landscape structure, resources and organisms. P: precipitation, E: evaporation, I: infiltration, R: runoff, S: sedimentation, D: dust deposition, W: wind, Hp: herbaceous plants, Sh: shrubs, Ar: Asphodelus ramosus, Cr: crust, An: ants, Po: porcupines and Is/Tr: isopods, termites and scorpions.

### *7.1.3 Landscape structure and organisms*

Landscape structure strongly influences the occurrence and establishment of organisms. In the rocky regions of the Northern Negev Desert, the often horizontally layered bedrock causes an alternation of bare bedrock and local thin layers of loess. Cracks and crevices in the bedrock provide additional sites for vegetation with a particular micro-climate, caused by reduced evaporation, lower temperatures, and collection of runoff (Wieder et al., 1985). As bedrock outcrops redistribute water to sediment-covered patches, they enable organisms to survive in a dryer climate than would be expected based on annual precipitation (Chapter 3) (Olsvig-

Whittaker et al., 1983; Yair, 1994). On the other hand, a large cover of bedrock reduces living space for plants and soil animals (Chapter 2).
Organisms influence the landscape structure slowly and often indirect. The shrub mounds studied in chapter 4 are a good example. The simulation results of chapter 4 indicate that shrubs collect sediments below their canopy, thereby raising the surface, whereas the surrounding crusts is eroded. The formation of shrub mounds takes 60 years or more (Abrahams et al., 1994; Shachak and Lovett, 1998), and influences resource flows and the trajectory of landscape evolution. A more direct effect, though probably as slow or slower, is the conversion of rock to soil by rock-eating snails, which in the more rocky parts of the Negev Desert feed on endolithic lichens inside calcareous rock (Jones and Shachak, 1990; Shachak et al., 1995).

### *7.1.4 Resource flows and organisms*

Organisms influence resource flows. Vegetation and biological surface crusts have a strong influence on water availability: vegetation increases infiltration of water in the soil, while biological surface crusts decrease the infiltration rate (Chapter 2) (Bhark and Small, 2003; Schlesinger and Pilmanis, 1998; Shachak et al., 1998). Also fauna influences resource flows in the desert. Porcupines (*Hystrix indica*) dig small foraging holes, creating sinks for resources and locally increasing biomass, vegetation density and species richness (Boeken et al., 1995). Termites (*Termitidae*), scorpions (*Scorpionoidea*), isopods (*Hemilepistus reaumuri*) and ants (*Messor* species) affect water and soil redistribution by increasing soil porosity during burrowing and by depositing easily erodible soil material on the land surface (Shachak and Yair, 1984; Wilby et al., 2001; Zaady et al., 2003). Isopods reduce the salt content of the subsoil by concentrating their digging activities on the salty layers (Shachak et al., 1995; Yair, 1995). So, these organisms are actively involved in redistribution of resources, and are therefore called ecosystem engineers (Van Breemen and Finzi, 1998; Yair and Shachak, 1982).
Resource flows in turn influence organisms by their availability or lack of it. Abundance of some resources has a negative influence on organisms, e.g. in case of strong erosion, salinization or sedimentation. In semi-arid and arid regions the feedbacks between vegetation and resource flows can lead to typical vegetation patterns (Rietkerk et al., 2004). Regular vegetation patterns can be formed on flat or gently sloping lands with homogeneous soils (Gilad et al., 2004; Valentin et al., 1999). However, as emphasised in chapter 2 and 4, irregular vegetation patterns are more widespread in the semi-arid and arid world, due to the common occurrence of heterogeneous landscapes. Only in catchments with homogeneous landscape characteristics biological interactions are strong enough to develop regular vegetation patterns.

## 7.2 Driving factors of landscape dynamics

In the Northern Negev Desert three main drivers of landscape dynamics can be distinguished: tectonics, climate and humans. Since the Early Pleistocene the region is tectonically stable and climate and humans are most relevant active driving factors of landscape dynamics (Ben-David et al., 2002; Garfunkel and Ben-Avraham, 1996).

Climate varied strongly over the last 50.000 years (Fig. 5.2) (Bartov et al., 2002; Roberts et al., 1999). In the Late Pleistocene the region experienced a humid climate, reflected in high water levels in the Dead Sea, and soil formation was active throughout the Northern Negev. The resulting palaeosols can still be recognized as red soil layers with calcium carbonate concretions (Bowman et al., 1986; Bruins and Yaalon, 1979; Geraedts, 2005). Due to the humid climate the precipitation isohyets were shifted southward compared to the current situation. Throughout the Negev a relatively abundant vegetation helped to stabilize the slopes. In combination with the high frequency and low intensity of precipitation events in the more humid climate, this lead to relatively stable landscapes (Chapter 5) (Avni et al., 2006). At the end of the Pleistocene strong climate fluctuations occurred. The Younger Drias was very dry and caused high incision rates throughout the Negev (e.g. Neev and Emery, 1967, and Avni et al., 2006). After a relative wet beginning of the Holocene (Migowski et al., 2006), the climate became more arid (Goodfriend, 1990; Magaritz, 1986; Robinson et al., 2006). The precipitation isohyets and vegetation bands shifted to the north, more or less to the current positions. As a result of the reduced vegetation cover and higher precipitation intensities, the arid rocky areas became more vulnerable to erosion (Avni et al., 2006). Since then erosion and desertification predominates here.

Since the Late Holocene humans act as a driving factor of landscape dynamics (Mieth and Bork, 2005; Vanwalleghem et al., 2006). Throughout history humans seem to have strongly increased climate-driven landscape dynamics worldwide, amplifying incision and aggradation phases (Foster et al., 2007; Rustomji and Pietsch, 2007; Schmitt et al., 2006). Human land use in the Negev was long confined to rainfed agriculture and pastoralism, depending on local circumstances, political rule and climate (Bruins et al., 1986). Especially in the loess belt (Fig. 7.2) human influence on landscape dynamics was great (Chapter 5 and 6). Rainfed agriculture locally caused tillage-induced sediment transport and gully infilling. Livestock grazing reduced vegetation cover and lead to increased runoff and slope erosion. The vegetation cover in the loess region might once have been steppe-like, similar to still preserved savanna systems in North and South America. Recently, the American savanna systems are degrading to shrub – crust landscapes (Abrahams et al., 1994; Rostagno and Del Valle, 1988). In the northern loess region this degradation phase might have started already long ago when livestock grazing of early inhabitants caused a transition from savanna systems to the current shrub – crust landscapes.

During the Byzantine era a second degradation phase occurred, when the large human population caused overexploitation of natural resources, overgrazing and strong tillage-induced sediment transport (Chapter 5 and 6). Strong pulses of sediment were transported and redistributed trough the landscape. In contrast, the large climate fluctuations of the Late Pleistocene and Early Holocene resulted in much smaller fluxes of sediment. The simulation study of different land use scenarios shows that the present landscape could only have formed by co-evolution of natural processes and human land use (Chapter 6). In the arid Negev Highlands (Fig. 7.2), particularly during Byzantine times, humans seem to have counteracted the natural erosion processes by actively taking soil conservation measurements, slowing down runoff and collecting water and sediments in the upper part of the catchments (Avni, 2005; Bruins et al., 1986). Some of the constructions of the ancient inhabitants of the Negev have survived throughout history and still have a soil conservation function today (Avni et al., 2006). It appears that in the whole Northern Negev humans are the main driver of landscape dynamics, either amplifying landscape dynamics or reducing it.

## 7.3 Landscape dynamics modelling

Modelling landscape dynamics with all its interactions, feedbacks and drivers, is a complex task and requires integration of interdisciplinary knowledge. Most available models, however, deal with only one or two of several relevant aspects: e.g. erosion, hydrology, land use or ecology (e.g. Muttiah & Wurbs, 2002, Gilad et al., 2007, Coulthard & Macklin, 2001, Favis-Mortlock et al., 1997, Peeters et al., 2006). The LAPSUS model, used throughout this study, is relatively interdisciplinary, and covers hydrology, sediment redistribution (including sedimentation), vegetation, tectonics, land sliding and land use (grazing and tillage) (Claessens et al., 2005; Schoorl et al., 2006; Schoorl et al., 2000). No models exist currently which are truly able to model landscape dynamics in all its aspects. LAPSUS lacks e.g. vegetation dynamics and processes involving soil organisms. It would therefore be valuable to develop full landscape dynamics models or to expand existing models. Spatially explicit models often suffer from spatial and temporal uncertainties, simplification and generalization of processes, incompatibility of process scale and model scale, need of parameter calibration and lack of validation data sets. Still models can be very valuable to gain process knowledge. In this study I used LAPSUS to extrapolate landscape dynamics beyond the range and circumstances on which the process descriptions in the model are based, in an effort to gain new insights in landscape dynamics of the Northern Negev Desert (Chapter 3, 4 and 6).

# 7.4 Landscape dynamics in the Northern Negev Desert

### *7.4.1 The Northern Negev Desert*

The Northern Negev Desert covers approximately 8850 km$^2$ stretching from the Beer Sheva region in the north to Mizpe Ramon in the middle of the Negev Desert (Fig. 7.2). The area can be divided in five different regions. Three of these have been more closely studied: the south-western corner of the Judean Hills incorporating the catchment of Lehavim, the loess belt including the catchment of Sayeret Shaked, and the Negev Highlands where the catchments of Halluqim and Avdat are positioned. The two other areas have not been considered in this research: the Nizzana sand field and the Arava valley. The Nizzana sand field is an extension of the Sinai continental sandy area and consists of linear west-east trending sand dunes (Tsoar and Moller, 1986). The upper part of the dunes is often bare, whereas the lower parts are covered by a smooth biological soil crust and herbaceous plants (Lange et al., 1992). The sandy soils and water-absorbing surface crusts trigger very different landscape dynamics than the ones active in the other studied regions. The Arava valley was formed during the Oligocene to Pliocene by rift valley formation, followed by incision of surrounding areas. It is a truly desert region with less than 75 mm annual precipitation (Fig. 1.1). As a result vegetation is scarce and only occurs in and near riverbeds and springs. The landscape dynamics here are, due to its high aridity, hardly comparable with the other regions.

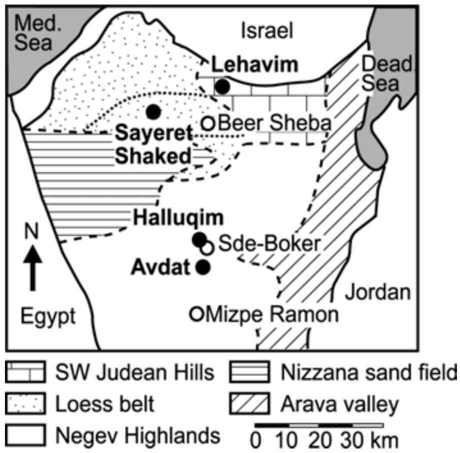


Fig. 7.2 Position of the five regions in the Northern Negev Desert. Mottled lines in loess belt delineate northern, middle and southern zone.

### *7.4.2 South-west Judean Hills*

The climatic gradient in the Judea Hills is strong (Fig. 1.2 and 7.2) (Kutiel et al., 1995). The western wettest part, which includes Lehavim, is dominated by smooth hills, with a dense shrub vegetation and local afforestation (Chapter 1 and 2). In theory this region can sustain a full vegetation cover during the wet season. The more arid south-eastern part is more rocky and resembles the Negev Highlands in landscape dynamics. The south-western region around Lehavim is characterized by shallow soils, horizontally banded bedrock outcrops and gullies formed during earlier incision phases. Bedrock weathering is active and soil formation occurs. Runoff connectivity is low, as the runoff-generating bedrock outcrops are patchy and not connected with the gully (Yair and Kossovsky, 2002). In the last years, even during large precipitation events, no channel runoff occurred (Yair and Kossovsky, 2002; Yair and Raz-Yassif, 2004). Nevertheless, the older colluvial deposits are being incised nowadays, thus under certain conditions active gully erosion must occur.

This region has been grazed since prehistoric times (5000 – 8000 years ago) and is mostly composed of grazing-resistant species (Noy-Meir and Seligman, 1979; Osem et al., 2004). The vegetation is adapted to the high grazing pressure. The area is covered by livestock tracks, with a strongly compacted soil surface. At these tracks infiltration rate of the soil is reduced and runoff formed, causing a slow, continuous erosion. On the slopes and in the gullies no strong erosion fluxes occur, due to a high vegetation cover leading to high infiltration rates and a low slope – gully connectivity. Vegetation patterning due to plant – biotic crust interactions is lacking, for three reasons: 1) the high annual precipitation reduces biological competition for water (Chapter 2), 2) the often high infiltration rates underneath plants inhibit water redistribution and 3) the high heterogeneity in surface characteristics and habitat conditions reduces the influence of biological interactions on vegetation occurrence. Under these conditions irregular vegetation patterns develop. A reduction of grazing pressure will, under the current wet climate, lead to regrowth of vegetation, indicating a relative resistant, but instable, ecosystem.

### *7.4.3 Loess belt*

During the Pleistocene thick layers of loess were deposited in the loess belt (Fig. 7.2) (Tsoar and Pye, 1987). It covered the older topography as a blanket. The result is an undulating landscape, with small gullies and loess-covered slopes. Only locally bedrock outcrops occur. The nutrient-rich loess is valuable for agriculture. In the northern, wettest part, intensive agricultural activities occur, whereby additional sprinkle irrigation is used. Slightly more to the south the crop lands make way for grazing lands for Bedouin herds and small-scale agricultural fields in gully positions (middle zone loess belt see Fig. 7.2). Because of the strong climatic gradient, insufficient precipitation is available for large-scale agriculture. Currently the vegetation cover in the heavily grazed Sayeret Shaked Park, the area surrounding the Sayeret Shaked catchment studied here (Chapter 1 and 2), is dominated by a shrub – crust landscape (Fig. 7.3). Herbaceous plants predominantly grow underneath shrubs where they are protected from grazing. A regular shrub – crust landscape can form here by a combination of three factors (Chapter 2 and 3). 1) The deep loessic soils provide homogeneous habitat conditions, allowing functional surface cover types to be dominantly influenced by biological interactions (Rietkerk et al., 2002; Rietkerk et al., 2004). 2) Bare loessic soil is very prone to crusting. The biological crusts have a low infiltration rate and relocate water towards shrub patches with higher infiltration rates (Chapter 2) (Eldridge and Greene, 1994; Eldridge et al., 2000). Sediments, nutrients and organic matter are concentrated below shrubs and shrub mounds are formed, raising the shrubs slowly above the surrounding surface (Chapter 4). 3) The high grazing pressure favours grazing-resistant shrubs and suppresses herbaceous plant growth (Schlesinger et al., 1990). As in this climate a shrub – crust landscape seems to form only under a high grazing pressure, removal of livestock is likely to halt formation of shrub mounds. In the Sayeret Shaked catchment, where livestock has been excluded since 1987, herbaceous plants now cover a larger surface than shrubs or crust, and grow in the interspaces between shrubs (Chapter 2). Increasing herbaceous plant cover in the absence of grazing may be helped by their denser rooting in the upper soil layers with more efficient water use than shrubs (Breshears and Barnes, 1999). Observations in the field seem to indicate that as a result shrubs are overgrown and perish for lack of light and water (Fig. 7.3). Dryer parts of the loess belt, more to the south, are practically devoid of vegetation for lack of precipitation and additional runoff (Yair, 1994), as runoff from the crusted surface is too low to enable vegetation growth.

The stability and resilience of the ecosystems in the loess belt vary. In the wettest part the natural ecosystem is relatively stable and resilient, although large-scale gully erosion can destabilize the landscape. The ecosystem in the more arid region around Sayeret Shaked is not stable, as it is easily disturbed by external driving factors like grazing. However, the ability of the ecosystem to recover seems to indicate a relatively resilient system. In this climate the resilience of the ecosystem is high enough to initiate ecosystem recovery when grazing is banned. Two different states of vegetation seem to occur in the region, depending on grazing pressure. Under an intensive grazing regime the vegetation forms a regular patterned shrub – crust landscape, whereas in the absence of grazing, a full herbaceous plant cover can form. The southern arid part is very stable and resilient, without vegetation.

Especially the wetter parts are since the Late Holocene strongly influenced by humans, which governed the landscape dynamics (Chapter 5 and 6). The landscapes here formed by co-evolution of natural processes and human land use.

Fig. 7.3 Picture of surface cover in the grazed Sayeret Shaked Park (left) compared with picture of the protected catchment of Sayeret Shaked.

*7.4.4 Negev Highlands*

The Negev Highlands are characterized by calcareous rocky hills with wider gullies in between (Fig. 7.2). Some loess accumulated in the valleys (Bowman et al., 1986). During the end of the Pleistocene and Holocene this loess was eroded and redeposited (Avni et al., 2006). Feedbacks between runoff and bare bedrock cause continuous ongoing natural erosion of the soil cover (Chapter 3) (Avni, 2005). Three landscape types can be distinguished here: 1) steeply incised areas with many bedrock outcrops, 2) flat plateaus with locally bedrock at the surface and sometimes a desert pavement, and 3) wide river valleys covered by sediments. The catchment of Halluqim fits the first landscape type. It is steeply incised and has many bedrock outcrops (up to 42% of the surface) (Chapter 1 and 2). The slope – gully connectivity is high, indicative of ongoing gully activity. On the slopes, soil concentrates in crevices and depressions on top of the horizontally layered bedrock. Larger soil patches are found in the gully behind natural and constructed dams and in a Pleistocene colluvial deposit. Vegetation grows dominantly in crevices and in the deeper soils in the gully. The vegetation distribution is dominantly influenced by the occurrence of bedrock outcrops and the ensuing water redistribution. This is particularly clear for *Asphodelus ramosus,* a Mediterranean species only occurring in positions that receive runoff (Chapter 3). The vegetation cover in this landscape type is even denser than in the southern part of the loess belt, even though it receives less precipitation (Yair, 1992a; Yair and Danin, 1980; Yair and Enzel, 1987).

The catchment of Avdat has all three landscape types with their different landscape dynamics (Chapter 1 and 2). Here a plateau and a wide gully bed occur as well. On the plateau water redistribution is very local and originates from positions with desert pavement and bedrock at the surface (Chapter 3) (Wood et al., 2005; Yair, 1999). Water is redistributed to neighbouring soil patches. Vegetation is scarce and mainly exists of equally distributed shrubs alternating with small crusts covered depressions. The wide gully bed is covered by sediments. Locally large shrubs occur, with some herbaceous plants during the wet season. The shrubs can survive by the high water storage capacity of the soil, combined with runoff from higher positions. In larger catchments gravelly gully beds can be aquiferous.

In the Negev Highlands the vegetation is dominated by shrubs, growing in a pattern determined by crevices in the bedrock and open spaces near dense desert pavements (Wood et al., 2005). Under the current climate conditions, this alternation of shrubs and crusts seems to be the natural vegetation optimum on slopes and plateau positions. Homogeneous soil patches outside the active gully bed receive insufficient water and are therefore bare. It seems that in the Northern Negev Desert only on a small area regular vegetation patterns can develop under natural conditions. Regular vegetation patterns on homogeneous loess soils are prevented by high rainfall near Sayeret Shaked and by low rainfall in the southern loess belt and the Negev Highlands.

The ecosystem in the Negev Highlands seems stable enough to withstand the natural fluctuations in climate and well-adapted to the extensive grazing originally practised in the area. However, the resilience of the shrub vegetation is low, partly due to the low growth rate of the local shrub species. Increased grazing pressure would lead to further reduction in vegetation cover. Under the arid circumstances, reduction in grazing pressure, already low, would barely increase vegetation cover.

The gully beds were already used for runoff farming during the Middle Bronze Age, by the farmers who took advantage of the runoff characteristics of the rocky catchments and capacities of the flat gully beds to collect and store water and sediment (Bruins, 1986; Evenari et al., 1961). By damming the gullies, backwards gully incision was halted. This triggered co-evolution of the landscapes with human occupation and land use (Bruins and Jongmans, 2004). Nowadays, due to neglect of the ancient structures, gully incision is active again, leading to removal of the sediments in the gully bed and further aridification of the region (Avni et al., 2006). Currently the region is used for extensive grazing by Bedouin herds and a little agriculture on some conserved old agricultural fields. The effect of humans in this region appears to have been major, but totally different from that in the more humid northern parts. Nowadays the effect of humans is reduced, as human occupation is low.

## 7.5 Future landscape dynamics

### *7.5.1 Predicted climate changes*

Semi-arid and arid areas are often far-from-equilibrium, event-triggered systems (Lavee et al., 1998). Small variations in driving variables can have large effects, often leading to land degradation and desertification (Van de Koppel et al., 1997). In the course of their history, all semi-arid or arid landscapes experienced several disturbances, which are thus part of the system (Van Langevelde et al., 2003). However, new disturbances or disturbances, larger than those previously experienced, can cause irreversible changes, pushing the system into a new trajectory (Puigdefabregas, 1998).
Climate change is threatening to disturb the semi-arid and arid regions greatly (IPCC, 2001). Predictions of future climate are difficult to make, in particular for the Northern Negev Desert, a region with a high climate sensitivity due to its position on the border between Mediterranean and desert climates and several precipitation systems (Roberts et al., 1999; Robinson et al., 2006). Future scenarios are therefore fraught with uncertainties. The climate predictions of the IPCC for Israel seem unreliable, as Israel is treated as the most western border of Asia, whereas from a climatological perspective the Northern Negev Desert is more part of the Mediterranean and Europe (IPCC, 2001). Therefore I used predictions made by the Israeli Government, even though these have a high uncertainty as well (Guy and Safriel, 2000). For Israel a mean increase in temperature is predicted of 1.6° to 1.8°C by the year 2100. Precipitation will be reduced by 4 to 8%, while evapotranspiration will increase by 10%. Winter rains will be delayed and shortened. Rain intensity will increase, as well as the frequency and severity of extreme climate events. Seasonal temperature variability will increase as well (Guy and Safriel, 2000).

### *7.5.2 Effect of climate change in the Northern Negev Desert*

According to these predictions precipitation will reduce from approximately 3.5 to 7 mm in the Negev Highlands to 11.6 – 23.2 mm in the south-western corner of the Judean Hills. Higher $CO_2$ levels may reduce evapotranspiration and improve water usage in plants, increasing productivity of the vegetation (Watson et al., 1998). However, in combination with reduced precipitation, increased evapotranspiration is expected, which will increase aridity and reduce vegetation cover (Guy and Safriel, 2000). The border of the arid and semi-arid regions will shift northward, as will the associated phytogeographical regions. Presently some Mediterranean species still survive in the rocky Negev Highlands. Due to the aridification these refugia are likely to disappear. The southern loess belt, with its arid characteristics, will probably block migration routes of these

species and lead to a strong shift northward of the Mediterranean phytogeographical region. Herbaceous plant cover is expected to reduce throughout the Northern Negev Desert, whereas shrub cover might even increase slightly in the northern part, following the observations of chapter 2 and 6. Biological surface crusts will cover a larger surface in 2100 compared to nowadays, occupying the bare spaces (Guy and Safriel, 2000).
The decrease in precipitation might lead to a reduction in landscape dynamics, as less water is available to redistribute sediments. In chapter 4 this is simulated at a small scale for shrub mounds. A doubling of total precipitation results in a strong increase in sediment redistribution, whereas a 50% reduction in annual precipitation would strongly decrease sediment redistribution. This is caused by a delayed response of vegetation to the changes in precipitation and resulting lack of surface protection (Knox, 1972). However, as precipitation intensity is expected to increase in future, it might lead to an increase in landscape dynamics instead (Guy and Safriel, 2000), as the larger runoff can redistribute more sediments.

*South-west Judean Hills* Herbaceous plant cover is expected to decrease here, whereas shrub cover might even increase (Chapter 2 and 6). Shrubs seem better capable of handling arid circumstances than herbaceous plants, by creating a source – sink system together with surface crusts, thus enhancing their survival. An irregular pattern of shrubs and crusts will probably develop. Total vegetation cover should decrease, reducing the carrying capacity of the system. Unless grazing pressure is reduced, strong erosion and degradation is likely to occur. The increase in high intensity precipitation events will strengthen this process.

*Loess belt* In the loess belt erosion is likely to increase due to the increase in precipitation intensity. The three aridity zones distinguished in the loess belt will shift northward, leading to an expansion of the southern zone barren of vegetation. The grazing lands of the Bedouins, currently covered by a shrub – crust landscape due to the high grazing pressure, might become a natural shrub – crust landscape at lower annual precipitation (§7.4.3 and 7.4.4). However, under the current high grazing pressure, an accelerated collapse of the system is more likely, leading to a bare landscape as found in the southern part of the loess belt nowadays. In a natural situation, the northern agricultural areas would change to a landscape dominated by herbaceous plants, as observed now in Sayeret Shaked, proving suitable grazing lands for Bedouins. However, the established agriculture will probably be maintained by means of additional irrigational schemes.

*Negev Highlands* In the Negev Highlands vegetation cover, including the shrubs, is expected to reduce further. As less water is available, less water can be redistributed towards the shrub patches, reducing shrub density and decreasing shrub – crust ratios (Shachak et al., 1998). Still vegetation will survive in the crevasses, on positions where the water redistribution and preferable micro-climate provide less hostile establishment sites. The plateaus and the smaller valley bottoms are likely to become bare, as the smaller water redistribution capacities are insufficient to sustain vegetation. The larger, aquiferous, gully beds are likely to remain vegetated. Further collapse of ancient water collecting structures will lead to backward gully retreat and upstream degradation and desertification (Avni et al., 2006).

### *7.5.3 Adaption to climate change*

Over the whole Northern Negev Desert the carrying capacity of the ecosystems is expected to decrease, probably leading to strong land degradation and desertification, particularly under wrong management (Kefi et al., 2007). Increased aridity will be most strongly felt in the loess belt and the plateaus and smaller valley bottoms in the Negev Highlands, where barely or little water is redistributed. The runoff-producing capacities of the more rocky areas will be better able to buffer the aridification and preserve a vegetation cover. The ecosystem in these areas seems relatively resilient to climate changes.

Climate change combined with stable or increasing human pressure can push dryland areas over a critical threshold (Puigdefabregas, 1998). At present, human pressure is greatest in the loess belt and the South-western Judean Hills. The combination of both climate and human effects makes the loess belt especially vulnerable. This region should therefore have first priority in implementing adaptation measures. The human pressure on the landscape of the current grazing lands should be strongly reduced to avert further degradation. As agriculture is likely to be maintained at all costs, because of its importance in the national food production, the only measure left to protect the loess belt is by removal of the Bedouin herds. This might lead to abolishment of the cultural heritage of Bedouin. From a water-protection point of view, however, it would be wisest to refrain from further agricultural production in the northern Loess belt. In that case the released lands can be used for some livestock grazing instead.

The Negev Highlands can, also in 2100, be used for extensive grazing, though at a lower intensity than presently. Important is that no semi-permanent Bedouin settlements are formed, as this will lead to a local strong increase in grazing pressure and initiate degradation. Secondly it is advisable to conserve and renovate the water-collecting structures build by formed inhabitants of the Negev. These structures can prevent further degradation and desertification (Avni et al., 2006).

The ecosystems in the Northern Negev Desert are well adapted to the desert climate, and increased aridity is not likely to have much effect. However, the interference of human land use reduces the resilience and stability of the ecosystems and can trigger ecosystem collapse. As throughout the Late Holocene, also in future humans will be the main driving factor of landscape dynamics in the Northern Negev Desert of Israel.

## 7.5 Research challenges

In the Northern Negev Desert the combined effect of climate change and human land use is likely to strongly amplify landscape dynamics. This will regionally lead to large scale degradation and desertification, decreasing the capacity of the land to sustain human activities. In light of the future climate change, a good knowledge of landscape dynamics is essential to prevent irreversible landscape changes. In the Northern Negev Desert the loess belt is especially vulnerable. Selecting optimal management schemes for this area, balancing ecosystem capacity and human needs, is therefore important. Modelling landscape dynamics can help in this respect and is valuable for testing the effect of different climate scenarios.

Modelling landscape dynamics is complex and requires integration of knowledge from different disciplines. Only few attempts are made to incorporate both physical and biological processes up to now (e.g. Boer and Puigdefabregas, 2005, Istanbulluoglu and Bras, 2006). In this thesis LAPSUS has been expanded to include the effect of vegetation cover and growth on geomorphological processes (Chapter 4) and to include human land use (Chapter 6). However, self-organization of vegetation, including seedling establishment and death (Rietkerk et al., 2002), and effects of soil animals and porcupines on landscape dynamics have not yet been incorporated. Adding these processes in LAPSUS should enable a more complete representation of landscape dynamics. Up to now I used LAPSUS only for small scale catchment studies in the Northern Negev Desert. By applying LAPSUS at large scales, a better grasp of the spatial effects of human land use and management on the landscape dynamics of the whole loess belt can be gained. This is necessary to help find solutions to avert large scale land degradation and desertification in this region.

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# Summary

This research is entitled '*Arid landscape dynamics along a precipitation gradient: addressing vegetation – landscape structure – resource interactions at different time scales*' with as subtitle '*A case study for the Northern Negev Desert of Israel*'. Landscape dynamics describes the interactions and feedbacks among landscape structure, resource flows and organisms. This study focuses on the Northern Negev Desert of Israel, a semi-arid to arid rock desert with local loess and sand cover. Climate and humans are important driving factors of landscape dynamics here.
Semi-arid and arid regions worldwide, are vulnerable to land degradation and desertification. A profound knowledge of the processes in these regions can help to avert land degradation and desertification. The objective of this thesis is to increase the knowledge on landscape dynamics and its drivers in semi-arid and arid regions by field and model studies in the Northern Negev Desert. This study can contribute to a sustainable future for the inhabitants of these areas.

• Chapter 1 is the introduction of this thesis and discusses among others the four studied catchments along a precipitation gradient: Lehavim receives at average 280 mm precipitation per year, Sayeret Shaked 200 mm $yr^{-1}$, Halluqim 93 mm $yr^{-1}$ and Avdat 87 mm $yr^{-1}$. Of the surface of Lehavim 53% is covered by vegetation and 15% by bedrock outcrops. The catchment is intensively grazed by livestock. Sayeret Shaked is covered by a thick layer of homogeneous loess. Vegetation cover is dense (62%). The catchment is taken out of grazing since 1987. In Halluqim only 20% of the surface is covered by vegetation. The catchment is very rocky, as bedrock crops out at 42% of the surface. Avdat, located close by, is much less rocky (7%). Here 22% of the surface is covered by vegetation. Both catchments are extensively grazed.

The thesis can be separated in three parts. In the first part the relationships between landscape structure and vegetation in the four catchments is studied by statistical analyses. This part gives insight in the landscape dynamics along a precipitation gradient and provides a system framework for the remainder of the thesis. The second part focuses on simulating water and sediment dynamics in the catchments using the landscape evolution model LAPSUS. The model is adapted to a semi-arid and arid climate, and vegetation cover is incorporated. The interactions between resource flows and vegetation is studied by model simulations. In the third part the system knowledge and modelling framework are applied at a longer time scale. Firstly the history of a valley fill is reconstructed by field observations, after which this valley fill is simulated with LAPSUS. Additionally the effect of land use on the valley fill development is tested by model simulations.

*Part 1: System framework*

• In chapter 2 the controls on functional surface cover types are studied in the four catchments along the precipitation gradient. First, four functional surface cover types are selected, based on their unique functionality in terms of water use and redistribution: shrubs, *Asphodelus ramosus*, other herbaceous plants and surface crusts (biological and physical). Percentage of surface cover of these functional surface cover types is estimated, and of bedrock outcrops and loose surface stones. Additionally, data is collected on soil depth, relative elevation, insolation, slope, profile curvature and plan curvature. Relations between functional surface cover types and landscape structure variables are analyzed with descriptive statistics, factor analyses and linear regressions. The landscape structure variables bedrock outcrop, relative elevation, soil depth and surface stones explain most of the cover variance in the catchments. In catchments with many bedrock outcrops, the occurrence of functional surface cover types is best explained by the landscape structure variables. In catchments with homogeneous soils reaching beyond the root zone, biological interactions between functional surface cover types are more important. Along the precipitation gradient the explanatory power of the biological variables decreases with decreasing precipitation, while the explanatory power of landscape structure variables appears unrelated. Only in homogeneous semi-arid catchments can regular vegetation patterns develop, in arid and heterogeneous catchments irregular vegetation patterns dominate.

*Part 2: Model framework*

• In chapter 3 the process of water redistribution at catchment scale is studied with the landscape evolution and erosion model LAPSUS. LAPSUS, formerly applied in Mediterranean regions, is modified to deal with the arid climate of the Northern Negev Desert of Israel. Daily model runs are used instead of yearly model runs, and the infiltration module is adapted to better represent the spatial diversity in water availability in an arid catchment. The model is calibrated for Halluqim and Avdat. First, a sensitivity analysis of the modified LAPSUS was done. Especially pore volume of the soil appears to have a strong influence on the modelling results. Second, the capability of LAPSUS to deal with varying surface characteristics was assessed by comparing the simulated water redistribution patterns in the two catchments with field data. Simulation results demonstrate that the catchments respond very different to precipitation. Water redistribution is larger in the dominantly bedrock-covered Halluqim compared to the dominantly sediment-covered catchment of Avdat. Consequently, Halluqim has more positions with water accumulation than Avdat, and can sustain a larger vegetation cover including Mediterranean species. Finally the modelled infiltration patterns are spatially compared with vegetation cover in the catchments. The results indicate that there is a broad agreement between infiltration and vegetation patterns, but locally there is a strong mismatch indicating that part of the involved processes are still missing in the model.

• In chapter 4 the interactions between resource flows and vegetation is studied and simulated in the loess-covered catchment of Sayeret Shaked. In semi-arid areas vegetation is scarce and occurs often as individual shrubs on raised mounds. The formation process of these mounds is still debated. In this chapter the hypothesis that shrub mounds are formed in part of the Northern Negev Desert by erosion and sedimentation is tested. Height and diameter of shrub canopy and shrub mounds are measured and micro-morphological techniques are used to reconstruct the formation process of the shrub mounds. The results suggests that shrub mounds are formed by accumulation of atmospheric dust and sedimentation of eroded material in the vicinity of the shrub, as well as by erosion of the surrounding crust. Model simulations are done for single events and longer time scale (100 years). In the simulations, mound formation appears most prominent at low shrub density and large shrub canopy diameter. Positive and negative feedbacks between shrubs and resource redistribution results in a meta-stable landscape. Long-term model simulations of the current climate indicates that initially formation rate of shrub mounds is high, but stabilized at lower rates. In dryer and wetter climates mound formation is unlikely to happen, as respectively too little or too many resources are redistributed, causing a stable or highly erosive landscape. Mound simulation with LAPSUS is successful and simulated shrub mounds resemble the actual shrub mounds in Sayeret Shaked. Consequently the model may prove to be valuable for the modelling of ecohydrological landscape processes in semi-arid areas.

*Part 3: Long-term application*

• In chapter 5 the interactions between climate change, human occupation and semi-arid landscape dynamics are studied to increase the insight in the effect of climate change and human land use. A Late Quaternary valley fill in the catchment of Sayeret Shaked is studied. The aggradation and incision history is reconstructed based on a transect study. The reconstructed valley fill is put in a temporal framework by correlation with local climate records and optically simulated luminescence and potsherd dates. Two Late Pleistocene and four Holocene aggradation and incision cycles are recognized, of which three in the last 2000 years. Contradictory to the expected positive relation between amplitude of climate fluctuations and cycles of aggradation and incision, the Late Holocene cycles are stronger than those in the Late Pleistocene and Early to Middle Holocene. The most significant cycle coincides with the rise and fall of the Byzantine Empire and appears related to the higher pressure on the landscape due to human occupation during that time. Human activity appears to have a strongly amplifying effect on aggradation and incision phases, which are initially triggered by climate fluctuations. This amplifying effect occurs only when human occupation crosses a threshold and triggers destabilization of the landscape. It causes collapse of the ecosystem and increases sediment redistribution.

• Chapter 6 aims to quantify the effect of humans on semi-arid catchments, by reconstructing the infill history of Sayeret Shaked using LAPSUS. First, the infill history of Sayeret Shaked between about 800 BC and 800 AD is simulated. Second, three land use scenarios are tested to quantify the effect of extensive grazing, intensive grazing and intensive grazing combined with rainfed agriculture. Especially intensive grazing combined with rainfed agriculture leads to strong landscape dynamics. Extensive grazing causes almost no landscape dynamics, resulting in an almost stable landscape. The results seem to indicate that this catchment is formed by co-evolution of human and natural induced processes. Rainfed agriculture leads to valley aggradation by tillage translocation, whereas intensive livestock grazing causes gully incision by increased slope runoff. Humans appear to be the main driven factor of landscape dynamics in this semi-arid catchment, much more than climate fluctuations. Only a short time period of strong human land use can irreversibly alter the development trajectory of a catchment. It is thus of high importance to manage the land sustainable, both in the present and future, to avoid further degradation of drylands.

• In chapter 7 the results of the different chapters are combined and the most important conclusions discussed. The four catchments display very different landscape dynamics, caused by a high variation in climate, land use and landscape structure. In Lehavim and Halluqim the landscape dynamics is strongly influenced by the landscape structure, because bedrock outcrops regulate positions for vegetation grow and stimulate water redistribution. In Sayeret Shaked water redistribution depends mainly on biological surface cover. In Sayeret Shaked interactions between shrub and crust patches can, under a more intensive grazing regime, lead to regular vegetation patterns. When grazing pressure is released the herbaceous plant coverage recovers, as is happening today. Avdat is a divers catchment, with steep rock outcrop, a flat plateau and a loess covered wide gully. Though the whole catchment is characterized by a high aridity, each zone experiences different landscape dynamics.

At a larger spatial scale, in the whole Northern Negev Desert, the most relevant interactions and feedbacks between landscape structure, resource flows and organisms are related to water availability and redistribution as well. Since the Late Holocene, the main driving factor of landscape dynamics is human land use, especially tillage and intensive livestock grazing. Climate fluctuations seem to have much less influence on the region. The influence of humans, even confined in a small period in time, strongly affects landscape development in the whole Northern Negev Desert, causing co-evolution and formation of cultural landscapes.

# Samenvatting

Dit onderzoek heeft als titel ‘Landschapsdynamiek van aride gebieden langs een regenval gradiënt: vegetatie – landschapsstructuur – hulpbronnen op verschillende temporale schalen’ met als subtitel ‘Een studie in de Noordelijke Negev Woestijn van Israël’.
Landschapsdynamiek beschrijft de interacties en terugkoppelingen tussen de structuur van het landschap, de stromen van water en sediment en de organismen erin. Samen vormen deze het landschap. Deze studie richt zich op de Noordelijke Negev Woestijn in Israël, een semi-aride tot aride steenwoestijn met lokale löss- en zandafzettingen. De landschapsdynamiek wordt hier vooral gedreven door klimaat en mensen. Semi-aride en aride gebieden wereldwijd zijn kwetsbaar en gevoelig voor landdegradatie en verwoestijning. Een diepgaande kennis van de processen die spelen in deze regionen, kan helpen om landdegradatie en verwoestijning te voorkomen of beperken. Het doel van dit proefschrift is dan ook om de kennis van de processen in deze regionen te vergroten door de landschapsdynamiek te bestuderen en te modelleren in de Noordelijke Negev Woestijn. Daarmee kan dit onderzoek bijdragen aan een duurzame toekomst voor de bewoners van deze gebieden.

• Hoofdstuk 1 is de introductie van dit proefschrift en behandelt onder andere de vier stroomgebieden die bestudeerd zijn. Deze liggen langs een neerslaggradiënt: Lehavim ontvangt gemiddeld 280 mm neerslag per jaar, Sayeret Shaked 200 mm $jaar^{-1}$, Halluqim 93 mm $jaar^{-1}$ en Avdat 87 mm $jaar^{-1}$. Lehavim is voor 53% van het oppervlak bedekt met vegetatie, terwijl dagzomend gesteente 15% van het oppervlak voor zijn rekening neemt. Het stroomgebied wordt intensief begraasd door vee. Sayeret Shaked wordt bedekt met een dikke laag homogene löss. Het oppervlak is dicht begroeid met vegetatie (62%). Sinds 1987 wordt het stroomgebied niet meer begraasd. In Halluqim is maar 20% van het oppervlak bedekt met vegetatie. Het stroomgebied is erg rotsig (42% van het oppervlak). Avdat, een dichtbij gelegen stroomgebied, is veel minder stenig (7%). Hier bedekt vegetatie 22% van het oppervlak. Beide stroomgebieden worden extensief begraasd.

Dit proefschrift bestaat uit drie delen. In het eerste deel wordt met een statistische analyse onderzoek gedaan naar de relaties tussen landschapsstructuur en vegetatie in de vier stroomgebieden. Dit deel geeft inzicht in de landschapsdynamiek langs een neerslaggradiënt en verschaft een systeemraamwerk voor de rest van dit proefschrift. Het tweede deel focust op het simuleren van water- en sedimentdynamiek in de stroomgebieden, waarbij het landschapsevolutie model LAPSUS wordt gebruikt. Het model is aangepast aan een semi-aride en aride klimaat en de vegetatiebedekking is toegevoegd. De interacties tussen stromen van water en sediment en vegetatie worden bestudeerd met modelsimulaties. In het derde deel worden de opgedane systeemkennis en het aangepaste model gebruikt op een langere tijdschaal. Eerst wordt de geschiedenis van een valleiopvulling gereconstrueerd door middel van veldobservaties. Hierna wordt deze valleiopvulling gesimuleerd met LAPSUS. Daarbij wordt het effect van landgebruik op het ontstaan van de valleiopvulling getest met modelsimulaties.

*Deel 1: systeem raamwerk*

• In hoofdstuk 2 worden de controlemechanismen op soorten bodembedekking bestudeerd in de vier stroomgebieden langs de neerslaggradiënt. Eerst worden vier functionele bedekkingstypes geselecteerd, gebaseerd op hun unieke functionaliteit met betrekking tot watergebruik en herverdeling: struiken, *Asphodelus ramosus,* andere kruidvegetatie en bodemkorsten (biologische en fysische). Het percentage van het oppervlak bedekt met deze functionele bedekkingstypes wordt geschat, alsmede van dagzomend gesteente en losse stenen aan het oppervlak. Daarnaast is data verzameld over bodemdiepte, relatieve hoogte, insolatie, hellingshoek en richting. De relaties tussen functionele bedekkingstypes en landschapsstructuur worden geanalyseerd met beschrijvende statistiek. De landschapsstructuur variabelen, dagzomend gesteente, relatieve hoogte, bodemdiepte en losse stenen verklaren het meest van de variatie in bedekking in de stroomgebieden. In stroomgebieden met veel dagzomend gesteente wordt het voorkomen van functionele bedekkingstypes het beste verklaard door de landschapsstructuur variabelen. In stroomgebieden met homogene bodems, dieper dan de bewortelingsdiepte van vegetatie, zijn de biologische interacties tussen de functionele bedekkingstypes zelf het belangrijkst. Langs de neerslaggradiënt neemt de verklarende kracht van de biologische variabelen af met afnemende neerslag, terwijl de verklarende kracht van de landschapsstructuur variabelen onafhankelijk van neerslag blijkt. Alleen in homogene semi-aride gebieden kunnen regelmatige vegetatiepatronen ontstaan. In aride en heterogene gebieden domineren onregelmatige vegetatiepatronen.

*Deel 2. Model raamwerk*

• In hoofdstuk 3 wordt het proces van waterherverdeling bestudeerd op stroomgebiedniveau. Dit wordt gedaan met het landschapsevolutie c.q. erosiemodel LAPSUS. LAPSUS, dat tot nu toe vooral werd toegepast in Mediterrane gebieden, wordt aangepast om met het droge klimaat van de Noordelijke Negev Woestijn te kunnen omgaan. Het model wordt per dag gedraaid in plaats van per jaar, en de infiltratiemodule is aangepast om de ruimtelijke variabiliteit van waterbeschikbaarheid in droge gebieden beter te kunnen weergeven. Het model is gekalibreerd voor Halluqim en Avdat. Ten eerste wordt een gevoeligheidsanalyse van het aangepaste model uitgevoerd. Vooral porievolume blijkt belangrijk te zijn voor de modelresultaten. Ten tweede wordt de capaciteit van LAPSUS om met afwisselende oppervlakte-eigenschappen om te gaan getest, door de gesimuleerde waterherverdelingspatronen in de twee stroomgebieden te vergelijken met veldgegevens. De simulatieresultaten tonen aan dat de stroomgebieden heel verschillend reageren op neerslag. In Halluqim, waar veel gesteente dagzoomt, wordt meer water herverdeeld dan in Avdat, dat vooral met sediment is bedekt. Als gevolg daarvan heeft Halluqim meer plekken waar water zich verzamelt dan Avdat en kan het meer vegetatie onderhouden. Zelfs Mediterrane soorten komen voor. Als laatste worden de infiltratiepatronen ruimtelijk vergeleken met de vegetatiebedekking in de stroomgebieden. De resultaten tonen aan dat er een brede overeenkomst is tussen infiltratie- en vegetatiepatronen, maar dat er lokaal grote afwijkingen zijn. Deze geven aan dat een deel van de betrokken processen nog mist in het model.

• In hoofdstuk 4 worden de interacties tussen vegetatie en stromen van water en sediment bestudeerd en gesimuleerd in het met löss bedekte stroomgebied van Sayeret Shaked. In semi-aride gebieden is vegetatie schaars en komt vaak voor als individuele struiken op heuveltjes. Hoe deze struiken worden gevormd, wordt nog steeds bediscussieerd. In dit hoofdstuk wordt de hypothese getest dat struikheuvels worden gevormd in een beperkt deel van de Noordelijke Negev Woestijn door een gecombineerd proces van erosie en sedimentatie. De hoogte en diameter van de struiken en de struikheuvels worden gemeten en micromorfologische technieken worden gebruikt om het proces van struikvorming te reconstrueren. De resultaten suggereren dat struikheuvels gevormd worden door accumulatie van atmosferische stof en sedimentatie van eerder geërodeerd materiaal onder de struiken, en door erosie van het omringende gebied. Model simulaties worden uitgevoerd voor losse regenbuien en voor langere tijdsreeksen (100 jaar). De simulatieresultaten geven aan dat struikheuvels vooral worden gevormd op hellingen met lage struikdichtheid en grote struikdiameter. Positieve en negatieve terugkoppelingen tussen struiken en stromen van water en sediment zorgen voor een metastabiel landschap. Lange termijn model simulaties onder huidige klimaatcondities geven aan dat struikheuvels in het begin snel vormen en daarna stabiliseren op lagere snelheden. In drogere en nattere klimaten worden geen struik heuvels gevormd, omdat respectievelijk te weinig of te veel water en sedimenten worden herverdeeld. Dit veroorzaakt een stabiel of juist een hoog erosief landschap. Het simuleren van struikheuvels met LAPSUS is succesvol en de resulterende struikheuvels komen overeen met de actuele struikheuvels in Sayeret Shaked. Het model lijkt dus waardevol voor het modelleren van ecohydrologische landschapsprocessen in semi-aride gebieden.

*Deel 3: Lange termijn applicatie*

• In hoofdstuk 5 worden de interacties tussen klimaatverandering, menselijke bewoning en semi-aride landschapsdynamiek bestudeerd om de bestaande kennis van het effect van klimaat en mensen te vergroten. Hiertoe wordt een Laat Kwartaire valleiopvulling bestudeerd in Sayeret

Shaked. De geschiedenis van opvulling en insnijding wordt gereconstrueerd met een transect studie. De valleiopvulling wordt in een temporeel raamwerk gezet door correlatie met lokale klimaatreeksen, Optically Simulated Luminescence dateringen en het dateren van potscherven. De valleiopvulling is opgebouwd uit twee Laat Pleistocene en vier Holocene cycli, waarvan drie gedurende de laatste 2000 jaar. In tegenstelling tot de verwachte positieve relatie tussen de amplitude van de klimaatfluctuaties en de cycli van opvulling en insnijding, blijken de Laat Holocene cycli sterker dan die plaatsvonden in het Laat Pleistoceen en het Vroeg tot Middel Holoceen. De grootste cyclus komt overeen met de opkomst en ondergang van het Byzantijnse Rijk en lijkt gerelateerd aan de hoge druk op het landschap door de hoge bewoningsdichtheid in die tijd. Menselijke activiteiten lijken een groot versterkend effect te hebben op opvullings- en insnijdingsfasen, die oorspronkelijk veroorzaakt zijn door klimaatfluctuaties. Dit versterkende effect lijkt alleen in werking te treden als de dichtheid van menselijke bewoning over een grens heen gaat en destabilisatie van het landschap veroorzaakt. Het veroorzaakt instorting van het ecosysteem en verhoogt de sedimentherverdeling.

• Hoofdstuk 6 heeft als doel het effect van mensen op semi-aride stroomgebieden te kwantificeren door middel van het reconstrueren van de invulgeschiedenis van Sayeret Shaked met behulp van LAPSUS. Ten eerste wordt de invulgeschiedenis van Sayeret Shaked tussen ongeveer 800 v C. en 800 na C. gesimuleerd. Ten tweede worden drie landgebruikscenario's getest om het effect van extensieve begrazing, intensieve begrazing en intensieve begrazing gecombineerd met regengevoede akkerbouw te kwantificeren. Vooral intensieve begrazing gecombineerd met regengevoede akkerbouw leidt tot sterke landschapsdynamiek. Extensieve begrazing veroorzaakt bijna geen landschapsdynamiek, wat resulteert in bijna stabiele landschappen. Het resultaat lijkt aan te geven dat dit stroomgebied is gevormd door co-evolutie van door mensen gestuurde en natuurlijke processen. Regengevoerde akkerbouw leidt tot valleiopvulling door de gerelateerde ploegerosie, terwijl intensive begrazing leidt tot insnijding van de gullies door sterkere hellingafstroming. Mensen lijken de belangrijkste sturende factor van landschapsdynamiek te zijn in dit semi-aride stroomgebied, veel meer dan klimaatfluctuaties. Zelfs een korte periode van sterk menselijk landgebruik kan het ontwikkelingstraject van een stroomgebied onherstelbaar veranderen. Het is dus van groot belang deze gebieden op een duurzame manier te beheren, zowel nu als in de toekomst, om verdere degradatie van droge gebieden te voorkomen.

• In hoofdstuk 7 worden de resultaten uit de verschillende hoofdstukken samengevoegd en de belangrijkste conclusies behandeld. De vier stroomgebieden tonen een heel verschillende landschapsdynamiek, veroorzaakt door een hoge variatie in klimaat, landgebruik en landschapsstructuur. In Lehavim en Halluqim wordt de landschapsdynamiek sterk beïnvloed door

de landschapsstructuur, omdat het dagzomende gesteente de posities voor vegetatiegroei reguleert en waterherverdeling stimuleert. In Sayeret Shaked hangt de waterherverdeling vooral af van de biologische bodemdekking. Interacties tussen struiken en korsten kunnen in Sayeret Shaked, onder de huidige intensieve begrazing, leiden tot regelmatige vegetatie patronen. Wanneer de begrazingsdruk wordt verminderd, herstelt de kruidvegetatie zich, zoals tegenwoordig gebeurt in Sayeret Shaked. Avdat is een divers stroomgebied met steile rotspunten, een vlak plateau en een wijde riviervlakte die met fijne sedimenten is bedekt. Hoewel het hele stroomgebeid wordt gekarakteriseerd door sterke droogte, ervaren alle zones andere landschapsdynamiek.
Ook op een grotere ruimtelijke schaal, in de gehele Noordelijke Negev Woestijn, zijn de belangrijkste interacties en terugkoppelingen tussen landschapsstructuur, stromen van water en sediment en organismen gerelateerd aan beschikbaarheid en herverdeling van water. De belangrijkste drijver van landschapsdynamiek was en is menselijk landgebruik, waarbij vooral ploegen en intensieve begrazing van belang is. Klimaatfluctuaties lijken een veel minder belangrijk effect te hebben op de regio. De invloed van mensen, zelfs als het maar gedurende een korte periode is, heeft een sterk effect op de ontwikkeling van een landschap in de hele Negev Woestijn en veroorzaakt co-evolutie en vorming van culturele landschappen.

# Curriculum Vitae

Eke Buis werd op 25 juni 1979 geboren te Delft. Na het behalen van het VWO-diploma aan de Openbare Scholen Gemeenschap Professor Zeeman te Zierikzee begon zij in 1997 met de studie Bodem, Water en Atmosfeer aan Wageningen Universiteit. Een eerste afstudeervak bij de leerstoelgroep Vegetatiekunde richtte zich op de invloed van rivier- en kwelwater op de bodem en vegetatie in het Biebrza Nationaal Park in Polen. Een tweede afstudeervak werd verricht bij de leerstoelgroep Bodeminventarisatie en Landevaluatie (tegenwoordig leerstoelgroep Landdynamiek) en betrof een onderzoek naar de oorsprong en opbouw van een vulkanische modderstroom in Kenia.

Een halfjarige stage bij het team Bodem, Water en Natuur van Alterra richtte zich op het schrijven van een computerprogramma voor de determinatie van humusprofielen als deel van een ecologische bodemtypering. In 2003 sloot zij haar studie af met als specialisatie Ruimtelijke Bodemkunde. Na een vijf maanden durend intermezzo als Invoerder Globis bij De Straat Milieuadviseurs in Heerlen, trad zij in dienst bij de leerstoelgroep Bodeminventarisatie en Landevaluatie (tegenwoordig Landdynamiek) en de voormalige leerstoelgroep Bodemvorming en Ecopedologie van Wageningen Universiteit als Assistent in opleiding (AIO). Sinds januari 2008 is zij hier in dienst als Universitair Docent (UD2), alsmede per februari 2008 als Post-Doc bij de Sectie Bodemkwaliteit van Wageningen Universiteit.

# List of publications

## In international journals

Veldkamp, A., Buis, E., Wijbrans, J.R., Olago, D.O., Boshoven, E.H., Maree, M., Van de Berg van Saparoea, R.M., 2007. Late Cenozoic fluvial dynamics of the River Tana, Kenya, an uplift dominated record. Quaternary Science Reviews, 26: 2897-2912.

Buis, E., Veldkamp, A. 2008. Modelling dynamic water redistribution patterns in arid catchments in the Negev Desert of Israel. Earth Surface Processes and Landforms, 33: 107-122. DOI: 10.1002/esp.1531.

## Submitted and in preparation

Buis, E., Temme, A.J.A.M., Veldkamp, A., submitted. Quantifying the effect of historical land use on landscape dynamics in the Northern Negev Desert of Israel: a simulation study.

Buis, E., Veldkamp, A., Boeken, B., Van Breemen, N., under revivsion for Journal of Arid Environments. Controls on plant functional types along a precipitation gradient in the Negev Desert of Israel.

Buis, E., Veldkamp, A., Wallinga, J., De Blécourt, M., under revision for Geomorphology. History of a valley fill in the Northern Negev Desert balancing between climate fluctuations and human occupation in the last 40 000 years.

Buis, E., Veldkamp, A., Boeken, B., Jongmans, A.G., Schoorl, J.M., Van Breemen, N., submitted. Modelling shrub mound formation and their stability on semi-arid slopes in the Negev Desert of Israel.

Peeters, I., Temme, A.J.A.M., Buis, E., Govers, G., Veldkamp, A., in preparation. Comparison of different landscape evolution model types in the Belgium Loess belt.

# 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)**

- The relationships among ecosystem engineering, landscape heterogeneity and resource dynamics in four semi-arid watersheds in Israel (2003)

**Laboratory Training and Working Visits (1.7 ECTS)**

- OSL dating preparation techniques; NCL-TU Delft (2006)

**Post-Graduate Courses (4.8 ECTS)**

- Field excursion of the conference on Palaeosols: memory of ancient landscapes and living bodies of the present ecosystems; University of Florence, Italy (2004)
- Land Science; Chairgroup of Land Dynamic (2005)
- Field excursion HighLand Conference 2006-Mekelle-Ethiopia; Katholieke Universiteit Leuven (2006)
- Preparation Land Science in South Africa-CLUE model; Chairgroup of Land Dynamic (2007)

**Deficiency, Refresh, Brush-up Courses (5.7 ECTS)**

- Global Change (MSc course); ESA (2004)

**Competence Strengthening / Skills Courses (4.4 ECTS)**

- Techniques for writing and presenting a scientific paper; WGS (2004)
- Afstudeervak organiseren en begeleiden; OWU (2004)
- An introductory workshop for PhD students and young authors; PE&RC (2004)
- PhD Assessment; WGS (2005)
- Career Perspectives; WGS (2006-2007)

**Discussion Groups / Local Seminars and Other Meetings (7.0 ECTS)**

- Spatial Methods (2005-2007)
- Leuven-Wageningen Discussions (2005-2007)

**PE&RC Annual Meetings, Seminars and the PE&RC Weekend (3.45 ECTS)**

- PE&RC day-Climate change and biodiversity (2003)
- PE&RC day-Spatial and Temporal scales in Ecology (2003) Current themes in Ecology 5: ecology in freshwater management (2003)
- PE&RC day-The truth of science (2005)
- PE&RC Tenth anniversary (2005)
- NBV dag-De bodem in natuurontwikkeling (2005)
- NBV dag-Verwoestijning (2006)
- PE&RC-Introduction weekend (2006)
- Multiple views on scale & scaling (2007)
- PE&RC day-Collapse (2007)

**International Symposia, Workshops and Conferences (4.1 ECTS)**

- Palaeosols: memory of ancient landscapes and living bodies of the present ecosystems; University of Florence, Florence, Italy (2004)
- Third International Postgraduate Symposium; Quaternary Research Association, Brussels, Belgium (2004)
- Luminescence dating: applications and research; Netherlands Centre for Luminescence dating, Delft, the Netherlands (2005)
- Workshop on spatial, temporal and spectral scales in agro-ecosystems (Israel-Wageningen); WUR, Wageningen, the Netherlands (2005)
- HighLand Conference 2006; Katholieke Universiteit Leuven, Mekelle, Ethiopia; two poster presentations (2007)
- Soil & Water Conference; SKB, Zeist, the Netherlands; oral presentation (2007)
- European Geosciences Union General Assembly – EGU – Vienna – Austria, two poster presentations (2007)

**Courses in which the PhD candidate has worked as a teacher**

- Soil Science I and II (2005 – 2007); LAD
- Integration course on Soil, Water, Atmosphere (2005 – 2007), LAD
- Fieldpractical Geology, Soils and Landscape of the Netherlands (2008), LAD

**Supervison of MSc students**

- 3 students, LAD