Modelling Nutrient Erosion by Wind and Water in northern Burkina Faso

Saskia M. Visser

Promotor
Prof. dr. ir. L. Stroosnijder
Hoogleraar Erosie en Bodem- en Waterconservering

Co-promoter
Dr. ir. G. Sterk
Universitair Docent Leerstoelgroep Erosie en Bodem- en Waterconservering

Promotiecommissie
Prof. dr. ir. E.M.A. Smaling, Wageningen Universiteit
Prof. dr. P.A.A. Troch, Wageningen Universiteit
Dr. J.H. van Boxel, Universiteit van Amsterdam
Dr. W. Cornelis, Universiteit van Gent, België

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The Fulbé says that the bush gives birth
without being pregnant

Riesmann (1990)

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Contents

Chapter 1

Introduction

Introduction

Ever since the existence of the first cultivators, mankind has stripped the soil from its natural vegetation and replaced it with crops. Through the removal of the protective vegetation cover, soils are temporally exposed to the impact of wind and water, often resulting in accelerated soil erosion processes. Without doubt erosion leads to the irreversible degradation of soils and to the loss of the ecological and economic functions (Warren et al., 2001). First warnings about the danger of soil erosion came from Plato more than 2000 years ago (Dregne, 1990) and from many other writers more recently (e.g. Lal, 1988; Eicker, 1986; Dregne, 1990). Since the late 1920’s agronomists and soil scientists have been warning for serious problems due to human induced soil erosion in the African Sahel. The Sahel is already one of the world’s poorest regions in the world, and most subjected to desertification (Hillel, 1991). Furthermore, the African population is growing at a higher rate than the food production (Eicker, 1986). To prevent large scale famine an urgent need exists to investigate the causes and consequences of land degradation by soil erosion.
The Sahelian zone of Africa is situated between the latitudes 13˚ and 17˚ N, and can be seen as the transition zone between the arid Sahara in the North and the more humid Sudanian zone in the South. The limits of the Sahelian zone correspond roughly with a mean annual rainfall of 200 mm in the North and 600 mm in the South (De Ridder *et al.*, 1982). Approximately 90% of the inhabitants of the Sahel live in small villages and depend on subsistence agriculture for a living (Thiombiano, 2000). The sedentary farming systems combine rain fed agriculture with free roaming livestock. The staple crop is pearl millet (*Pennisetum glaucum)*, which is often found intercropped with cowpea (*Vigna unguiculata*). Traditionally the farmers applied a fallow-cultivation rotation system, to restore soil structure and chemical fertility (Charreau and Nicou, 1971). Due to a growing population pressure the fallow period decreased rapidly since the 1970s and is now completely absent in certain areas (Thiombiano, 2000).
The Sahelian climate is characterised by a dry season lasting from October till May and a short wet season from June till September. Sahelian rainfall has a typical large variation both within a year and between years. Due to this large variation in rainfall, farmers are forced to apply a risk avoidance strategy resulting in less than optimal yields (Hillel, 1991). In the Sahel two distinct periods, during which wind-blown sediment transport may occur, can be distinguished. During the dry period from October till May the north-eastern Harmattan winds dominate. These winds originate from over the Sahara desert and transport large amounts of fine sediments and nutrients. Parts of this nutrient enriched dust is deposited in the Sahel, increasing the nutrient content of the Sahelian soils (Herrmann *et al.*, 1996). The second and most important wind erosion period occurs in the early rainy season when high intensity rainfall is often preceded by strong winds (Casenave and Valentin, 1989, Shao, 2000). The wind erosion events are usually short-lived, lasting from a few minutes up to one hour, and may result in intense particle transport causing severe wind erosion (Sterk and Stein, 1997, Bielders *et al.*, 2000, Rajot, 2001). The intense rainfall, which often directly follows the wind erosion events, causes partial deposition of raised dust and limits further wind erosion, but may result in severe water erosion. Sediment first eroded from a field by wind may partly be returned by the runoff that immediately follows the wind erosion event. Otherwise, the forces of the runoff may enhance erosion started by the forces of the wind. Clear, in the Sahel, and typically in the early

rainy season, the processes of wind and water erosion occur almost simultaneously and are closely related.

Sahelian soils generally have a sandy to sandy-loam texture. They are prone to crusting and hard setting, resulting in a low infiltrability (Van der Watt and Valentin, 1992). Additionally, climatic conditions are harsh with a potential evapo-transpiration that is higher than precipitation for most of the year. The soils have a low fertility, with phosphorous and nitrogen being the most limiting nutrients for crop production (Thiombiano, 2000). The combination of the low fertility soil with climatic conditions result in the world's worst soil organic matter status that is known for agricultural land (Breman *et al.*, 2001). Furthermore, ongoing soil erosion by wind and water results in ever-decreasing soil productivity. Bationo *et al.* (1998) state that the soil fertility in traditional, but intensified (due the shortening of the fallow period) farming systems can only be maintained through integrated plant nutrient management with effective recycling of organic matter such as crop residue, compost or manure in combination with mineral fertilizer and using rotations with legumes.

A nutrient budget is often used to obtain insight in the flow of nutrients at various scales. Since the 1980s model studies on nutrient budgets form an increasingly important source of evidence on soil degradation (e.g. De Jager *et al.*, 1998; Pol, 1992; Stoorvogel and Smaling, 1990). These studies all come with alarming conclusions about the farmers in the Sahel and the way they are currently exhausting their soils. However, little attention has been paid to the contribution of soil erosion in this area. Nutrient loss by soil erosion forms the main loss term in the budget but is often calculated based on average soil loss per hectare (measured on runoff plots) and precise measurements of nutrient content of the eroded sediment are lacking. Furthermore the effect of wind erosion in the nutrient budget is often overlooked. From the work of a small group of researchers (e.g. Bielders *et al.*, 2002; Geelhoed, 1995; Ribolzi *et al.*, 2003; Sterk *et al.*, 1996) we can conclude that at the scale of a Sahelian field nutrient losses due to both wind and water erosion are large especially when compared to annual uptake by a millet crop. However due to the large spatial variation in erosion and deposition under influence of both wind and water (which can even be witnessed at the scale of a field), combined with the almost simultaneous occurrence of the processes, the net effect of each process is difficult to determine. Therefore, in the semi-arid environment of the Sahel both processes should be investigated simultaneously at the same site. To evaluate the role of wind and water erosion and their interaction in the loss and gains of nutrients at the scale of a field, a physically based, combined wind/water erosion model can be a useful tool.

The processes

Wind erosion

Wind erosion might become a problem whenever the soil is loose, dry, bare or nearly bare and the wind velocity exceeds the threshold for initiation of particle movement (Fryrear and Skidmore, 1985). Wind erosion contributes to soil degradation by the loss of topsoil. Furthermore, wind erosion is a size-selective process, and preferentially removes organic matter and the finer soil particles. Sterk *et al.* (1996) showed that at the scale of a field, saltation transports soil particles and nutrients over short distances from bare, unprotected areas, towards areas with more vegetation or mulch cover. Furthermore, they indicated that during a single convective event, the loss of nutrients from a cultivated field due to saltation transport could exceed the annual input.

Apart from its contribution to soil degradation, wind erosion causes direct damage to crop seedlings (Michels *et al.*, 1995). Abrasion damages the plant by the scouring effect of saltating soil particles. Seedlings buried by sand suffer from the weight of the sand, high soil temperatures and reduced photosynthesis. The damages range from reduced crop growth, resulting in lower yields, till complete destruction of crops.

Water erosion

Water is a major limiting factor in arid and semi-arid agriculture (Lal, 1991). In the Sahelian zone of Africa, it is not always the limited amount of annual rainfall that constraints crop production, but rather the proportion of rainfall that enters the root zone and becomes plant-available soil moisture (Sivakumar and Wallace, 1991). Maximizing the rain-use efficiency, and therefore limiting runoff is an important issue for farmers (Le Houérou, 1984). Apart from carrying away the valuable water, once runoff is generated it causes erosion and is the transporting agent for dislodged soil particles and plant nutrients.

The onset of soil loss due to water erosion starts when a raindrop hits the soil surface, dislodging soil particles; this process is called splash erosion. These dislodged particles become available for transport by overland flow. The combination of the processes, a thin layer of water flowing over the soil surface together with rain splash, is called sheet erosion and can cause tremendous soil loss (Kiepe, 1995). Sediment transport capacity of sheet flow is low due to the general low stream velocities and the thin laminar flow. Therefore, sheet flow mainly transports the finer, but nutrient rich, particles, resulting in a degradation of the nutrient contents of the topsoil. Sheet erosion is not recognisable in the landscape. The colour of the runoff water flowing over the soil surface is often the best indication for the occurrence of sheet erosion.

When overland flow concentrates, rills are formed. The flow in rills can carry away the larger sediments that were detached by rainfall. Further, the water flow in rills can develop enough momentum to dislodge soil particles itself, resulting in rill erosion (Rose, 1993). Whereas sheet erosion is a rather slow continuous process, rill erosion occurs abruptly and can locally remove the complete topsoil.

Apart from its contribution to soil degradation, overland flow might also cause direct damage to the crop. Young plants are damaged by the effect of flowing water resulting in reduced yields (Veihe, 2000). Furthermore, plants die because of the effects of stagnating water.

Interaction of wind and water erosion

At the scale of a field, the processes of wind and water erosion are controlled by crust development (Valentin, 1995). To illustrate the interaction between the two processes, consider a field with a uniform vegetation cover. Due to overgrazing or human activities some parts of the field might become bare. On sandy soils, the impact of raindrops from the first rainfall will lead to the formation of a structural crust, consisting of a plasmic seal overlain by loose sand (Valentin and Bresson, 1992). The plasmic seal hampers infiltration, resulting in runoff during the next rainfall. During the rainy season parts of the loose sand on top of the plasmic seal will be removed by runoff, so that the plasmic seal is exposed and an erosion crust is formed. The sediment will be deposited downstream creating a depositional crust. During the following dry season loose sand is removed and trapped in the surrounding vegetation and crop residues gradually forming micro-dunes. These micro-dunes can partly be degraded in the subsequent wet season, but due to the increased micro-relief convergence of stream-flows takes place and rills and gullies can be formed.

The above-described example illustrates how the dislocation of soil by the impact of raindrops controls not only crust formation and water erosion, but also influences wind erosion processes. Therefore, wind erodibility cannot be considered without taking into account the previous water erosion history (Valentin, 1995). Furthermore, due to the abrading forces of particles in saltation mode under influence of wind, crust characteristics change (Zobeck, 1991), therefore water infiltration and water erodibility can’t be considered without taking into account the previous wind erosion history. In the interaction between wind and water erosion in the Sahel is crust formation one of the key processes.

Modelling

A model of the environment is a representation or an imitation of complex natural phenomena that can be discerned by human cognitive processes. Dynamic distributed environmental models have a scientific value mainly because they can be used to improve the understanding of environmental processes; e.g. to test hypotheses regarding the driving forces of changes in the environment. These models provide a means to communicate scientific knowledge. Further, dynamic spatial models are all-important for environmental planning and management, since they can be used to make predictions for future behaviour of an environmental system, or to evaluate the impact of changes in the environment made by people or organisms (Karssenberg, 2002).

In the Sahel soil conservation possibilities are limited and it is important to warily manage them. A model can be a useful tool in the battle against soil erosion since it can predict erosion risk under various land management practices. After simulation the best practices can be determined and applied in the field.

Roughly, two main types of models are available; empirical and physically based models. Empirical models are based on identifying statistical significant relationships between assumed important variables. In order to establish those relationships an extended database is required (Morgan, 1995). Physically based models are those models that use physical-based mathematical expressions to simulate erosion processes. The underlying philosophy behind the physical approach is that, given a high degree of understanding of processes and how they respond to stresses, the system’s response to any set of stress can be predetermined, even if the magnitude of the new stresses falls outside the range of historically observed stresses (Konikow and Patten, 1985).

Due to the limited availability of data in the Sahel it is very difficult to establish empirical relationships for both wind and water erosion. However, provided a good insight in the interaction between the processes of wind and water erosion, a physical approach might result in a model that correctly predicts the (interactive) effects of both processes.

Wind erosion models

The foundations of present day wind erosion prediction technology lie in the work on wind blown sand and desert dunes of Bagnold (1941). This theory was extended by Woodruff and Siddoway (1965) to provide a model that could be applied to agricultural fields, which resulted in the Wind Erosion eQuation (WEQ). The WEQ predicts potential average annual soil loss based on factors for soil erodibility, ridge roughness, climate, unsheltered distance across a field and the vegetation cover. When WEQ was developed approximately 40 years ago, it was necessary to make it a simple mathematical expression; readily solvable with the computational tools available. The model was developed primarily based on laboratory and field wind tunnel studies. Modern farming systems incorporate many practices not represented in WEQ. Consequently, estimates of wind erosion were questionable outside of the Central Great Plains, where the model was developed. With the release of the Revised Wind Erosion eQuation (RWEQ), a model that allows advanced farming practices to be evaluated, a wind erosion model became available that can be used throughout the entire USA. RWEQ is an empirical model that makes annual or period estimates of wind erosion based on a single event simulation, including factors for climate, soil roughness, erodible fraction of the soil, crusting and vegetation cover (Fryrear *et al.*, 1998a).

Unlike WEQ and RWEQ, the Wind Erosion Prediction System (WEPS) (Hagen, 1996) is a process-based, continuous, daily time-step model that simulates weather, field conditions, and erosion. The program has the capability of simulating spatial and temporal variability of field conditions and soil loss/deposition within a field. WEPS was designed to be used under a wide range of conditions in the USA and to be easily adapted for use in other parts of the world.

Water erosion models

As for wind erosion, the first mathematical approach to describe water erosion, resulted in an empirical model; the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1965). The USLE was derived by correlating the amount of soil loss gained from experimental plots with various topographic, climate, soil and land use parameters. The USLE technology is revised with RUSLE 2 (Revised Universal Soil Loss Equation); a computer-implemented prediction tool that can more accurately predict soil erosion, particularly for more modern farming practises (Renard *et al.* 1997). The RUSLE 2 maintains the empirical state of the USLE, its applicability is therefore restricted to those areas with climatic conditions falling within the range of the reference dataset. In the future the physically based Water Erosion Prediction Project (WEPP) (Flanagan and nearing, 1995) will replace the RUSLE 2. The WEPP model is a process-based, distributed parameter, continuous simulation, erosion prediction model (Flanagan and Nearing, 1995). The model is capable to simulate hill slope erosion processes (sheet and rill erosion), as well as the hydrologic and erosion processes on small watersheds. Like WEPS, WEPP is designed to be used under a wide range of conditions in the USA and to be easily adapted to other parts of the world.

Apart from the in the USA developed modelling tools a wide variety of physically based models is available from all over the world, each with its own unique tools for simulating routing of sediment, and erosion. Table 1 gives an overview of some of these models and years of first release. As can be seen from this table, development of physically based wind erosion models is more recent than development of water erosion models.

Combining wind and water erosion models

In the semi-arid environment of the Sahel the processes of wind and water erosion occur almost simultaneously at the same site and both processes contribute significantly to total soil erosion at that site. Furthermore, due to the development of soil crusts, a large interaction between the two processes exists and wind erosion can’t be considered regardless the previous water erosion history and vice versa. So, when one wants to apply an erosion model to the Sahelian semi-arid environment, both the processes of wind and water erosion should be included in the model.

Table 1) Brief overview of physically based soil erosion models

Model name	Author	Type of erosion
CREAMS	Knisel (1980)	water erosion
AGNPS	Young *et al.* (1987)	water erosion
KINEROS	Woolhiser *et al.* (1990)	water erosion
EUROSEM	Morgan *et al.* (1992)	water erosion
WEPP	Flanagan and Nearing (1995)	water erosion
LISEM	De Roo *et al.* (1996)	water erosion
WEAM	Shao *et al.* (1996)	wind erosion
WEPS	Hagen (1996)	wind erosion
AEOLUS	Namikas and Sherman (1998)	wind erosion
IWEM	Lu and Shao (2001)	wind erosion

Gao *et al.* (2002) were the first to combine a water erosion model with a wind erosion model. By combining the empirical wind erosion model of Buckley (1987) with parts of the RUSLE, WEPP and LISEM they developed a semi-empirical model that could predict soil losses by wind and water erosion for sandy grassland areas in northern China. The model is suitable for application on large areas (several km^2).
In order to completely understand the impact of and the interaction between the two processes of wind and water erosion a physically based model is more suitable than a (semi-)empirical since physically based models use physically-based mathematical expressions rather than statistical relationships. Furthermore, to obtain a good insight in the processes it is advisable to start modelling at a field scale. So far a physically based model, which combines the effects of wind and water erosion, has never been developed.

Aim

The aim of the study described in this thesis is to model the nutrient dynamics as influenced by wind and water erosion in the Sahel. First the interaction between these processes is investigated. In particular an attempt is made to identify sediment transport by the processes related to wind and water erosion and to determine the direction and patterns of deposition of this mass transport. Finally, a physically based model that can predict mass transport by both wind and water at a field at various geomorphologic units in the Sahel will be developed. The model will be extended with nutrient modules to give an indication of the impact of both processes on the nutrient balance.

Study outline

The fieldwork for this thesis was performed during two measurement campaigns in northern Burkina Faso, at three geomorphic units; a degraded site, a field on an ancient dune and a field in the valley. Each measurement campaign lasted 6 months from April till the end of September, in the years 2000 and 2001. During the fieldwork wind-blown and water–driven sediment transport was measured.
To obtain an impression of the farmers' knowledge of the wind and water erosion and deposition processes, the damage to crops and the traditional and new techniques for wind and water erosion control, in total 60 farmers were interviewed. Chapter 2 describes the results of this research.
In chapter 3 the similarities and the differences between wind and water erosion are described. Moreover, the different measurement techniques for both processes are described and a set up for simultaneous quantification of wind and water erosion is proposed.

Chapter 4 describes the sediment catcher that is used to measure horizontal mass fluxes of wind-blown sediment transport and a method to calculate the total mass transport rate at the point of observation. Furthermore, it describes the geostatistical method, which is used to simulate the spatial variation in wind-blown sediment transport. Now that it was clear that a large spatial variation in wind-blown sediment transport exists, even at the scale of a field (80 x 80 m), two wind erosion models with a spatial component (the empirical RWEQ and the physically based WEPS) were tested on their suitability for the Sahelian situation (chapter 5).

In chapter 6, the physically based EUROSEM model is adapted to be applicable to the Sahelian situation. Finally WEPS and EUROSEM are combined and extended with nutrient modules. Chapter 7 discusses the spatial distribution of nutrients by wind and water separately and the simulation of a combined wind/water erosion event.

The soil and nutrient losses measured and simulated in this thesis are measured at the scale of a single field. To exactly quantify the combined impact of wind and water erosion at village scale, different measurement and simulation techniques are necessary. In chapter 8, the nutrient dynamics by wind and water at village scale are discussed. The new hypotheses are applied on the area around the village Dangadé, resulting in a qualitative impression of the impact of one combined wind/water erosion event on the nutrient balance. Chapter 9 finally summarises the main conclusions of this thesis.

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Chapter 2

Farmers' perceptions of erosion by wind and water in northern Burkina Faso

S.M. Visser, J.K. Leenders and M. Leeuwis

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Abstract

Wind and water erosion are widespread phenomena throughout the Sahel, especially in the early rainy season, when high-intensity rainstorms are often preceded by severe windstorms. This paper describes the results of a survey on the farmers’ perceptions of wind and water erosion processes and control measures. In three villages in northern Burkina Faso, 60 farmers were interviewed using semi-structural questionnaires. According to most of the farmers wind-blown particle transport has an influence on the fertility and the infiltration capacity of the soils. They considered wind-blown particle transport damaging for their crops. Seedlings are damaged by scouring grains of sand or lost when buried in sand deposits. Only 32 per cent of the farmers observed runoff and 15 per cent observed erosion and deposition during periods of high intense rainfall. According to 22 per cent of the farmers intense rainfall has a negative effect on crop production. Plants die because of the effects of stagnating water and plants are damaged by the forces of flowing water.

All farmers are familiar with techniques to reduce soil erosion and 96 per cent applied one or more of these techniques. The indigenous techniques are application of manure and mulch. The main constraints to apply these techniques are lack of labour, manure and mulch. New techniques introduced by agricultural organisations are zaï and half moons, stone rows and sand bunches.

Farmers have a good knowledge of wind erosion processes but do not report the effects of water erosion processes. The farmers are willing to apply new techniques to control soil erosion, but the main constraints to apply these measures are insufficient knowledge and lack of labour.

Introduction

Wind and water erosion are widespread phenomena throughout the Sahel especially in the early rainy season (May-July) when high intense rainstorms are often preceded by severe windstorms (Sterk, 1997). Several studies performed in the northern Sahel have revealed that sand transport by wind may cause severe damage to young crops (Michels *et al.*, 1995, Gaouna, 1996, Sterk and Hagis, 1998). Also water erosion has been reported to cause crop damage (Thiombiano, 2000). Others showed that soil productivity declines with the removal of fertile topsoil by wind or water erosion (Mainguet and Chemin, 1991, Sterk *et al.* 1996, Thiombiano, 2000, Veihe, 2000). Even though wind and water erosion have been intensively studied in the Sahel, little research has been performed on their interaction. So far only Visser (2001) and Rajot *et al.* (2002) have performed a simultaneous research on the two processes in the northern Sahel. Casenave and Valentin (1989) and Valentin and Bresson (1992) showed that the, in general sandy, soils in the Sahel are vulnerable for crusting, causing a higher risk to both wind and water erosion. Rajot *et al.* (2002) measured in a small catchment in northern Burkina Faso a total soil loss of 7.5 ton ha^{-1} for the whole area caused by both wind and water erosion.

For introduction of soil conservation techniques, the cooperation of the farmers is necessary; therefore it is of interest to evaluate the farmers’ perceptions of the processes of wind and water erosion in the northern Sahelian zone. Sterk and Haigis (1998) found that farmers consider wind-blown particle transport to damage their cropping systems and think that wind erosion causes losses of fertile topsoil. To cope with these problems farmers use millet residues and tree branches as protective mulch after harvest. In addition Taylor-Powell (1991) and Thiombiano (2000) found that farmers considered also sand deposition from water runoff a constraint. Farmers say that sand deposition from runoff limits the cultivable area and buries the young crops. This phenomenon is considered to be more widespread and harmful than gully erosion (Taylor-Powell, 1991).

We interviewed land users in three Sahelian villages to i) evaluate the awareness of the farmers of the processes of wind and water erosion ii) investigate which soil erosion control techniques the farmers apply and iii) to evaluate the willingness of the farmers to apply new techniques, introduced by agricultural organisations.

Research area

In May - June 2001 a survey was conducted in northern Burkina Faso (Fig. 1), which belongs to the western part of the Sahelian zone of West-Africa. The semi-arid climate has a long dry season from October till May, with the northeast Harmattan winds blowing from December to March, and a short rainy season with south-western monsoon winds from June to September. Generally the rainy season lasts from June till September and the mean annual precipitation in this area is 420 mm. However, the mean annual precipitation can drop as low as 150 mm and the rainy season can last less than 2 months. (Claude *et al.,* 1991).

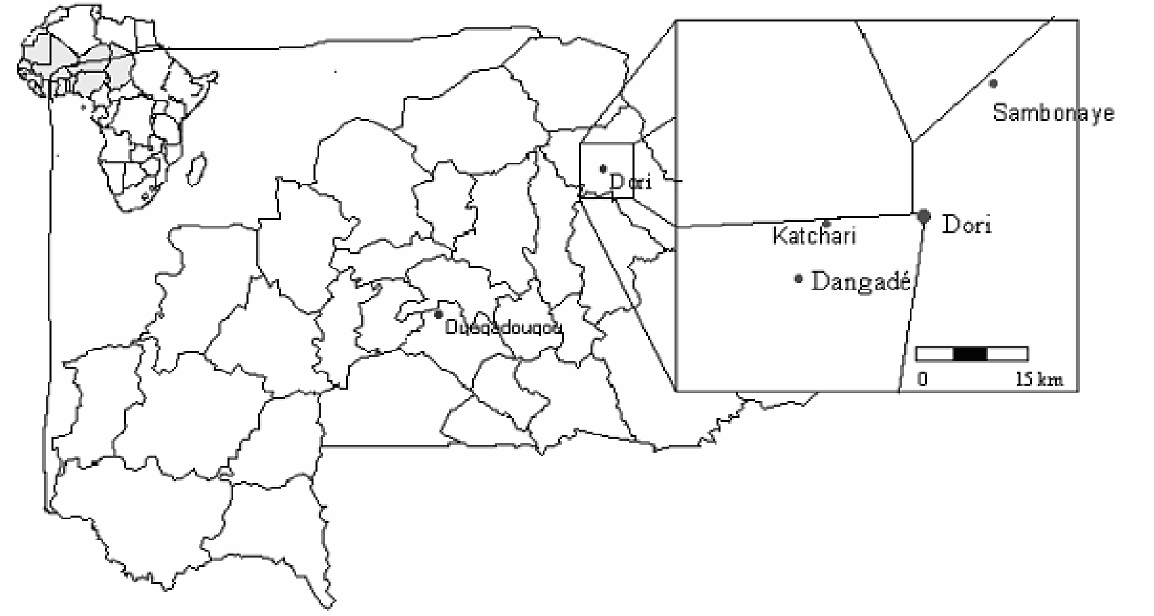

Figure 1) The location of the study area in northern Burkina Faso

Although real forest with *Anogeissus leioca pus* and *Crataeva adansonii* are found in depressions with hydromorphic soils and vertisols, the characteristic vegetation of the area is arboraceous and/or scrubland steppe, with small trees or shrubs. The most common species in the area are the *Acacia senegal, Acacia radiana* and *Adansonia digitata.* The mainly annual grasses tend not to form a continuous soil cover except in certain zones such as clayey soil depressions. The prevailing grass species are *Panicum laetum, Schoenfeldia gracillis* and *Cenchrus bifloris* (Thiombiano, 2000, Claude *et al.*, 1991).

A total of 60 farmers of three Fulani villages was interviewed. The village of Dangadé is situated 17 km southwest and Katchari 11 km west from Dori (14°00" N-0°10" W), the capital of the Seno province (Figure 1). The village Sambonaye is situated 25 km northeast from Dori. Katchari is located on an old and flattened dune band that belongs to an extensive sand dune system, which is more than 40.000 years old (Delfour and Jeambrun, 1970). Almost the whole dune complex is cultivated and the borders of fields are often indicated with trees. The slopes of the dune complex are relatively short (75-100m) and gentle (1-2°). Dangadé is situated on the border of this dune system on the valley floor. The valley floor is deeply incised by an ephemeral river and has a high natural vegetation cover (60-80%) existing mainly of trees and shrubs. The pediplane near Dangadé and Katchari is characterised by short (± 75 m) and gentle (2-4°) slopes. To get a representative overview of the region, Sambonaye was included in the survey. This village is located on a flat pediplane north of this dune system. The area is characterised by long slopes (>200m) with an angle of 4 to 6° and the occurrence of recent and sometimes mobile dunes. We supposed that, due to the longer slopes and more clayey soils of the pediplane, the farmers in this area would have more water erosion related problems than the farmers of Dangadé and Katchari. Table 1 shows the percentage of farmers' fields per geomorphologic unit.

In 1998 a dam was constructed at the location of the village Sambonaye, which forced all villagers to migrate. The farmers are dispersed over the area surrounding the new lake, but bonds between the farmers are still strong and maintained by the authority of the village chief. Some of the farmers' fields are now at large distances, approximately 3 km, from their new compounds.

In Katchari and Dangadé crop production is said to be the most important agricultural activity. In Sambonaye crop production and animal husbandry are equally important according to the farmers. The main crop for all villages is pearl millet (*Pennisetum glaucum*) often intercropped with cowpea (*Vigna unguiculata*) or a local herb (*Triumfetta pentandra)*. Other crops grown by the villagers are sorghum (*Sorghum bicolour*) and groundnut (*Arachis hypogaea*). In general, sowing is done after the first rain event that exceeds 20 mm (Sivakumar *et al.*, 1981). In millet intercropping systems, the second crop is not sown until 2 or 3 weeks after the first crop (Spencer and Sivakumar, 1987).

Table 1) Percentage of farmers' fields per geomorphologic unit

	Old Dune	Recent Dune	Pediplane	Valley Floor
Dangadé	31	0	47	22
Katchari	40	0	35	25
Sambonaye	0	49	22	29

Survey methodology

For the interviews a semi-structured questionnaire was used. In a semi-structured questionnaire the main topics are structured but within a topic, room for new questions is available depending on the responses of the interviewee. This results in a flexible tool for covering the central topics while providing an opportunity for the farmers to express new ideas (Baarda and de Goede, 2000). The questionnaire was applied with a mixture of open-end questions (75%) and questions with coded answers (25%). A pre-survey was held with 5 farmers to get an idea of the possible answers given and to test the questions. Because farmers in the selected villages only speak Fulfuldé, their local language, the interviews were held with help of an experienced translator. All interviews were held with by the same interviewer who also wrote down the responses.

In the first part of the interview, the farmers were asked to give some general information about themselves and their fields such as: age, family situation, how much fields they own, how long they have their fields and the distance between their compounds and the fields. The second part dealt with wind erosion. First some general questions were asked to see if the farmer recognises wind erosion as a problem and can indicate the period of highest wind activity. Then more specific questions about differences in erosion between fields and the influence of wind-blown particle transport on fertility and infiltration were asked. Furthermore, questions were asked about the influence of wind-blown sand transport on the crops. The third part had the same set up as the second part but dealt with water erosion. The fourth part dealt with soil conservation techniques.

Results and discussion

When asked for their major problems in relation to cultivation, 90 per cent of the farmers reported lack of rain. Lack of manure (50 %) and lack of labour (18 %) were also seen as major constraints. Erosion by wind or water was seen as a major problem by only 4 per cent of the farmers.

The considerable importance given to rain by the farmers is most probably linked to the drought of 2000, which completely destroyed the crop in this area. This agrees with the results found by Bielders *et al.* (2001) in Niger. Farmers who had suffered from drought in previous years ranked drought as the single most important constraint to agriculture whereas farmers from other areas ranked insect pests and soil fertility as most important.

The fact that only 4 per cent of the farmers in our research area indicate soil erosion as a major problem in relation to cultivation does not mean that the farmers do not experience soil erosion. When asked what they observe in periods with strong winds, the farmers reported erosion (93 %) and deposition (85 %) on their fields (Table 2). Of these farmers, 81 per cent related erosion and deposition to the degree of vegetation or mulch cover. Twenty percent mentioned to observe crop damage during periods of strong winds (Table 2). In general they believed that sediment transported by wind travels only limited distances, from and to neighbouring fields. None of the farmers thought that sand may travel over longer distances. All farmers said that the period with the strongest winds lasts from May till July; the beginning of the rainy season.

When asked what they observed during periods of high intense rainfall, the farmers answered good millet growth (42 %), runoff of water (32 %), erosion and deposition of sediment (15 %) and flowing water damaging young millet plants (3 %). The farmers that mentioned good millet growth all came from Dangadé and Katcheri and all the farmers that observed runoff live in Sambonaye. This difference in perspective is most probably linked to the geomorphologic settings of the village. In general, the sandy soils of the dunes around Katchari and Dangadé have a higher infiltration capacity than the mostly clayey soils of the pediplane around Sambonaye.

Table 2) Farmers' observations in periods with strong winds and periods with intense rainfall (n=60)

	Observation	Percentage
Periods of strong wind		
	Erosion	93
	Deposition	85
	Crop damage	20
Periods of intense rainfall		
	Good millet growth	42
	Runoff	32
	Erosion and deposition	15
	Crop damage	3

Furthermore, the slopes at the fields at Sambonaye are longer and steeper. Most of the farmers that mentioned to observe runoff stated that, although the water had the colour of the soil, no erosion of the field occurred. When asked after the direction of the runoff water, the majority (57 %) said the runoff flows to the neighbouring fields, while 43 per cent mentioned it flows to the closest river and leaves the area.
When the farmers were asked which process, wind-blown particle transport or processes caused by high intense rainfall, is more important in the region, 62 per cent said wind-blown particle transport is more important and 33 per cent named the interaction between the processes of wind and water.

Wind erosion

No distinct differences between villages in opinions of farmers on wind-blown particle transport were found. Therefore, the 60 farmers in the three villages are regarded as one sample population in most of the analyses, as presented in the tables. When asked more specifically about differences in erosion intensities in and between fields, and the influence of wind blown particle transport on soil fertility and infiltration capacity, 82 per cent of the farmers reported to notice differences in sand transport between fields (Table 3). These differences were said to be related to differences in tree and mulch cover, sand availability and topography. Ninety per cent of the farmers said that the fertility of their fields changes due to wind-blown sand transport. Of these farmers 13 per cent simply said the fertility decreases. However, most of the farmers related the fertility changes to erosion (a decrease in fertility) and deposition (an increase in fertility) (Table 3). This agrees with the results of Sterk *et al.* (1996) in Niger. They found that wind may transport considerable amounts of sediment and nutrients over short distances resulting in an increase in soil productivity at places with deposition and a decrease in soil productivity at eroded areas.
The farmers understand the influence of a mulch cover on the fields very well. Some farmers stated that they could gain a deposition of approximately 5cm sediment a year by simply placing a lot of mulch on the fields, and that at locations where mulch was applied fertility increased. The amount of mulch was not further specified. These perceptions agree with the results of Buerkert *et al.* (1994), who found that application of mulch reduces soil degradation and might even invert the process of soil erosion.

Table 3) Farmers' perception on the influence of wind blown particle transport

Observation	**Reason**	**Yes (%)**	**No (%)**	**No answer**	**n** *
Erosion differences		82	18	-	60
	Mulch cover	37	63	-	49
	Tree density	29	71	-	49
	Sand availability	18	82	-	49
	Topography	14	86	-	49
Fertility changes		90	10	-	60
- Decrease	Erosion	76	24	-	54
- Decrease	No reason given	13	87	-	54
- Increase	Deposition	61	39	-	54
Infiltration changes		77	13	10	60
-Increase	No reason given	87	13	-	46
-Increase	Deposition	2	98	-	46
-Decrease	Erosion	4	96	-	46

* *n=number of farmers interviewed on specific questions*

Asked if they observed any effect of windblown particle transport on infiltration capacity in their fields, 77 per cent of the farmers indicated that they observed changes, 13 per cent said that wind-blown particle transport does not influence the infiltration of water in the soil and 10 per cent did not answer this question (Table 3). Of the farmers that observed changes, 87 per cent mentioned simply an improved infiltration. Only 6 per cent related infiltration changes directly to erosion (4 %) or deposition (2 %) of wind-blown material. This result is differs from the results of Bielders *et al.* (2001). During their survey in 41 villages in Niger they found that in 51 per cent of the villages hardpan formation and surface crusting were considered the most important consequence of wind erosion. Hardpan formation and surface crusting generally lead to a lower infiltration capacity. In our case, most of the 40 farmers, which reported better soil moisture characteristics, had applied mulch and branches on "bad" places in their fields and had observed deposition on locations with a lot of mulch. Mando (1997) showed that mulch attracts termites, which can significantly improve water infiltration by breaking up crusts. So where farmers think that infiltration capacity increases because of deposition of wind-blown particles, this is most likely due to the combination of application of mulch and branches and termite activity.

Asked about the effect of wind-blown particle transport on the crops, all farmers reported observing plant losses during the first few weeks of the rainy season. In total 58 per cent of the farmers said they loose seedlings because the plants were damaged by the moving sand (Table 4). In extreme cases of abrasion, farmers are forced to resow their fields resulting in late development of the crop and therefore possibly a lower production. Furthermore, 76 per cent of the farmers reported that when wind erosion events occur late in the rainy season the large plants are broken by the wind causing a production loss. According to 88 per cent of the farmers, young seedlings are covered by the sand (Table 4). These plants often die because of lack of light for photosynthesis, the weight of the sand and the high soil temperatures during the day (Michels *et al.* 1995). According to 78 per cent of the farmers, the plants covered due to wind storms do not die if it rains within 2 or 3 days after a wind erosion event. They say that the rain washes away the sand that covers the plants.

Table 4) Farmers' perception of plant damage by wind blown mass transport and in periods with strong winds (n=60)

	Response (%)
Young plants damaged by abrasion	58
Large plants broken by hard wind	76
Young millet covered with sand	88

Water erosion

When asked more specifically about differences in erosion and runoff intensities between their fields, 55 per cent of the farmers reported observing differences in water erosion between fields (Table 5). Reasons for differences in runoff and erosion by water between fields were: geomorphologic location, infiltration, slope, mulch coverage, soil type and vegetation coverage. According to 92 per cent of the farmers, August, in the middle of the rainy season, is the month with most rain-related problems and 8 per cent mentioned the period from May till June, the beginning of the rainy season. Since August is the period with the most intense rainfall events and it hardly rains in May and June it is assumed that the farmers who mentioned the period May and June found the lack of rain in this period a problem.

Table 5) Farmers' perception on the influence of water erosion

Observation	Reason	Yes (%)	No (%)	n [*]
Erosion differences		55	45	60
	Geomorphologic location	34	66	33
	Infiltration	30	70	33
	Slope	27	73	33
	Mulch coverage	24	76	33
	Soil type	21	79	33
	Vegetation coverage	9	91	33
Fertility changes		100	0	60
-Increase	No reason given	92	8	60
-Increase	Deposition	2	98	60
-Decrease	Erosion	3	97	60
-Decrease	Flowing water	3	97	60
Infiltration changes		93	7	60
-Increase	No reason given	59	41	56
-Increase	Addition of fertilizer	4	96	56
-Increase	Deposition	2	98	56
-Decrease	No reason given	70	30	56
-Decrease	Stagnation	30	70	56
-Decrease	Erosion	4	96	56

[*] *n=number of farmers interviewed on specific questions*

More specific questions about the influence of water erosion on fertility and infiltration capacity were asked (Table 5). The farmers said that with rain the millet grows well and so the fertility increases (92 %). However they do not give a specific reason for the increased fertility. Apparently, they do not link the production of the field with the fertility of the soil, but with amount of available water. Only 5 per cent of the farmers linked erosion (2 %) and deposition (3 %) with fertility and 3 per cent said the fertility of the entire field decreases because of the flowing water (Table 5). Van Dissel and De Graaff (1998) similarly found in South Africa that farmers thought that it was not erosion, but a lack of soil moisture which caused a decline in soil fertility even though scientists found that clay and organic matter, and so nutrients, were being washed out of the soils of their fields. Veihe (2000) reported that Ghanaian farmers said to experience soil erosion by the loss of nutrients and declining soil fertility causing reduced crop yield. However those Ghanaian farmers experienced soil loss through the formation of gullies and rills, reduced grain head sizes, increased occurrences of drought, roots getting exposed and, in some cases, the soil being degraded to the point where it can no longer be farmed. In our research only two farmers reported to have had serious problems with water erosion ten years earlier. Gully formation had taken large parts of their fields. This view confirms with the results of Van Dissel and De Graaff (1998), where the farmers only recognize the formation of gullies and rills as erosion.

When asked if they observed any effect of high intense rainfall events on the infiltration capacity in their fields, 93 per cent of the farmers reported changes in infiltration (Table 5). Several reported an increase on some parts of their fields and a decrease on other parts but gave no explanation for these differences. Thirty percent of the farmers reported stagnating water on their fields. Only 6 per cent of the farmers linked erosion and deposition with infiltration capacity and 4 per cent reported that at places where fertilizer was added infiltration increased (Table 5). Stagnating water is most probably caused by the development of soil crusts since all farmers that reported to have those problems later said infiltration increases after cultivation. Also the spatial decrease and increase in infiltration capacity, which most farmers observed is thought to be related to soil crusting. Research by Thiombiano (2000) and Visser (2001) show that in this area soils are vulnerable to crusting and that infiltration capacity decreases significantly with crust development. According to 22 per cent of the farmers, intense rainfall has a damaging effect on crops (Table 6). Plants die because of the effects of stagnating water (14 %) and young plants are damaged by the effect of flowing water (8 %). Veihe (2000) reported that also the Ghanaian farmers experience plant losses when seedlings and plants are washed away during heavy rains.

Table 6) Farmers' perception of plant damage by water

	Response (%)
No damage	78
Where stagnation, plant die	14
Seedlings damaged by runoff	8

n=59

Soil erosion control

Even though wind and water erosion are not felt as the most urgent problems, the farmers do know and apply techniques to reduce soil erosion (Table 7). The indigenous techniques (mulching and applying manure) were known by all farmers. The main reasons for not applying these techniques are lack of labour, mulch or manure. For the farmers of Sambonaye the long walking distance to the fields (around the new lake) was also an important reason for not applying erosion control techniques on these fields. None of the farmers reported leaving crop residues on theirs field as a protection. However, when visiting the fields, it was noticed that most farmers who said to apply mulch, simply left crop residues (standing and lying). In approximately 25 per cent of the fields of the farmers who applied mulch it was noticed that they had actively cut and brought branches and/or crop residues to the fields. According to 98 per cent of the farmers the manure fertilises the soil, prevents wind erosion and stimulates deposition. In Sambonaye 20 per cent of the farmers said that manure diminishes also runoff. Furthermore, farmers that applied mulching explained that it decreases wind and water erosion and fertilises the soil. The fact that the farmers apply mulch and manure to protect and fertilise the soil is an indication that they are conscious that they are able to exercise influence on maintaining the soil. This agrees with results found by Krogh and Paarup-Laursen (1997), who found that

Table 7) Knowledge and application of erosion control measures in Burkina Faso (n=60)

Control measure	**Uses (%)**			**Knows, doesn't use (%)**			**Does not know (%)**		
	D	K	S	D	K	S	D	K	S
Application of manure by hand	30	34	25	3	0	8	0	0	0
Application of manure by grazing animals	24	30	28	10	3	5	0	0	0
Mulching	34	30	33	0	3	0	0	0	0
Stone rows	15	0	0	17	22	22	2	11	11
Sand ridges	2	3	0	0	0	0	32	30	33
Half moons	3	0	0	15	7	0	15	26	34
Zaï *	3	0	0	20	8	2	10	25	32
Tree planting	0	0	0	0	2	2	34	31	31

D=Dangadé, K=Katchari, S=Sambonaye, in each village 20 farmers were interviewed

**Soil tillage methods from Burkina Faso, using pits filled with compost for sowing crops* the Fulani of northern Burkina Faso are aware of and active in management of soil fertility. Contrary to this Lindskog (1994) found in northern Burkina Faso that local people do not recognise that human actions have influence on land degradation and that land degradation is merely to be attributed to God or Allah.

It is interesting that none of the farmers mentioned fallow as a conservation method. When asked whether they do practise fallow periods on their field all farmers gave a negative response. Thiombiano (2000) shows that the total cultivated area in this region rose from 19.4 per cent in 1956 till 42.3 per cent in 1995. The pasturage area decreased from 80.6 per cent in 1956 till 57.7 per cent in 1995. In 1956 20 per cent of the cultivated area was left fallow, but in 1995 fields were no longer left fallow. The farmers say that with the growing population, the demand for food is too high to leave fields uncultivated.

Methods, newly introduced by agricultural projects are stone rows, sand ridges, zaï and half moons. These methods were known and applied by a number of farmers (Table 7). According to the farmers, stone rows and sand ridges do not function as erosion control but act as a water conservation measure by diminishing the velocity of the runoff and stimulating infiltration. The obstacles for applying these techniques are lack of knowledge and labour and availability of stones. Zaï and half moons make use of pits with a diameter of 10-15 cm and 2-2.5 m respectively, filled with compost for sowing. They are no direct erosion control measures but more traditional practices to improve soil fertility. As a result of these practices plants grow and develop better, making plants more resistant against damage caused by soil erosion (Buerkert *et al.*, 1994, Roose *et al.*, 1999). According to Lamers and Feil (1995) application of zaï and half moons is limited by availability of manure and organic matter for the pits. In the present study many farmers said they were not familiar with the effects of zaï (67 %) and half moons (75 %) for erosion control (Table 7). The farmers who knew this method said that lack of labour and insufficient knowledge are the main constraints in applying these methods. Tree planting was only known by 4 per cent of the farmers as an erosion control measure. They did not apply this method because there were no sprouts available.

Zaï and half moons are only applied by farmers from Dangadé and sand ridges by farmers from Dangadé and Katchari. Agricultural projects introduced these techniques in Dangadé and the farmers of Katchari learned it from the farmers of Dangadé. The only new technique that is used in Sambonaye is stone rows (Table 7). Given the fact that only one farmer from Sambonaye knew some but did not apply any of the other new techniques, it is assumed that no information exchange between Dangadé and Katchari on one hand, and Sambonaye on the other hand exists. We found that the farmers of Katchari and Dangadé visit the weekly, regional market of Dori, whereas the farmers of Sambonaye visit another weekly, regional market (approximately 10 km East of Sambonaye).

Despite the fact that the farmers do not explicitly express the effects of zaï and half moons, 6 per cent of the farmers do apply these techniques (Table 7). Furthermore, 20 per cent of the farmers apply stone rows and sand bunches. This implies that the farmers are willing to apply new methods for soil conservation.

Conclusion

Farmers from three villages in northern Burkina Faso are aware of the problems relating to wind and water erosion. In general they have a good knowledge of wind erosion and its effects on crops and soils. They do not report the negative effects of water erosion and tend to see mainly the positive effects of rain. These conclusions conform to research of Sterk and Hagis (1998) for wind erosion and Taylor-Powell (1991) for water erosion. According to the farmers, seedlings are often damaged by wind blown particle transport and forces of flowing water. Furthermore seedlings die because of burial after a wind erosion event or as a result of stagnating water after a rainfall event. The farmers do recognise some of the sediment transporting capacities of flowing water, saying that plants covered due to wind storms do not die if it rains within 2 or 3 days after a wind erosion event. They say the rain washes away the sand that covers the plants.

Moreover the farmers think that soil fertility is negatively affected by erosion (by both wind and water) and that deposition of sediment results in a better soil fertility. Most of the farmers report to notice infiltration changes (both increase and decrease) due to wind-blown particle transport and the processes following high intense rainfall. Most of these farmers can't indicate a clear reason for these infiltration changes. Apparently they do not directly relate the negative changes to crust development by the processes of wind and water erosion. However, they do undertake actions to break the crusts by applying manure and fertiliser at places with a low infiltration capacity and they do notice infiltration is higher after cultivation.

Almost all farmers apply traditional techniques to combat wind and water erosion. Traditional techniques are application of manure and mulching with crop residues or tree branches. In general, application of these measures is limited by labour, mulch and manure.

Measures that have been promoted by an agricultural development project in Dangadé include the introduction of stone rows and sand bunches and the application of zaï and half moons. Stone rows and sand bunches were thought to reduce stream velocity of runoff and enhance the infiltration and were applied by 20 per cent of the farmers. Even though the effect of zaï and half moons is unknown to the farmers, 6 per cent applies these techniques. These techniques were introduced in Dangadé and taken over by the farmers of Katchari; this implies that the farmers are willing to apply new techniques. In general lack of knowledge and labour availability were the main constraints in applying these new measures. Given that Sambonaye does not use any of these newly introduced techniques it can be concluded that the distance between villages is the limiting factor for communication between villages.

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Chapter 3

Techniques for simultaneously quantifying wind and water erosion in semi-arid regions

S.M. Visser, G. Sterk and O. Ribolzi

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Techniques for simultaneously quantifying wind and water erosion in semi-arid regions

Abstract

Wind and water erosion are usually studied as two separate processes. However, in semi-arid zones both processes contribute significantly to soil degradation. Whereas for water erosion the direction of sediment transport is controlled by topography, in wind erosion the direction of transport is controlled by the wind direction. Furthermore, the spatial pattern of erosion and deposition for wind erosion is determined by the spatial distribution of source material, soil erodibility factors and non-erodible roughness elements. Given this difference in dependence on topography, different approaches are needed to determine the mass balance for a given area. For water erosion, the research area has to be defined such that no input of sediment occurs, whereas in wind erosion the in- and output fluxes of sediment should be measured, or a non-eroding boundary should be created.

In semi-arid regions, wind erosion events are often followed immediately by heavy rain. As wind and water erosion occur almost simultaneously at the same site, the effect of wind and water erosion at a given site should be studied concurrently. To do so, a number of measurement techniques with different spatial and temporal scales are necessary. The research should be started at the scale of a Sahelian field. For a complete insight into the processes at a site, the research should include measurement techniques that quantify the impact of wind and water erosion separately and techniques that quantify their combined effect.

Introduction

Soil erosion by wind and water is a threat to sustainable agriculture and environmental quality. Wind and water erosion are often studied as two separate processes. They are generally believed to be related to a specific climate zone: wind erosion to more arid regions, and water erosion to more humid regions. But in semi-arid regions, both erosion processes contribute significantly to total soil erosion and can occur almost simultaneously (Mc Tainsh *et al.* 1992). For instance, in the West African Sahel, convective rainstorms are preceded by strong windstorms. Hence, sediments transported by wind in one direction may be removed in a different direction by runoff. Water erosion can either increase the soil degradation caused by the preceding wind erosion event or return some or all the eroded sediments, thus decreasing the effect of wind erosion. If the aeolian sediments are subsequently removed by water erosion, but all the erosion is ascribed to water erosion, then the role of water erosion in soil degradation will be greatly overestimated. So, to better understand the impact of wind and rainfall on soil degradation in semi-arid areas, both processes should be studied simultaneously in the same area.

Wind erosion measurements by different researchers on the sandy tropical soils in Niger (Sterk, 1997, Rajot and Valentin, 2001) show that large amounts of sand can be mobilised by the wind, which may result in considerable soil loss on the scale of a field. By measuring mass fluxes on a field of 2400 m^2 Sterk and Stein (1997) calculated a soil loss of 45 t ha^{-1} for 4 wind erosion events. Buekert *et al.* (1996) estimated soil loss by measuring changes in the micro-topography and calculated a soil loss of 160 t ha^{-1} y^{-1} on a bare plot with an area of 0.5 ha. In similar plots, Bielders *et al.* (2000) measured a soil loss of 80 t ha^{-1} $year^{-1}$ for a bare soil and a deposition of 40 t ha^{-1} $year^{-1}$ for a soil covered with 2 t ha^{-1} flat lying and standing crop residues. In traditionally cultivated fields Bielders *et al.* (2001) measured a deposition of 5 t of sediment ha^{-1} in the first year of cultivation and a loss of 5 t ha^{-1} in the second year. The loss was ascribed to a decrease in vegetation cover.

It is interesting to compare the figures for wind erosion mentioned above with the figures available for water erosion in the Sahel. Collinet and Valentin (1985) performed rainfall simulations in West Africa and obtained a strong South–North gradient for potential soil losses, ranging from 80 t ha^{-1} year in Ivory Coast (2000 mm of rain a year) to 2 t ha^{-1} year in the northern Sahel (150 mm of rain a year). In the Sahelian zone of Niger, Vuillaume (1969) measured soil losses ranging from 0.2 t ha^{-1} in an entirely cultivated catchment of 9.1 ha to 2.3 t ha^{-1} on a much less cultivated one of 4.7 ha. Karambiri *et al.* (in press) measured soil losses varying from 4.0 to 8.4 t ha^{-1} year^{-1} at the outlet of a small (1.4 ha) grazed catchment in northern Burkina Faso. In Senegal, Albergal *et al.* (2000) reported values of 0.38 to 3.5 t ha^{-1} year^{-1} for a 90 ha catchment. All these results show that both wind and water erosion contribute significantly to total soil erosion. However, research methods and scales differ and therefore total measured erosion losses are difficult to compare. For research results to be comparable and capable of being extrapolated to other regions it is important for quantification techniques and methodologies to be standardised.

In this paper we therefore set out to: (i) briefly review the similarities and differences between wind and water erosion processes and describe the possible interaction between the two processes in the Sahel, (ii) summarise the major techniques for quantifying wind and water erosion, and (iii) describe the different techniques needed to simultaneously quantify wind and water erosion in semi-arid regions.

Soil erosion processes

Air and water are both fluids but they differ greatly in density and viscosity. Air behaves in many ways like water but is about 800 times less dense. This restricts the size of the particles that can be moved by air (Livingstone and Warren, 1996). Molecular viscosity is the capacity of a fluid to resist stress. All fluids show viscous behaviour when deforming under stress. However, the extent to which a fluid is deformed by a given force varies between different fluids. Since water is more viscous than air, it is moved less easily, but once it is moving at a certain velocity it can carry more sediment than wind moving at the same velocity.

Soil erosion and sedimentation are the result of soil particle transport processes. Erosion is the loss of soil material (soil particles, nutrients, and organic matter) at a certain location, whereas sedimentation is the deposition or gain of transported material at a certain location. A range of processes occurs before either erosion or sedimentation can be established (table 1). First, the material needs to be detached or dislodged. Wind and flowing water cause similar shear stresses on the solid surface. Once the flow shear stress exceeds the critical shear stress for movement of soil particles, the associated lift and drag forces exerted on the soil particles cause them to be entrained in the flow. The critical shear stress that can be exerted on a soil surface depends on particle shape, size, density, packing arrangement and cohesion. In wind, grains that are already entrained and make a jumping movement over the surface (saltation) cause additional detachment. Each time a particle hits the surface it exerts energy on other particles, which become detached from the surface. This process is called bombardment. Falling raindrops that strike the surface cause a similar kind of detachment called splash. If no water is flowing over the surface at the same time, the particles are moved over limited distances only. But under conditions of wind-driven rain, or when the drops fall on a sloping surface, soil particles may be moved over longer distances, up to several metres (Sharon, 1980). Furthermore, when the drops fall in a shallow layer of overland flow, the energy created by the drops can cause the flow to become turbulent, and there is a significant increase in the detachment of soil particles by flow (Kiepe, 1995). Once the depth of the water is more than several times the drop diameter, the impact of falling drops becomes negligible (Savat and Poesen, 1981).

A detached grain can travel with the fluid in several modes (table 1). The mode depends on the grain size, shape and density, the turbulent properties of the flow and on the fluid density, viscosity and speed. In water the four modes of transport are sliding, rolling, saltation and suspension (Allen, 1994). In air, the modes of transport are surface creep, saltation and suspension (Bagnold, 1941). Surface creep in wind-blown transport can be compared with rolling and sliding in transport by water. The particles involved in surface creep are sufficiently large to remain in contact with the surface. However, during surface creep the particles are mainly set in motion by the bombardment of saltating grains, whereas rolling and sliding is mainly caused by the drag forces of the flowing water. Saltation is the jumping movement of smaller particles over the surface, while suspension is the mode by which the finest particles are carried over large distances in the body of the fluid. Creep and rolling/sliding are able to transport particles horizontally over distances ranging from a few centimetres up to several metres. Saltating grains are transported over a distance ranging from several metres to a few hundred metres (Allen, 1994, Bielders, 2002), whereas suspended material may travel up to thousands of kilometres (Allen, 1994, Prospero, 1999).

Entrained particles in a fluid flow are subject to the gravity force that pulls them back to the surface. Each particle has its own fall velocity, which is dependent on the particle size, shape and density, and on the fluid's viscosity and density. The fluid velocity and related turbulence can keep particles entrained, but once the velocity decreases, e.g. due to a change in gradient (in the case of water transport) or because of increased terrain roughness (in the case of wind transport), the sediment transport capacity declines and the coarser particles begin to be deposited. If the velocity decreases further, the finer particles will also be deposited. This differential settling of the material gives rise to sediment sorting. Two other forms of deposition can occur: accretion and encroachment (Livingstone and Warren, 1996). Accretion occurs when grains moved by creep come to rest in sheltered positions such in the lee of ripples or between adjacent grains. Encroachment occurs if the surface suddenly changes, e.g. an abrupt step up or down. Saltating grains may pass over the obstacle, but creeping or rolling and sliding material is held up.

Both wind and water erosion perform selective transport and deposition. The finer, nutrient-rich particles transported in suspension are carried away over large distances Walling, 1994, Zobeck and Fryrear, 1986a). Both wind and water erosion perform selective transport and deposition. The finer, nutrient-rich particles transported in

Table 1: Similarities and differences between wind and water erosion processes

Process	Wind erosion	Water erosion
Detachment	Lift and drag forces	Lift and drag forces
	Bombardment	Splash
Transport	Creep	Rolling and sliding
	Saltation	Saltation
	Suspension	suspension
Deposition	Declining transport capacity	Declining transport capacity
	Accretion	Accretion
	Encroachment	Encroachment

(suspension are carried away over large distances (Walling, 1994, Zobeck and Fryrear, 1986a). Therefore the eroded sediment of both processes is enriched in nutrients (Zobeck and Fryrear, 1986b, Drees *et al.*, 1993, Sterk *et al.*, 1996). Furthermore, in water erosion, the combined effect of runoff and splash may cause additional nutrient erosion (Ahuja, and Lehman, 1983).

Although the processes are similar in many ways, wind and water erosion (including transport and deposition) behave differently with respect to topography (McTainsh, *et al.* 1992). In water erosion, topography entirely determines the direction of sediment movement. Soil material is generally moved downslope with the runoff from the catchment, and once the flow has been concentrated in rills, gullies or the natural drainage systems, the sediment is moved towards the outlet of the catchment. Some of the detached sediment is redeposited before reaching the outlet. Wind-blown sediment transport is not confined by topographical boundaries. In an erosive windstorm, the sediment is moved in the general direction that the wind is blowing, which might alter for successive storms and even during a storm. The spatial distribution of source material, soil erodibility factors and non-erodible roughness elements determine the spatial pattern of erosion and deposition areas.

Thanks to the work of several researchers in the Sahel it is possible to describe the interactions between the processes of wind and water erosion. For example, in the Sahelian zone of Niger the dynamism of the fine particles plays a key role in fertility management in a traditional cultivation system, in which periods of cultivation alternate with periods of fallow (Rajot and Valentin, 2001). Under a rainfall regime of 500 mm per year, the intensity of wind erosion is closely related to the moment of cultivation. In the early rainy season, only fields without their natural vegetation cover are eroded, whereas the fallow areas generally have sufficient vegetation cover to prevent serious erosion. The fields become a source of fine particles and the fallow area becomes a sink (Bielders *et al.*, 2002, Rajot *et al.*, in press). Furthermore the soils in this area have low clay contents (3% at the surface) and crusting is extremely sensitive to small variation in fine particle content. With increasing fine particle content, the soils have an increased tendency to crust formation, which can be observed in fallow areas (Ambouta *et al.*, 1996). The increasing crust development leads to more runoff and therefore possibly to more water erosion. However, crust formation might also result in the topsoil being more resistant to erosion. On the other hand, when fine particle content decreases; crust formation will no longer occur. De Rouw and Rajot (in press) have observed this on fields that had been cultivated for ten years or more. The disappearance of the crusts improves infiltration capacity, which will eventually result in lessivage and so in a decreased chemical fertility.

From the above it is clear that wind erosion and water erosion are closely related. At a much larger scale, Valentin (1995) states that dust plumes originating in West Africa during the dry season are much more substantial than the plumes formed during the rainy season. According to others, e.g. McTainsh (1986), the sediment of the Harmattan aeolian system, which may carry half of the world's mineral aerosol, originates from various sources in West Africa, where water erosion has caused deposition of large quantities of sediments during late Quaternary wet periods in which river systems drained inland regions. As a result, there is now an important supply of sediment available for entrainment by dust storms.

Quantification techniques

The quantification of soil particle transport by wind and by water in the field is difficult because of the large temporal and spatial variability in mass fluxes. At a given location, the number of windstorms and rain showers differs from year to year

(Wilson and Cooke, 1980, Sterk and Stein, 1997, Karambiri et al, in press.). During a particular year, windstorms and rain showers differ in duration, wind speed, wind direction, rainfall intensity and drop size distribution. This results in a wide range of wind-blown and water-driven particle mass fluxes. Moreover, soil erodibility is determined by several variables such as soil texture, soil structure, surface roughness and organic matter content. These variables usually show spatial variation, resulting in spatial variability in soil erodibility and thus also in particle mass flux.

Erosion and deposition are usually quantified by applying a mass balance concept for the area being studied. This means that the input and output of sediment along the boundaries of the experimental area are quantified and the input should be subtracted from the output. A positive balance means more input than output, hence sedimentation, and a negative balance means erosion. A zero balance means transport only and thus no net gain or loss of soil particles. There is an important difference between the techniques used to quantify wind and water erosion; it is related to a difference in these processes' dependence on topography. In water erosion studies, a mass budget is usually determined for an area that only produces an output of sediment; e.g. a whole catchment or a section of a slope. This can only be done because the boundaries are determined by topography. In wind erosion, however, the boundaries are usually not clear and have to be selected. A manually created non-erodible boundary is often used as field boundary. Although creep and suspension are assumed to be zero at this non-erodible boundary, suspension may be present and should be measured. Another technique is to quantify input and output of sediment by measurements of wind-blown particle fluxes.

Measurement techniques of wind-blown particle transport can be divided into direct and indirect techniques. These are described below.

Direct measurement techniques for wind erosion

Direct measurement techniques sample fluxes of wind-blown particles at a fixed position. The different devices can be divided into two groups. The first group consists of catcher-type (Fig.1) and filter-type samplers, which have a relatively low temporal resolution. For instance, sediment catchers continuously trap particles during storms, but mass fluxes can only be determined after the storm by weighing the trapped material. Total mass transport fluxes at the point of observation are obtained by integrating the measured mass flux profile across height (e.g. Fryrear and Saleh, 1993, Sterk and Raats, 1996). Filter-type dust samplers, which suck dust-laden air through a filter, also have a low temporal resolution. These samplers measure horizontal transport of suspended dust. After a certain period of operation the filter is replaced. The mass of dust on the filter is equal to the total mass flux for that period (e.g. Rajot *et al.*, 2000). Vertical dust deposition is easily measured with a device developed by Orange and Gac (1990). It consists of a simple pyramidal receptacle of 40 cm depth and a 0.25 cm^2 collecting surface. It is positioned 5 m above the ground and when washed daily with distilled water delivers deposited dust into a collecting bottle. The samples are filtered through 0.45 µm pore-size filters, dried and weighed. This method allows only the insoluble matter to be sampled; the dissolved fraction can be analysed from the filtrate.

The second group of direct wind-blown particle samplers has a high temporal resolution. These samplers record soil particle transport continuously. The Suspended Sediment TRAp (SUSTRA) was originally developed for trapping suspended matter only, but it can measure saltation fluxes on a high temporal scale, (Janssen and Tetzlaff, 1991) because the balance positioned under the inlet can measure incoming sediment continuously.

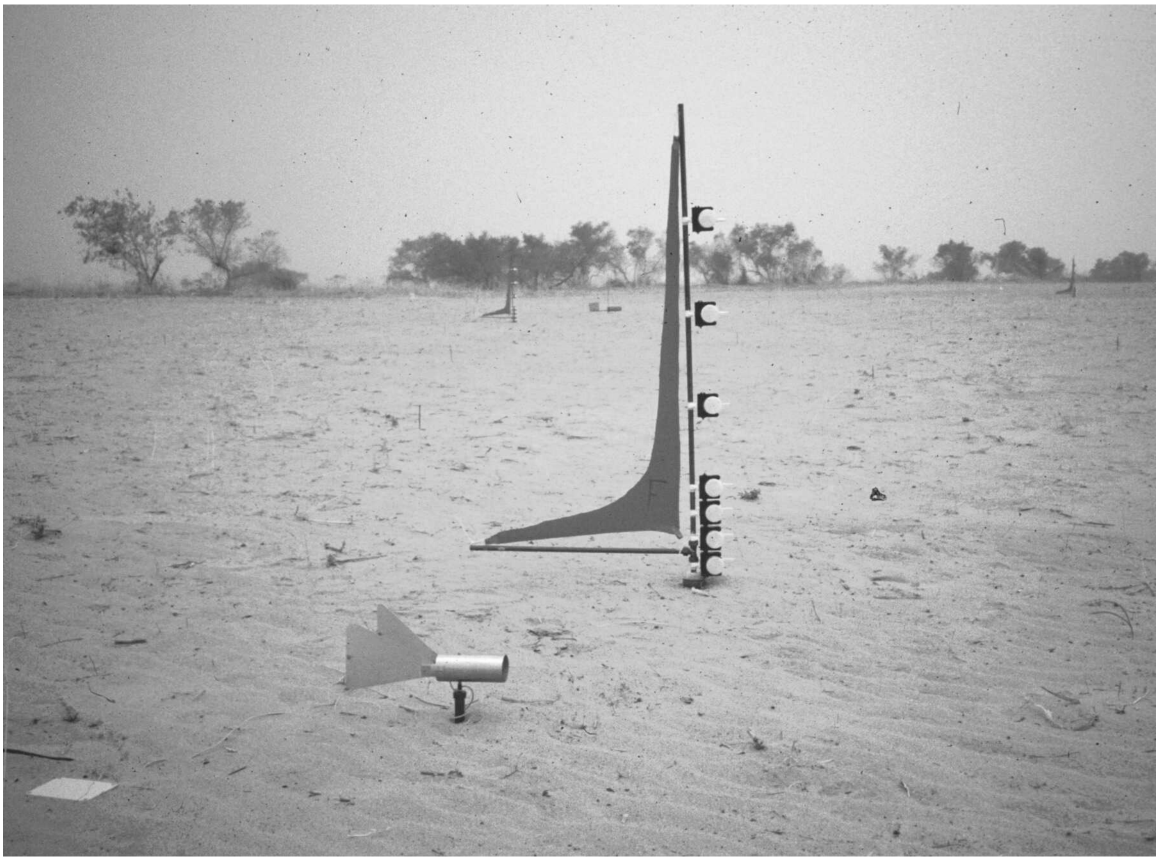

Figure 1) The Modified Wilson and Cook sediment catcher (background) and the Saltiphone

There are at least two devices that measure saltation transport by detecting particle impact. One uses a microphone (Saltiphone, Fig.1) (Spaan and Van Abeele, 1991) and the other uses a piezoelectric crystal (Sensit) (Stockton and Gillette, 1990). One of the main advantages of this type of equipment is that the moment of initiation and the moment of cessation can easily be recorded, and thus the total duration of the storm is known. Furthermore, threshold wind velocity can be determined if wind speed is measured simultaneously. There are several instruments that continuously record transport of dust in suspension. For instance a device developed by Koch *et al.* (1997) continuously monitors light scattered by three dust size fractions.

As the wind erosion process is very complex, wind tunnels are often used to isolate a small part of the erosion process for intensive study under controlled conditions. Wind tunnels generally have a long section designed to develop a turbulent boundary layer whose velocity profile and turbulence characteristics match those of the simulated atmospheric boundary layer. They are generally stationary constructions in a laboratory, but there is a wide variety of portable wind tunnels (e.g. Leys and Raupach, 1991, Scott, 1994 and Lee *et al.*, 2002). At the International Centre for Eremology (ICE), Ghent University, Belgium, a wind tunnel has been installed that not only enables wind and water erosion processes to be studied separately, but also allows the interaction and the combined effect of wind and water on soil movement to be investigated (Gabriels et al, 1997).

Indirect measurement techniques for wind and water erosion

Indirect measurement techniques do not quantify soil-particle transport itself, but determine the erosion or sedimentation rate in a given area. Examples are the use of erosion pins to measure changes in soil surface elevation (Gibbens et al, 1983) or the ^{137}Cs isotope technique (Chappel et al, 1996, De Roo, 1993). These techniques provide point information with a temporal resolution varying from days to several tens of years. The description of erosion features in geomorphologic studies (e.g. Cornish 1900, Jawad Ali and Al-Ani, 1983) and the use of remote sensing, for instance to trace sand and dust movement in the Saharan desert (e.g. Mainguet, 1984) are examples of indirect techniques for wind erosion working on large spatial and temporal scales.

These indirect techniques for quantifying wind-blown particle transport can also be used to assess water erosion. In fact, in semi-arid areas the changes in soil surface elevation are the result of both wind and water driven transport processes. This means that using only these methods it is virtually impossible to ascertain the erosion rate of one of these processes. However, the combined effect of wind and water erosion is easily measured. Chappel (1996) measured total sediment redistribution with the ^{137}Cs isotope technique and combined these measurements with a stream power index to provide a measure for water erosion and an index of susceptibility to aeolian processes. Using this method he was able to indicate the relative intensity and spatial distribution of the intensity of wind erosion and of water erosion separately.

Direct measurement techniques for water erosion

The direct techniques for quantifying water erosion can be divided into three groups based on the spatial scale of measurement (Mutchler *et al.*, 1994). The first group consists of small-scale measurements. These measurements are typified by the square metre plots used by Meyer and Harmon (1985) or by slightly larger plots. In general, the small plots are used for quantifying inter-rill erosion, either with natural or simulated rain. Rain simulations can be performed both in the field and in the laboratory. Laboratory plots are also used to isolate a small part of the erosion process for intensive study under controlled conditions. To quantify the amount of water erosion by runoff, the sediment needs to be collected at the outlet of the erosion plot. The temporal scale of the measurements is determined by the user and can range from minutes to one event. A large variety of rainfall simulators for water erosion research is available—all differing with respect to drop size distribution, drop impact, rainfall intensity, research area, angle of impact and portability. Meyer (1994) gives a detailed overview of the available rainfall simulators for soil erosion research.

Another quantification technique used in plots at this scale is the splash cup (Fig. 2A). These cups provide point measurements of transport by splash erosion. The measurements can be performed in the field and in the laboratory (Savat and Poesen, 1981).

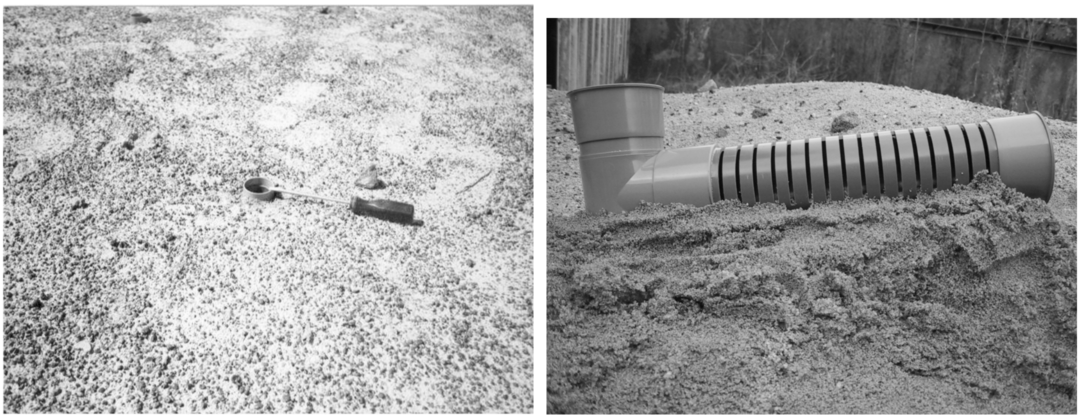

Figure 2) The splash cup (A) and the overland flow detector (B).

The overland flow detector (Kirkby *et al.*, 1976) gives information about the occurrence of runoff at this small scale (Fig. 2B). However, large numbers of this device are often used at the catchment scale to obtain information about the occurrence of runoff at a larger scale (e.g. Vertessy *et al.*, 2000).

The second type of water erosion research plot is large enough to represent the combined process of rill and inter-rill erosion. Good examples are the standard erosion plots (length 22.1 m, width 1.83 m) used to develop the Universal Soil Loss Equation (USLE) (Wischmeier and Smith, 1978). These plots, which are wide enough to minimise the edge effect and large enough for development of down-slope rills, are generally installed in rows parallel to the slope. In this case, too, to quantify the total plot erosion all the sediment mass needs to be collected at the outlet. The temporal scale of the runoff measurements can vary according to research needs. A very common method is to drain the runoff into gutters and then into large containers placed in the ground, which can be cleared of sediment and water after each rainfall event (e.g. Ollesch and Vacca, 2002). Researchers who need a smaller temporal resolution can use a water discharge recorder (e.g. Zoumoré *et al.*, 2000) or a tipping bucket (e.g. Visser, 2001). These types of equipment record runoff discharge in regular time periods.

The third type of water erosion research plot is a small catchment. It should be large enough to include at least one natural drainage way (Reid and Dunne, 1996). These catchment-scale plots are sufficiently large to include inter-rill erosion, rill erosion, gully erosion, stream bank erosion, and deposition. However, it is difficult to quantify the different processes. Usually, only the net sediment yield is determined at the outlet by taking runoff samples during and immediately after events. This can be done by hand (e.g. Karambiri et al, in press) or using an automatic device like the Coshocton flume sampler (Brakensiek *et al.*, 1979). The gross sediment yield, which is the total mass of all sediments that have been redistributed within the catchment, can only be estimated using erosion survey techniques like the Assessment of Current Erosion Damage (ACED) technique of Herweg (1996).

Simultaneous quantification of wind and water erosion

For simultaneous quantification of wind and water erosion, different measurement techniques must be used within the area. To understand the magnitude of the different processes in the study area, it is best to start the measurements at the scale of a Sahelian field. This scale is small enough for detailed process studies, and sufficiently large to include all wind erosion processes, as well as inter-rill, rill, and sometimes gully erosion processes. Preferably, standardised quantification techniques should be used. This enables results from different areas and different studies to be compared. However, most equipment and calculation methods for both wind and water erosion are not standardised. The only standard method seems to be the USLE-type runoff plot for water erosion studies. This lack of standard techniques should be a major concern to all scientists working on soil erosion, because progress in the understanding of the processes and the prediction of their impact on future land quality is possible only if adequate and standardised quantification methodologies are available (Lal, 1994). Of course, this does not mean that for a given parameter there is only one measurement technique that is optimal in all circumstances. But there should certainly be standardised reporting. For instance, in wind erosion measurement you should not only describe the sediment samplers and their distribution in the research plot but you should also give information about the trapping efficiency and the method used for calculating the vertical saltation flux profile. Only if a complete description of the experimental set up, the calculation methods and the erosive events is given, researchers can compare their results with those of others. Below, we describe the type of measurements that should be applied for simultaneous quantification of wind and water erosion in semi-arid regions.

For both types of erosion it is necessary to collect basic data on soil type, soil texture, surface crusting, nutrient and organic matter content of the soil, topography, vegetation and crop cover, land use and management. For wind erosion, the soil moisture content of the top few millimetres is an important controlling parameter that should be monitored continuously, preferably with an automatic sensor so that soil moisture content at the onset of a wind erosion event is known. For water erosion, the potential infiltration rates and capacities, as well as saturated conductivity values of the topsoil should be measured. Many methods are available to measure these parameters. Which method should be used depends on the research objectives and soil types. For instance, if you want to measure the infiltration capacity of a soil with a crust, rainfall simulations will most probably provide the best estimate (e.g. Hoogmoed and Stroosnijder, 1984). If the soil is not prone to crusting, a good and inexpensive technique is the inverse auger hole technique of Kessler and Oosterbaan (1974).

An automatic weather station is needed to collect basic meteorological data on air temperature, air humidity, solar radiation, soil moisture content, wind speed, wind direction, and precipitation. Wind speed measurements are preferably taken at several heights, so that a logarithmic wind profile is obtained from which the average shear stress at the surface can be derived, which is used as the driving force for sediment movement in most wind erosion models. The mast on which the anemometers are mounted should be put where it will measure a wind profile that may be considered representative for the study area. Precipitation should be measured with a tipping-bucket type rain gauge, which measures the total rainfall as well as the rainfall intensity. If the study area covers more than one field, several rain gauges should be installed, as the precipitation in semi-arid regions is generally very variable in space and time (Hoogmoed and Stroosnijder, 1984).

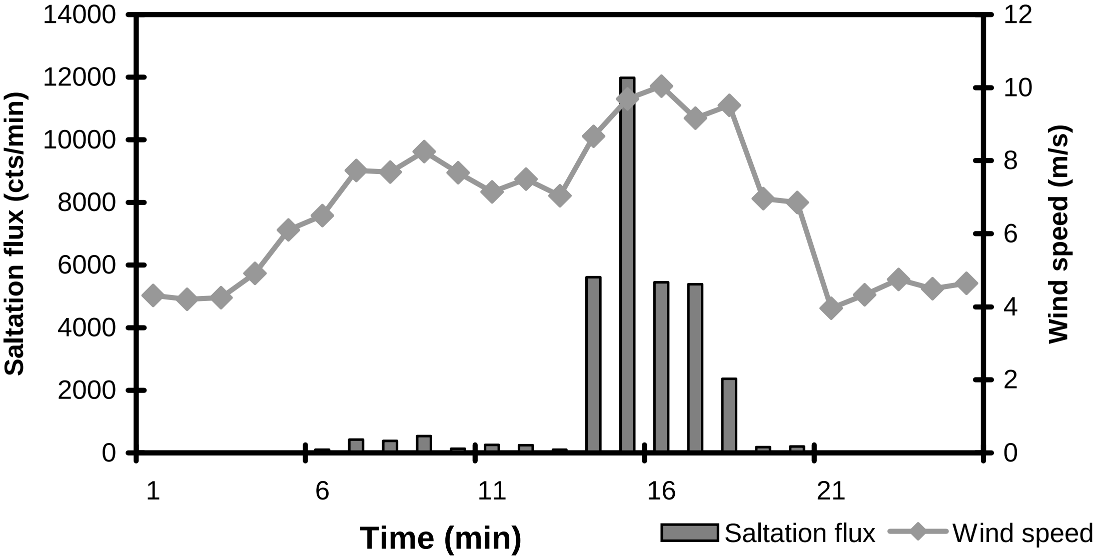

Figure 3) Average wind speed at 2 m and related saltation flux as recorded with the Saltiphone for a wind erosion event in the Katchari catchment (Burkina Faso) on 14 June 2001. The soil is a sandy Cambisol

At least two types of wind-blown particle samplers should be used. The first type is a sensor that continuously records saltation particle transport, e.g. the saltiphone. This sensor should be connected to the automatic weather station, to ensure continuous measurement during an event. The output gives the start, duration and temporal variability of saltation transport, which can be related to wind speed conditions and so allow threshold wind velocity to be determined (Fig. 3). It is best to install several saltiphones in the field, so that the spatial variability of the sediment fluxes can be determined.

The second type of catcher installed should catch saltation and creep-size material. Several catchers are needed. They should be put along the boundaries of the experimental area. If they are installed in a regular grid (but for this, there must be sufficient catchers and sufficient manpower) they will give information on the spatial variability of saltation and creep transport. An important consideration for selecting a catcher type is the sensitivity to splash erosion and thus the inlet area of the trap, many wind erosion events in semi-arid regions precede thunderstorms. Thus wind erosion may be immediately followed by very heavy rain. As wind speeds usually remain high at the beginning of the rainstorm, a lot of splash material can be trapped in the sediment catchers, and it is impossible to distinguish it from wind-blown material afterwards. If the catchers are not emptied after each event, sediment from various events accumulates. Data from the saltiphone can help in determining the contribution of each separate event.

A third type of equipment that might be needed is a dust sampler. The devices developed by Orange and Gac (1990) enable daily dust deposition to be measured. When these measurements are performed continuously over a period of at least a year, the contributions of dust deposition from the two different wind systems (the Harmattan and the monsoon) can be determined (Fig. 4). When nutrient budgets are calculated, this will be important since the dust from the Harmattan originates from the Sahara desert but the dust from the convective storms during the early rainy

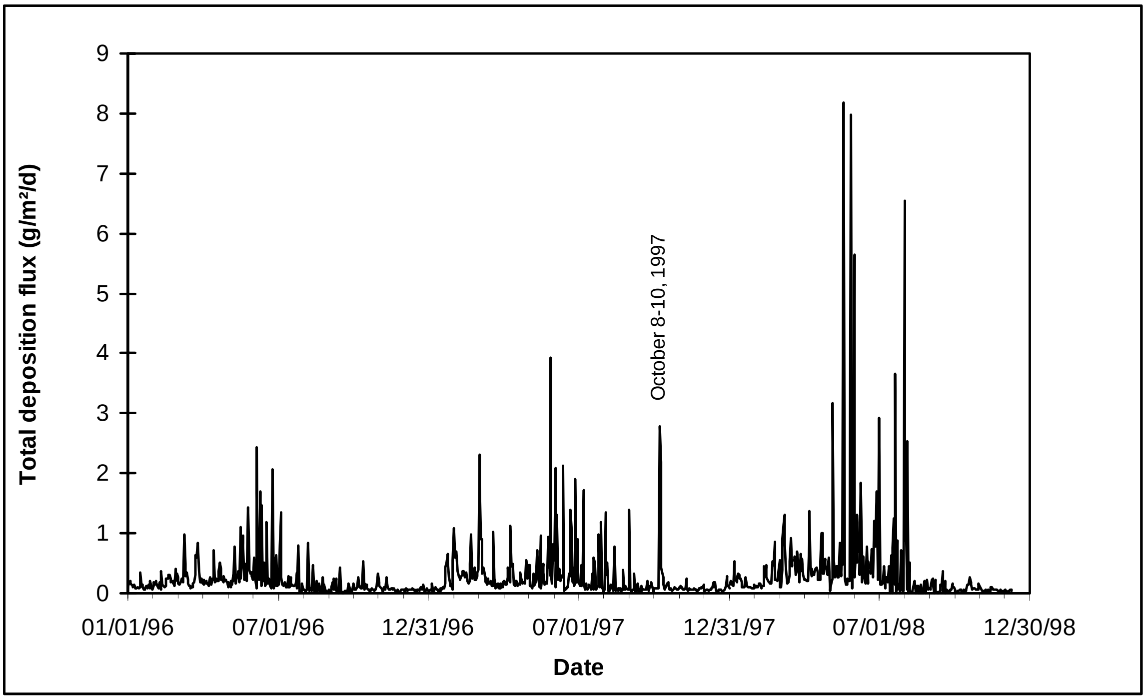

Figure 4) Seasonal trend of total mass deposition (g m^{-2} d^{-1}) during the period from 1996 till 1998 as measured by a passive CAPYR collector in a fallow area Banizoumbou, southwest Niger(reproduced with permission of Rajot, 2001) .

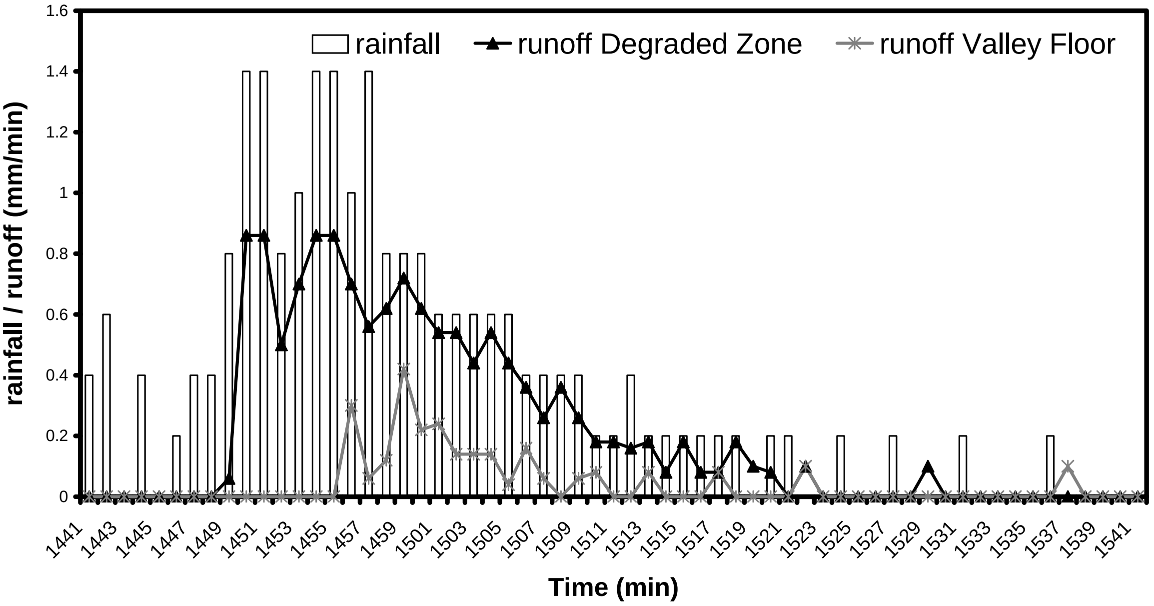

Figure 5) Rainfall and runoff intensity for two different geomorphologic units in the Katchari catchment for a rainfall event on 18 August 2000.

season is local. Therefore the nutrient contents of these types of dust differ (Herrmann *et al.*, 1994). The other instruments available to quantify dust or suspension transport include the wedge dust flux gauge (WDFG) of Hall *et al.* (1993). However, whether it is actually necessary to quantify suspension transport depends on the aim of the study. If the focus is on sand transport, for instance to elucidate dune formation, the suspended transport is not relevant. If a study aims at quantifying nutrient losses, it is necessary to quantify suspension transport, as this contains the highest concentration of soil nutrients (Sterk, *et al.*, 1996, Zobeck and Fryrear, 1986b). However, from measurements made in a single field, Sterk *et al.* (1996) concluded that the resulting nutrient fluxes moved by suspension are an order of magnitude lower than the saltation nutrient fluxes. For this reason it is better to measure nutrient fluxes in saltation transport rather than to measure nutrient fluxes in suspension transport. To quantify water erosion at field scale, USLE-type runoff plots should be installed to quantify runoff and sediment transport processes for the specific soil type. Several runoff plots may have to be installed if there are many different types of land use, soils, and slope classes in the study area. Moreover, for each condition, several plots need to be installed, as the output usually contains a large variation (Nearing *et al.*, 1999). When much maintenance and data collection are required, but time and labour are limited, a good option is to move the plots from unit to unit. This approach entails obtaining data from three of four rainfall events in one land use unit and then moving the plot to the next unit (Romero and Stroosnijder, 2002). This is an inexpensive and fast way of getting information on runoff from a large number of land use units. To get an impression of the response of the soil surface to the rain, measurements of runoff intensity can be compared with measurements of rainfall intensity. These measurements are important in water erosion modelling, since the moments of initiation and cessation of runoff are measured (Fig. 5). Splash cups should be installed to quantify the resistance of the soil to detachment by raindrop impact for the different surface types. In addition, splash boards (Poesen, 1986) should be installed to calculate net splash transport. In a semi-arid environment, where wind speeds may have a sufficiently large effect on splash direction, it is necessary not only to install the splash board upslope and down slope from the plot but also along the sides of the plot.

Data from the small USLE runoff plots can’t be extrapolated directly to the catchment scale. In runoff plots there is only erosion, and no sedimentation, but at catchment scale both occur. Therefore if the runoff plot data were directly extrapolated, erosion would be greatly overestimated. In order to be able to extrapolate, discharge and sediment concentration measurements must be taken at well-defined outlets (of the field or the catchment). The runoff plot data should be linked with field-scale or catchment-scale outlet data by means of detailed erosion surveys immediately after erosion events. These surveys can be made either by mapping the erosion and deposition features by hand (which is time consuming) or by mapping them from photos taken from a kite. The surveys give qualitative data on the spatial distribution of inter-rill erosion, rill erosion, gully erosion, and sedimentation. If possible, the amounts of erosion and sedimentation should be estimated by simply measuring the depth and width of rills and gullies, and the depth and area of sedimentation layers. The information obtained can be stored in a geographic information system (GIS), which is useful for modelling in a later stage.

To quantify total nutrient erosion, enrichment ratios (ER) for eroded sediments and nutrient content of runoff water should be determined. An ER is the ratio that indicates how much the sediment is enriched with a specific nutrient in comparison with the original soil. The runoff water should be captured and filtered over fine pore size filter paper. The filtrate should be analysed for solute nutrients. For wind erosion measurements at a field scale, measuring nutrient ER’s of sediment from saltation transport is recommended over measuring nutrient ER’s of sediment from suspended transport (Sterk et al, 1996). For water erosion ER’s should be measured from the sediment that is captured from the runoff plot and from the suspended load.

The transition from wind-driven sediment transport to water-driven sediment transport is an important moment. Generally the air is still filled with sediment, either in suspension or saltation mode. The suspended sediment contains a high concentration of nutrients. The suspended load that rains out the moment the rain starts can be captured with a wet-only rain gauge. The principle of this device is that it stays closed between rain events and opens automatically when rain starts (e.g. Galy-Lacaux, 1998). The measurement techniques described above are merely the same techniques that would be used when measuring either wind or water erosion alone. However, combining the measurements on one field gives a good impression of the impact of the separate processes. To get an idea of the total effect of both erosion processes you can use kite aerial photography after each event (Fig. 6). Using the resulting series of pictures, areas of erosion and deposition can easily be identified. To quantify total erosion and deposition the aerial pictures should be combined with field measurements of erosion and deposition (e.g. with erosion pins). Combining total erosion and deposition with the measured mass fluxes gives a total impression of the impact of each process separately and the combined effect of wind and water erosion.

Conclusion

Since in semi-arid environments both wind and water erosion are important and can occur almost simultaneously and to be able to get a good overview of total soil erosion in the area it is necessary to measure both processes at the same moment for the same area. Although the processes of wind and water erosion are similar in many ways, they behave differently with respect to topography. For water erosion, topography alone determines the direction of sediment movement. For wind erosion, the direction of sediment transport is determined by the wind direction, which might

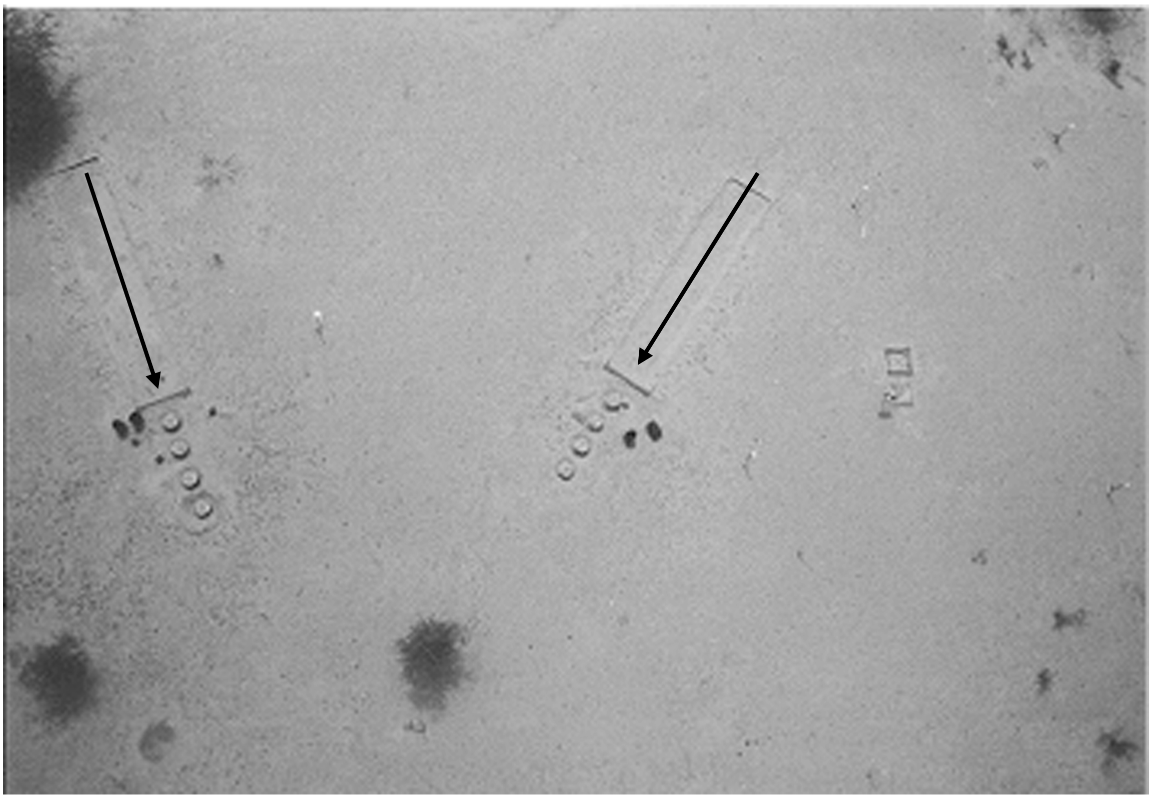

Figure 6) Aerial picture of the dune in the Katchari catchment (Burkina Faso) taken with a kite at a height of approximately 50 m. Length of the runoff plots in the picture is 20 m.

change from one event to another, or even during an event. Furthermore, the spatial pattern of erosion and deposition is determined by the spatial distribution of source material, soil erodibility factors and non-erodible roughness elements. This difference in the dependence on topography of the two processes makes it necessary to use different approaches to determine a mass balance for a certain area. For water sediments, whereas for wind erosion, the input and output of sediment are usually erosion, a mass budget is determined for an area such that there is only an output of quantified by measuring wind-blown particle fluxes.

A large range of quantification techniques is available for measuring wind erosion, water erosion, or both, either directly or indirectly. However, none of these techniques is standardised. Yet standardisation of quantification techniques, or at least standardisation of reporting, is necessary so that results can be compared and can be extrapolated to other regions and other studies.

For the simultaneous quantification of soil and nutrient erosion by wind and water, a number of measurement techniques at different temporal and spatial scales are necessary. To get a good insight into the interaction of both processes, it is advisable to start the research at the field scale. To obtain a complete insight into the processes at a research site, the research should include measurement techniques that quantify the impact of wind and water erosion separately and techniques that quantify the combined effect of wind and water erosion.

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Chapter 4

Spatial variation in wind-blown sediment transport in geomorphic units in northern Burkina Faso using geostatistical mapping

S.M. Vissser, G. Sterk and J.J.J.C. Snepvangers

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Spatial variation in wind-blown sediment transport in geomorphic units in northern Burkina Faso using geostatistical mapping

Abstract
Due to rapid population growth, farmers in northern Burkina Faso have started to cultivate areas less suitable for agricultural production. In fields, situated at various geomorphologic settings, erodibility is highly variable resulting in variable wind-blown sediment fluxes. Furthermore, at a field scale observations of wind-blown mass transport often show spatial variation.

This study examines the mass transport rates in three main geomorphic units in northern Burkina Faso and the spatial variation in mass transport in a single geomorphic unit. In the 2001 rainy season, wind-blown mass transport was measured on fields in the valley and on the dune and on a degraded plot in the Katchari catchment. Differences in total mass transport between geomorphic units are related to sediment availability in and around the research plots.

Geostatistical theory was applied to produce event-based maps of mass transport by stochastically simulating the spatial correlation structure. The conditionally simulated maps showed large spatial variation in mass transport. It is concluded that in the Sahelian region of northern Burkina Faso it will be useful to distinguish erosion and deposition areas in the field. So to be able to deal with spatial variation, a wind erosion model suitable for the Sahelian situation should at least have a spatial component. Furthermore, differences in intensity of sediment transport between geomorphic units indicate that the user should have information about the geomorphic settings of a field to be able to set the boundary conditions.

Introduction

The Sahelian zone of northern Burkina Faso has a population density of about 20-30 inhabitants per km^2. About 90% of the population lives in small villages and largely depends on subsistence agriculture (Thiombiano, 2000). The sedentary farmers often combine free-roaming cattle with rain-fed crop production. The major crop is pearl millet (*Pennisetum glaucum*), which is often intercropped with cowpea (*Vigna unguiculata)* or groundnut (*Arachis hypogaea*) (Sterk, 1997).

The soils, which have in general a sandy or sandy loam texture, are prone to crusting and hard setting, and have low water holding capacities (Payne *et al.*, 1990; Valentin, 1995).

The Sahel has a long dry season from October till May with the Harmattan winds blowing from the northeast, and a short rainy season, with south-western monsoon winds blowing from June till September. In the early rainy season, when rainfall comes with heavy thunderstorms, strong dust storms may develop. These events are usually short lived, 10-30 minutes, but may involve intense sediment transport (Sterk, 1997). Crop seedlings suffer from abrasion and burial in sand during these early rainy season events. Damage to the plants ranges from reduced or delayed growth and development to complete destruction of the crop (Michels *et al.*, 1995; Sterk, 1997). Apart from damage to the crop, wind erosion contributes to soil degradation by the loss of the nutrient-rich topsoil (Lal, 1988). Several researchers (Bielders *et al.*, 2002; Mainguet and Chemin, 1991; Sterk *et al.*, 1996) have shown that wind erosion is a serious threat for agricultural production in the Sahel and therefore wind erosion control is necessary.

Due to rapid population growth and continuing degradation of the soil, farmers in northern Burkina Faso have started to cultivate areas less suitable for agricultural production. Fields are situated in a range of geomorphic units ranging from dune complexes to valleys and pediplains (Thiombiano, 2000). Due to these different geomorphic settings and the large variety in field sizes and shapes, the erodibility of the different fields is highly variable, resulting in variable mass fluxes. Furthermore, within a field, observations of wind-blown mass transport often show spatial variation due to differences in erodibility determining factors such as soil characteristics, surface roughness, topography, vegetation, soil crusting and land management (Wilson and Cooke, 1980).

For successful application of wind erosion measures in the Sahel, a good insight into the effect of wind erosion on various geomorphic units is necessary. Furthermore, for future application and/or upscaling of wind erosion models it is necessary to understand the interaction between the various geomorphic units. For example, one unit might be the source of sediment for the other and with changing wind direction the first unit becomes a sink or merely a transportation zone. Little research has been done so far on spatial variation in mass fluxes at and between different geomorphic units in the Sahel. Sterk and Stein (1997) introduced a method to map spatial variation at a field in Niger using kriging and stochastic simulation. Bielders *et al.* (2002) measured in- and out-going fluxes on traditionally managed cultivated fields and adjacent native vegetation in Niger.

The present paper examines differences in mass transport rates between three main geomorphic units and within one unit in northern Burkina Faso.

Materials and methods

Study area

During the early rainy season of 2001 field data for wind erosion events were measured, in the Katchari catchment in northern Burkina Faso (14°00”N, 0°05”W). The Katchari catchment covers an area of 12 km^2 and is situated in the Seno province, 11 km west from Dori, the provincial capital (Fig. 1). The climate is characterised by a short rainy season of 3 to 4 months, starting in June with a maximum rainfall in August. Mean annual precipitation is 480 mm, but is highly variable from year to year. The first rains of the season generally come from the East and are often preceded by short (10-30 minutes) windstorms. The strong winds blowing over the seasonally bare, unprotected fields may cause severe wind erosion.

The sedentary farming system in the area combines pastoral activities with rain-fed agriculture. The main crop is pearl millet (*Pennisetum glaucum*). Sowing is generally done after the first good rain event in the early rainy season. Field data of wind erosion events were collected within three geomorphic units; a degraded plot on a pediplain, a field in a valley and a field in a dune complex. Table 1 shows the soil types and texture of the top 5 cm soil for each unit.

In the pediplain a wide variety of surface types ranging from completely bare areas with an erosion or gravel crust to areas with the characteristic arboraceous and/or shrub land steppe, with small trees and shrubs exists.

Table 1) Soil class and texture on three geomorphic units in the Katchari catchment in northern Burkina Faso. The standard deviations are shown in brackets.

	Soil type	% Sand	% Silt	% Clay
Degraded site	Eutic Cambisol	59 (1.5)	19 (5.0)	22 (3.7)
Valley	Arenic Cambisol	79 (6.5)	16 (6.2)	5 (0.8)
Dune	Arenosol	84 (3.5)	13 (3.0)	3 (0.9)

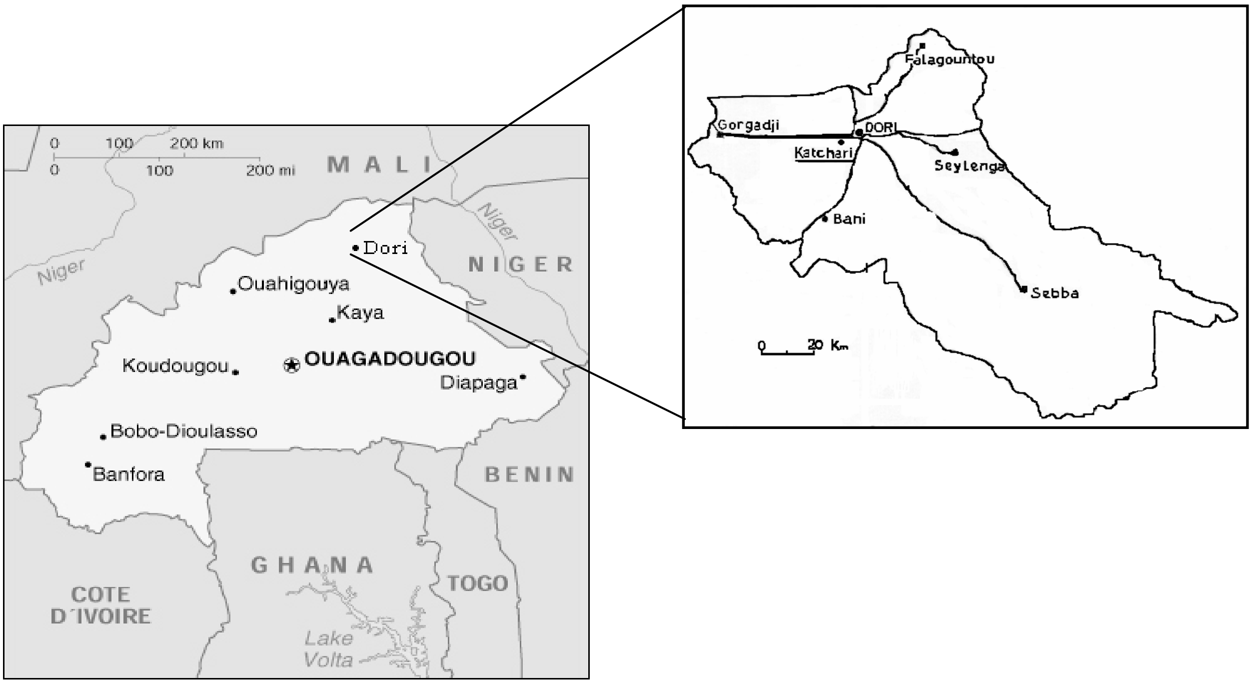

Figure 1) Location of the study area in northern Burkina Faso.

The mainly annual grasses tend not to form a continuous soil cover, except for certain areas such as clayey soil depressions (Claude *et al.*, 1991; Thiombiano, 2000). The pediplain was generally used for grazing and for woodcutting, but now some areas are cultivated. It was chosen to perform measurements on a degraded plot with a gravel crust on the pediplain, since this is the type of surface often seen at the edges of cultivated areas. The loose gravel coverage ranges from 40% to 80%. Under the gravel coverage there is a well-developed erosion crust (Valentin and Bresson, 1992). The research plot is bare except for some trees in southeast, where the degraded plot merges into steppe and the southern and south-western part where the degraded plot borders the valley (Fig 2A).

The valley consists of a deeply incised ephemeral river bordered on each side by a band (± 50 m) with high vegetation cover (60-80%) and several abandoned riverbeds. The annual grasses form a continuous soil cover (Claude *et al.*, 1991; Thiombiano, 2000). The area directly next to this band with high vegetation cover is often cultivated and is characterised by a rather high tree cover (± 20%) and runoff in the form of sheet flow in the direction of the main river. The research plot is situated 350 m south from the degraded plot and cultivated with millet. Trees and shrubs are scattered over the area with an average coverage of 18% (Fig. 2B). The top 20 cm of the soil is classified as loamy sand and is prone to crust formation by high intensity rainfall in the early rainy season.

The crust is generally broken twice in the rainy season when annual herbs are removed by hoeing. However, the area with the still depositional crust in the south-western part of our research plot was not cultivated and so this crust was not broken.

The dune in the Katchari catchment is part of an extensive sand dune system, which is more than 40.000 years old (Delfour and Jeambrum, 1970). Almost the whole dune system is cultivated with pearl millet. The research plot on the dune is situated approximately 2300 m west of the degraded area. As for the soil of the valley, the soil of the dune is prone to crust formation. The natural vegetation on this plot consists of trees indicating the borders; however these trees do not form a continuous row as in a wind barrier. Several shrubs can be found inside the field, but natural vegetation cover of trees and shrubs does not exceed 8% (Fig. 2C). As for the valley, annual herbs are

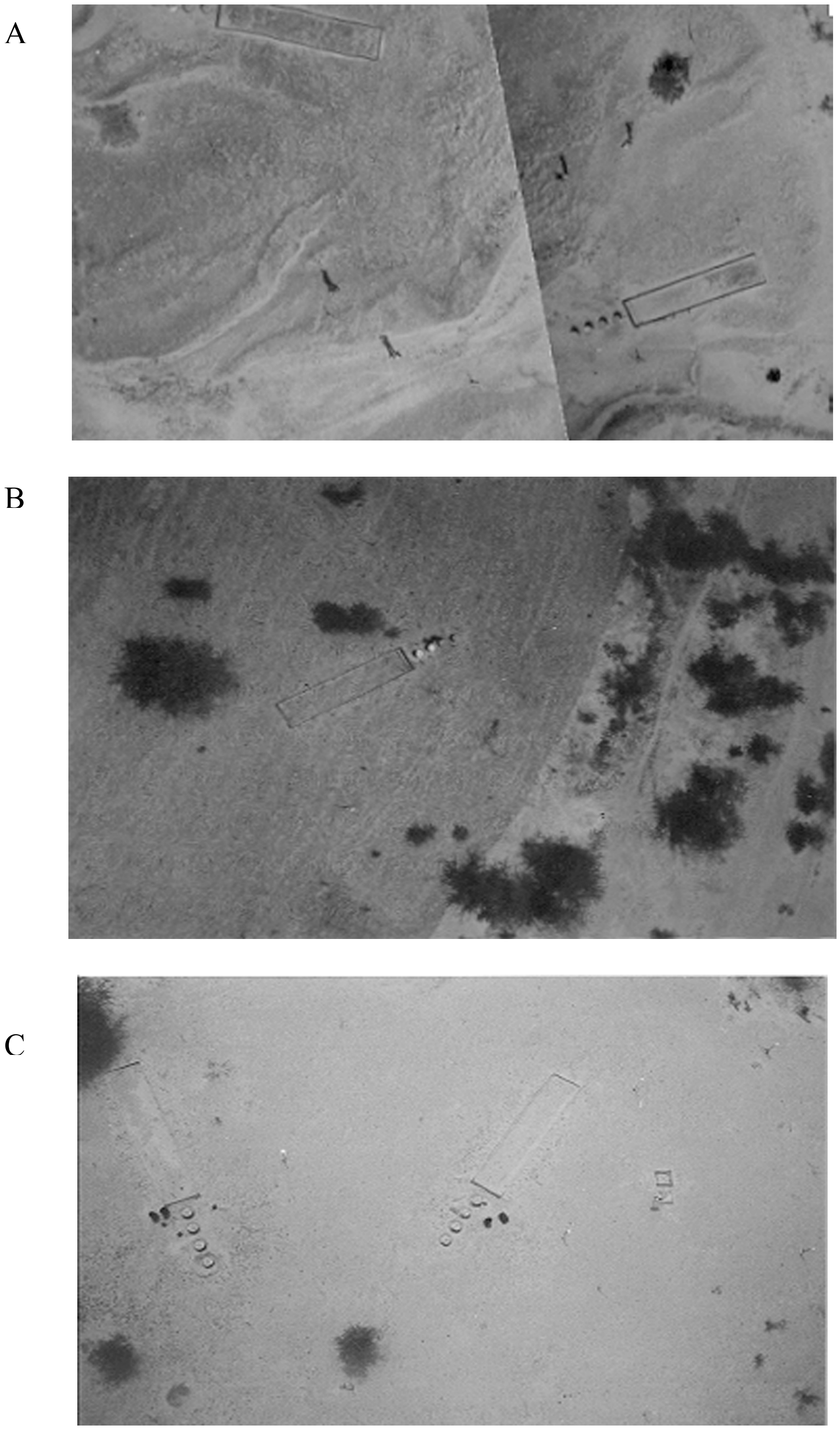

Figure 2) Arial photos of (parts of) the research area at the degraded site (A), the valley (B) and the dune (C). Pictures are taken in the early rainy season, from a height of approximately 60 m by making use of a kite. The runoff plots at the pictures have a length of 10 m.

removed twice in the rainy season by hoeing. The field is fertilised by depositing manure and household-ashes in high concentrations at small areas.

All research plots are characterised by an undulating topography. Maximum height differences at the dune were ≈0.5 m. At the valley and the degraded plot the distances between depressions and crests ranged from 10 to 40 m, with maximum height differences of ≈1 m.

Instrumentation and methods

Fully automatic weather stations were installed on the dune and the degraded plot. Since the research plot in the valley is situated about 350 m apart from the degraded plot, weather data for the degraded plot was also used for the valley. Wind speed was recorded with a Vector anemometer at one-minute intervals at a height of 2 m above the soil surface. The range of wind speeds that could be measured was 0.25-75 m s^{-1} with an accuracy of 1%. Wind direction was measured with a Vector windvane at one-minute intervals at a height of 2 m above the soil surface. The windvane had an accuracy of ± 2 degrees at wind speeds above 5 m/s. Furthermore, on all plots an automatic rain gauge (tipping bucket) was installed to determine the exact moment of the onset of rainfall.

Saltation transport was measured with saltiphones. The output of the saltiphone in counts per unit of time is a relative measure of the saltation flux at the height of the microphone. Due to its fast response the saltiphone is ideal for indicating moments of initiation and cessation of mass transport and therefore particle transport duration can easily be determined from saltiphone data. Spaan and Van den Abeele (1991) give a complete description of the device.

On the dune and the degraded plot two saltiphones were installed around the weather station. The height of the centre of the microphones above the soil surface was 0.12 m. The saltiphones were connected to a pulse count expansion (SM-SW8A) on a CR10 datalogger. No saltiphones were installed in the valley. However, observations showed that when sediment was being transported at the degraded site, sediment transport also occurred at the valley, so it was assumed that the duration of mass transport at the valley was at least equal to the recorded duration on the degraded plot. Both rain gauges and saltiphones recorded at one-minute intervals.

In this study the Modified Wilson and Cooke (MWAC) sediment sampler was used for measuring the horizontal sediment flux. Wilson and Cooke (1980) first developed a wind erosion sampler that traps wind-driven saltation and suspension material. Each trap consists of a plastic bottle with an in- and outlet glass tube. The traps are mounted to a frame of copper tubes with a wind vane so that the traps rotate about a central pole and it is assured that the inlet tubes point into the wind. Wind-borne particles enter through the inlet, air escapes through the outlet and the sediment stays behind in the bottle (Sterk and Raats, 1996). The glass in- and outlet tubes of the plastic bottles have an inner diameter of 8 mm, resulting in an inlet area of 50.3 mm^2. Sterk (1993) tested and calibrated the MWAC-catchers in a wind tunnel with Sahelian sand and found an average overall trapping efficiency (η) of 0.49 (from 12 runs with wind speeds ranging from 9.9 to 11.5 m s^{-1}). Since the event and soil characteristics of the study of Sterk (1993) are comparable with this study, the trapping efficiency of 0.49 is used in this study.

From the weights of the trapped materials, the area of the opening of the inlet tube and the event duration, mean horizontal mass fluxes q (z) (kg $m^{-2}s^{-1}$) at height z (m) can be calculated. According to Vories and Fryrear (1991), the relationship between horizontal mass flux and height can be described by:

$$q(z) = ez^{-b} + c\exp(-dz) \qquad \text{(eq. 1)}$$

where q (z) is the mass flux at height z and b, c, d and e are regression coefficients. To overcome problems with the first term (going to infinity when z approaches zero) and problems with having too many coefficients to fit the equation, (Sterk and Raats, 1996) introduced a constant length (ε) and rewrote eq. 1 as:

$$q(z) = e'(z+\varepsilon)^{-b'} + c\exp(-dz) \qquad (\varepsilon > 0) \qquad \text{(eq.2a)}$$

which can be rewritten as:

$$q(z) = e''(z'+1)^{-b'} + c\exp\left(-\frac{z}{\beta}\right) \qquad (\varepsilon > 0) \qquad \text{(eq. 2b)}$$

where $e'' = e'\varepsilon^{-b'}$ and $z' = z\varepsilon^{-1}$. Both c and e'' have dimensions of mass flux (kg m^{-2} s^{-1}). The sum of the coefficients e'' and c represents maximum mass transport at z=0. The coefficient b' (dimensionless) and the length scale β (m) can be interpreted as measures of the decrease in mass flux with height. Sterk and Raats (1996) tested Equation 2 for various values of ε and concluded that setting ε at 1 m was a reasonable assumption.

The NONLIN module of the SYSTAT statistical package that makes use of a quasi-Newton minimization method (Wilkinson, 1987), was applied for fitting equation 2 through the measured mass fluxes. The curves were not extrapolated beyond 1m, since no observations above this height were available. Integration of equation 2 across height (z=0 to z=1m) resulted in measured mass transport rates q (kg $m^{-1}s^{-1}$) at the point of sampling. To obtain total mass transport rates q_t (kg $m^{-1}s^{-1}$), q was corrected for the overall trapping efficiency (η=0.49). A value for total mass transport Q (kg m^{-1}) was obtained by multiplying q_t by the event duration. Q is equivalent to the mass of soil passing a strip of 1m width perpendicular to the mean wind direction (Sterk and Raats, 1996).

On each geomorphic unit an experimental plot of 80 by 80 m was selected and instrumented with 17 MWAC sediment samplers. At each sampler 5 traps were attached and the intended measurement heights were 0.05, 0.12, 0.19, 0.26 and 0.75 m above the soil surface, but these changed (-50 to +20 mm) after soil surface changes. Due to the placement height of the traps, creep particles were not trapped, and the trapped material were a mix of saltation and suspension. The samplers were regularly distributed so that in each main wind direction a line of five samplers was erected (Fig. 3). The samplers were 15 m apart along a line. Since actual sediment transport at the geomorphic unit was measured, the natural vegetation was not removed before placement of the samplers. Clear, non-eroding boundaries could not be identified at the selected plots and thus saltation and creep particles could freely enter the field.

Stochastic spatial modelling

Due to difficulty of measuring the distribution of all factors that account for spatial variation in wind-blown sediment transport, Sterk and Stein (1997) developed a method for sediment transport mapping. They produced event-based maps of sediment transport in a field in southwest Niger by making use of geostatistics. The maps gave a good overview of the spatial distribution of measured sediment transport and, when combined with maps of soil erodibility factors gave a good insight in the erosion hazard in the area (Sterk and Stein, 1997). Chappell *et al.* (2003) applied the method recently for a 25 km^2 playa in western Queensland, Australia. They found that this method not only gives good insight in the spatial distribution of sediment transport, but also provides further insight into the influences of erodibility and erosivity upon wind erosion.

Geostatistical theory uses the concept of spatial correlation, which assumes that observations of a spatial variable close to each other are more similar than observations at a larger distance. In geostatistics the variogram is used to model this spatial correlation. In a variogram the distance between paired measurement points is plotted against their semivariance. A common rule in geostatistics is that at least 30-50 measurements are needed to obtain representative variograms (Goovaerts, 1997).

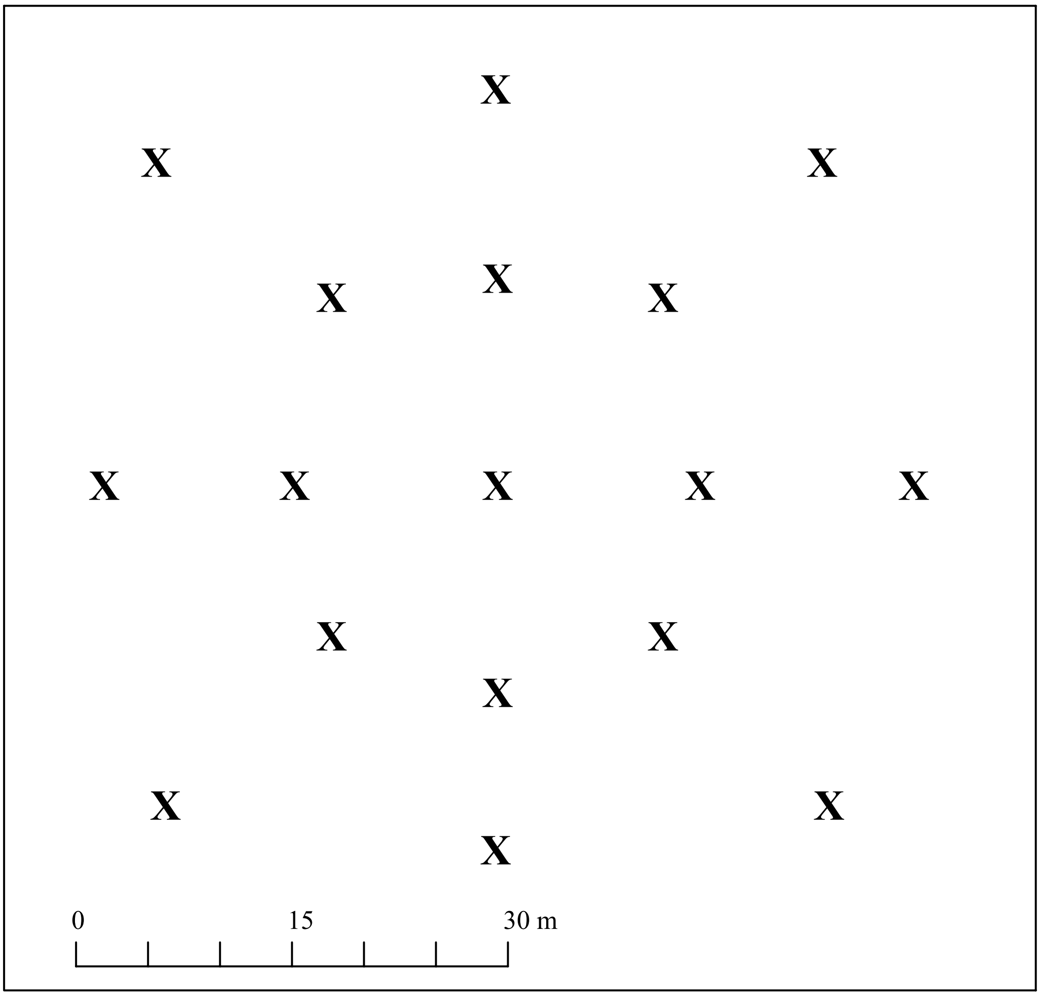

Figure 3) Spatial distribution of MWAC sediment samplers on each plot.

In this study, only 17 observations per event for each plot were available. Therefore, following the example of Sterk and Stein (1997), the analysis of the spatial variability was extended into the space/time domain by combining the observations of all events in one overall variogram per plot. This implies the assumption that sediment transport at the research plots can be characterised by a spatial correlation structure that is similar for each individual event; therefore mass transport for different events can be characterised by the same variogram. However, it does not mean that the spatial distribution of mass transport was the same for each event.

The mass transport values are measured on the three plots for n successive events, denoted by $Q_{ij,}$ with $i = 1, \ldots 17$, being the spatial location (Fig. 3), and $j = 1,\ldots n$, being the event number. Since we deal with events of variable mass transport intensity and the range of spatial variability strongly depends on the event mean mass transport, the events are standardized using the mean mass transport of the events and equation 3:

$$Q'_{ij} = \frac{Q_{ij} - \mu_j}{\sigma_{sj}} \qquad \text{(eq. 3)}$$

Where Q'_{ij} is the standardized mass transport at observation location i for event j, and μ_j is the events mean mass transport and σ_{sj} is the events standard deviation. As the events are mutually uncorrelated, we assured that only observations of the same event could form a variogram pair by using the following equation:

$$\hat{\gamma}(h) = \frac{1}{2n(h)} \sum_{j=1}^{j=n} \sum_{i=1}^{n_j(h)} (Q'_{ij} - Q'_{i+n,j})^2 \qquad \text{(eq. 4)}$$

where Q'_{ij} and $Q'_{i+n,j}$ denote the ith pair of standardized observations at time j, separated by the vector h. In total $n_j(h)$ pairs are available for variogram estimation. In this way each pair of observations within the same event contributes to estimate the standardised variograms, irrespective of the time that the measurements were made. The variogram can be modelled using three parameters: the range, the sill and the nugget (Webster and Oliver, 1992).

Several model forms are available for modelling a variogram. Here we used the spherical variogram model, which is defined as:

$$g(h) = \begin{bmatrix} C_0\left[1-\delta_k(h)\right] + C\left(\dfrac{3h}{2a} - \dfrac{h^3}{2a^3}\right) & 0 \le h \le a \\ C_0 + C & h > a \end{bmatrix} \qquad \text{(eq. 5)}$$

where the Kronecker delta function, $\delta_k(h)$, is 1for h = 0 and vanishes elsewhere. The parameter C_0 is the nugget constant, C is the sill parameter and a is the range parameter of the spherical variogram model. The parameters C_0, C and a were estimated with non-linear regression.

Cross-validation is performed to test the variogram model for self-consistency and lack of bias (Burrough and McDonnell, 1998). During cross-validation the variogram model is used to re-predict actual observations from neighboring observations. It involves computing the moments of the distribution of $(\hat{t}(x_i) - t(x_i))$ for all data points, when each data point is successively left out and predicted from the rest of the data (with $\hat{t}$ being the estimated value of data point t when t is left out and predicted). The T score is a measure for the correctness of the variogram model and is calculated as follows (Burrough and McDonnell, 1998):

$$T_{score} = \frac{Q_{pij} - Q_{oij}}{\sigma_{pij}} \qquad \text{(eq. 6)}$$

in which Q_{pij} the predicted value of mass transport, Q_{oij} is the observed value of mass transport and σ_{pij} is the prediction standard deviation. With a perfect variogram model the mean cross-validation T score should be 0 with a standard deviation of 1.

To obtain spatial maps of windblown mass transport several geostatistical interpolation techniques are available. Kriging interpolation methods provide each cell with a local optimal prediction and a standard deviation that depends on the variogram and the spatial configuration of the data set (Burrough and McDonnell, 1998). Kriging provides best linear unbiased estimates for mass transport at each unsampled location and is therefore suitable for calculating net soil losses from the plot (Sterk and Stein, 1997). However, in kriging details and extreme values of the original data set will be smoothed out. This is not the case with conditional stochastic simulation. Since we are not only interested in differences in mass transport between geomorphic units but also within a single geomorphic unit, the overall standardised variogram is used in conditional stochastic simulation, with the gaussian simulation technique. In conditional stochastic simulation, simulated values at x grid cells will have the same mean, variance, histogram and variogram as the original set of observations. The simulation is called conditional because the measurement values are used as a stable boundary condition during simulation. Extreme values of mass transport, which create most soil and crop damage, will be more distinct in maps provided by conditional simulation (Sterk and Stein, 1997). The standardised, conditionally simulated maps are transformed in actual mass transport maps using equation 3.

Multiple conditional simulated maps of one event will be different from each other, except at the measurement locations. The differences among the realisations provide a measure of spatial uncertainty (Deutsch and Journel, 1992; Sterk and Stein, 1997). For each event 10 simulations were made and the correlation between all possible pairs was determined from all simulated values of each realisation. For a certain event 45 correlation coefficients were calculated and the average correlation coefficient was determined. All geostatistical operations were carried out using the geostatistical software package GSTAT (Pebesma and Wesseling, 1998).

Results and discussion

In the rainy season of 2001 eleven wind erosion events occurred. Generally, the first rains come from East. However, measured wind direction can be variable, depending on the location relative to the centre of the storm (Sterk, 1997), and may vary during the event while the storm passes by. The wind direction during our sampled events varied from North to South, average wind speed ranged from 7 to 11.9 m s^{-1} and the duration ranged from 14 to 43 minutes (Table 2). Generally, average wind speed on the dune was higher than average wind speed at the degraded plot indicating a larger fetch at the dune. Furthermore events on the dune lasted longer than the events on the degraded plot.

Table 2) Date, duration and the average wind speed (U) at 2 m. and wind direction at the degraded plot and the dune in the Katchari catchment, Burkina Faso, 2001 rainy season.

Date	Dune			Degraded plot		
	Duration min	U m s^{-1}	wdir	Duration min	U m s^{-1}	wdir
20 May	27	7.7	N	27	7.7	N
22 May	26	8.6	S	26	8.6	S
3 June	38	7	SE	14	7.2	SE
9 June	36	9.3	NE	21	8.8	ENE
19 June	40	8.5	E	40	8.5	E
22 June	21	11.8	E	19	9.2	E
29 June	37	8.6	N	37	7.5	N
3 July	20	7.5	N	19	7.4	N
10 July	20	9.5	SE	22	9.0	SE
11 July	43	9.5	NE	38	8.4	NE
13 July	26	9.9	NE	25	8.2	NE

Table 3) Summary statistics of windblown mass transport during 11 wind erosion events in 2001 rainy season at the valley plot, the dune plot and the degraded plot in the Katchari catchment, Burkina Faso. $\overline{Q}$ =Mean mass transport (kg m^{-1}), σ = standard deviation (kg m^{-1})

Date	Valley			Dune			Degraded		
	$\overline{Q}$	Range	σ	$\overline{Q}$	Range	σ	$\overline{Q}$	Range	σ
20 May	32.6	4.6-75.6	19.3	49.6	4-57.7	61.2	-	-	-
22 May	88.3	19.9-169.9	41.9	72.9	31.1-120.9	72.9	13.6	4.9-25.8	6.5
3 June	20.5	1.4-47.9	13.7	59.4	26.6-59.4	2.8	4.6	1.6-16.3	3.5
9 June	54.8	19.0-122.9	31.5	119.1	52.7-206.2	50.7	12.2	5.5-29.8	6.2
19 June	43.8	12.9-129.3	26.1	136.3	47.1-269.4	68.0	50.6	21.7-109.1	21.1
22 June	56.1	14.8-157.8	33.7	100.7	8.1-182.8	47.9	43.4	9.8-96.2	25.5
29 June	17.8	5.3-43.1	11.7	53.6	12.9-74.2	17.7	10.6	2.1-38.4	9.4
3 July	51.0	17.2-84.2	23.7	40.7	8.5-87.7	26.9	15.7	4.0-34.7	8.0
10 July	51.0	13.8-141.2	30.3	69.3	44.5-113.8	21.4	28.6	6.6-103.3	21.7
11 July	8.4	1.3-16.9	4.5	36.1	5.8-77.9	23.0	13.7	6.7-32.5	6.3
13 July	47.3	14.2-102.8	27.7	40.9	9.4-69.2	17.3	49.2	19.5-96.1	22.0

On 20 May the samplers on the degraded plot were not functioning well, therefore these measurements were not analysed. In terms of total mass transport we find the events were very different in magnitude (Table 3). The events of 3 June, 29 June and 11 July can be classified as weak, the events of 9, 19 and 22 June can be classified as strong and the other events as average. Average mass transport measured with the same type of catcher by Sterk and Stein (1997) in Niger was of the same order of magnitude as our measurements and ranged from 14.2 to 149.9 kg m^{-1}.

Most mass transport occurred on the dune, then on the valley and least mass transport occurred on the degraded plot. For all events the range in mass transport was large in comparison to the mean, indicating that mass transport is indeed variable in space (Sterk and Stein, 1997).

Measured mass transport of the three plots was standardised with equation 3 and then used for variogram modelling using the spherical model of equation 5. Then for each variogram cross-validation was performed and the T-score was calculated. The model parameters of the overall variograms and the cross-validation results can be found in Table 4. The valley variogram showed only noise, so no spherical model could be fitted. Comparing the parameters of the dune and the degraded plot, it is clear that for both plots the nugget to sill ratio is very high, indicating a large contribution of the short distance variability for both plots. Furthermore the range value of the degraded plot is much larger than for the dune plot. This can easily be explained by the lack of residue cover, the more homogeneous crusting pattern and the lack of vegetation at the degraded plot.

Sterk and Stein (1997) found smaller nugget/sill ratios (0.01) at their site in Niger. This can be explained by the fact that they performed their experiment at a more or less homogeneous plot, whereas our research has been performed under natural conditions, causing a larger spatial variability in soil management, vegetation cover and soil crusting. Therefore the variation due to spatially non-correlated sources at our plots is rather large resulting in larger nugget/sill ratios.

Table 4) Parameters of the standardized spherical variogram model and the results of the cross-validation for the valley, the degraded plot and the dune in the Katchari catchment, Burkina Faso.

Plot	C_0	C	*a*	Total mean T	Total st-dev T
Valley	0.9	-	-	0.16	0.75
Degraded	0.4	0.7	63.8	0.07	0.9
Dune	0.3	0.7	24.4	0.13	0.8

The cross-validation of the variogram of the degraded plot was good, but for the dune and the valley the cross-validation was less good. This means that the variograms of the valley and the dune are weak. One way to obtain better variograms is to carry out more, at least 50 but preferably 100, measurements per event (Webster and Oliver, 1992). In wind erosion, sampling at such a high density is usually not done because of the high costs of equipment and labour. Furthermore, such a high density of samplers will probably affect the wind field in such a way that no realistic patterns of erosion and deposition will be measured. Another possibility to obtain better variograms is to use a nested sampling strategy. Chappell *et al.* (2003) applied an unstratified nested sampling approach with 40 samplers at a 25 km^2 playa in western Queensland, Australia and successfully produced variograms. Especially for a heterogeneous area such as the plot of the valley, where crust development and vegetation cover have a major influence on mass transport, a nested sampling strategy, taking into account the spatial variation of the erodibility of the soil surface, might be useful for obtaining better variograms.

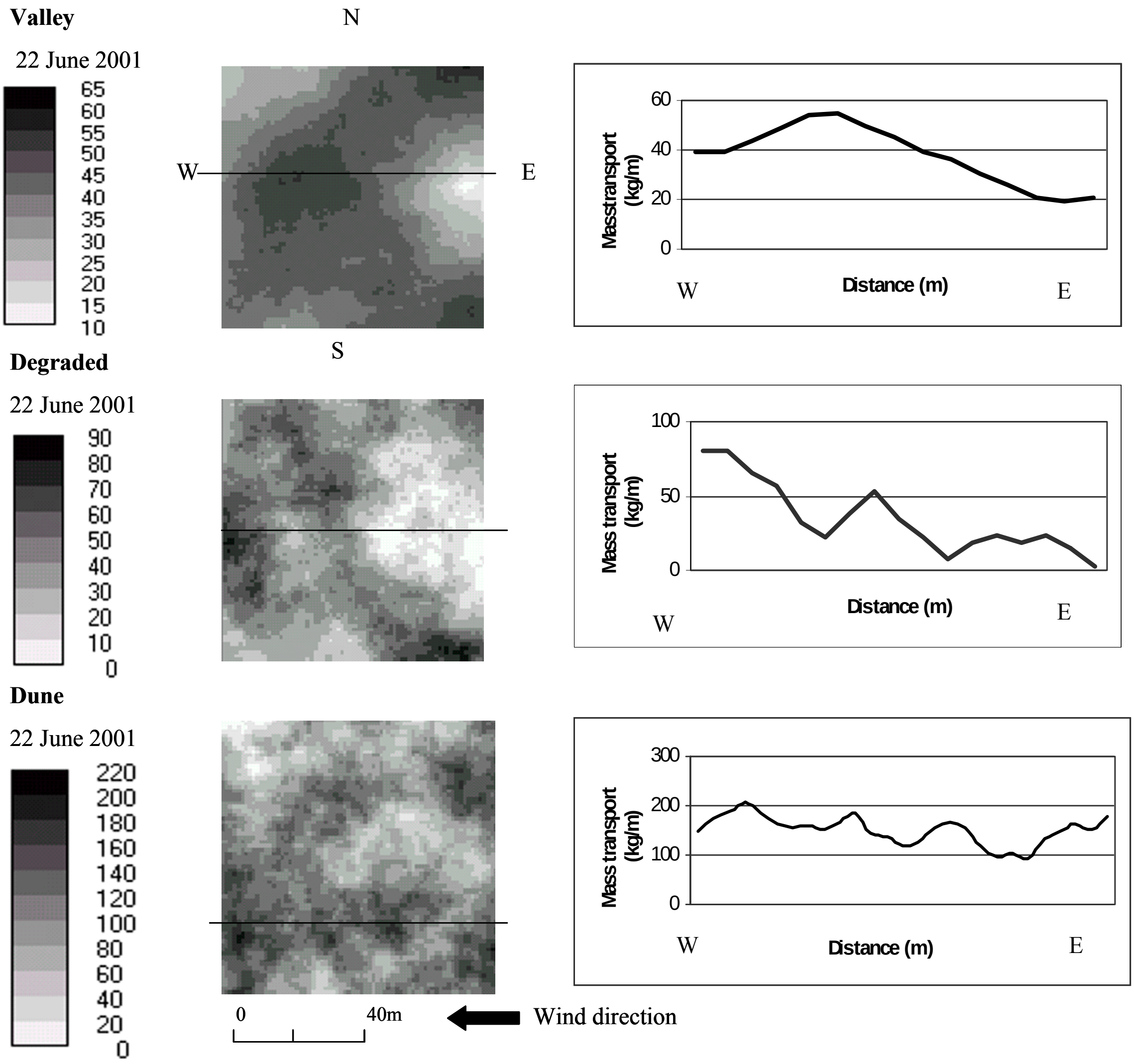

Figure 4) Maps and transects of mass transport for the wind erosion event of 22 June 2001 on the valley, dune and degraded zone in the Katchari catchment, Burkina Faso. Maps are produced by stochastic simulation with GSTAT. Black lines indicate location of transect. Transects should be read along the wind direction, positive gradients indicating erosion, negative gradients indicating deposition.

Table 5) Correlation coefficients calculated from 10 realizations of conditional simulated maps of wind-blown mass transport for 11 events in the 2001 rainy season at the valley plot, the dune plot and the degraded plot in the Katchari catchment, Burkina Faso.

Date	Valley	Dune	Degraded
20 May	0.16	0.56	-
22 May	0.32	0.26	0.40
3 June	0.12	0.25	0.55
9 June	0.30	0.32	0.52
19 June	0.10	0.31	0.36
22 June	0.30	0.43	0.58
29 June	0.14	0.21	0.48
3 July	0.19	0.50	0.52
10 July	0.12	0.51	0.64
11 July	0.17	0.31	0.51
13 July	0.11	0.34	0.42

Despite the weak variograms, conditional stochastic simulation is performed using the standardised variograms. The standardised, conditional simulated maps were transformed in actual mass transport maps using equation 3. Figure 4 shows one realisation of the event of 22 June for each research plot. In stochastic simulation, reproducing the variation that was present in the original observations is more important than the local best estimate. Maps produced by stochastic simulation emphasize the strong variation in mass transport across short distances (Fig. 4). Occurrence of erosion or deposition can be distinguished from the plot by following downwind gradients. Positive gradients (from low to high values) are associated with erosion, negative gradients (from high to low values) with deposition and zero gradients with transport only. Since conditional simulation provides different realisations for each simulation of an event, the correlation between maps of 10 simulations of one event was calculated (Table 5). Correlation coefficients for the valley plot were extremely low. This is due to the variogram for the valley, which showed only noise. So even though we can produce maps with conditional simulation, the spatial uncertainty is so high that one can’t base any conclusions on these maps. Correlation coefficients for the plot on the dune and the degraded plot are for several events high enough ($r^2 > 0.5$) to assume that the simulated patterns of mass transport represent the real, unknown sedimentation pattern.

Sterk and Stein (1997) found that their 21 sediment samplers were sufficient to characterise the spatial variation of mass transport in their experimental plot. In our case only 17 sediment samplers were available and even though we managed to produce maps with patterns of mass transport, 17 samplers was not in every case sufficient. The variograms of the valley and dune were weak, and even in simulations with the somewhat stronger variogram of the degraded plot, correlation coefficients were sometimes low. Therefore we suggest that for relatively complex fields more samplers and a stratified sampling scheme as suggested by Chappell *et al.* (2003) should be used.

For all but two events, average mass transport at the dune plot was the highest, then at the valley plot and least mass transport generally occurred at the degraded plot. Differences in intensity in mass transport are, apart from differences in tree and shrub cover, most probably also related to sediment availability at and in the surroundings of the research plots. On the degraded plot the availability of sediment for transport was close to zero, whereas on the valley plot and the dune plot sediment availability was high. The differences in intensity of mass transport between the dune plot and the valley plot can be explained by the surroundings. The field in the valley is bordered by a band with a high vegetation cover next to the river and on the other side by a degraded area. From neither direction high sediment input into the field can be expected. The fetch of the wind in the valley is low, resulting in possible lower mass transport fluxes. Fields with the same surface characteristics as previously described for the dune border the dune plot. In this area the wind has a longer fetch and therefore a high sediment input into the field can be expected, resulting in possible higher mass transport fluxes. Bielders *et al.* (2002) measured soil mass balances over a field and in an adjacent bush fallow. Their results indicate that sediment fluxes in a cultivated field increased linearly over distances up to 76 m and 89% of the deposition occurred in the first 20 m of the bush fallow. This emphasizes the importance of fetch length and the boundary effect.

For protecting crops against the scouring effect of windblown sediment it suffices to know where most sediment transport occurs. However high average mass fluxes do not necessarily mean high erosion rates. When incoming mass fluxes are close to the transport capacity of the wind, high fluxes will be measured but hardly any erosion will occur. To obtain an impression of erosion rates on a field one has to compare in- and out-coming sediment fluxes. However, in Sahelian fields strong variation in mass transport fluxes occurs (Fig. 4). The large range in measured mass transport fluxes (Table 3) confirms this conclusion; therefore it is not enough to simply compare in- and out-coming fluxes to obtain an idea of erosion rates. Especially in the Sahel, it is useful to distinguish erosion and deposition areas in the field (Sterk and Stein, 1997). An important consequence of the previous conclusions is that in wind erosion modelling in the Sahel one can't suffice with describing soil loss per unit area as is traditionally done. A wind erosion model that is applicable to the Sahelian situation should at least incorporate a spatial component to be able to deal with spatial variation and when modelling at the scale of a field, one should have information about the geomorphic settings of the field and its surroundings to be able to set the boundary conditions (e.g. input sediment possible, limited or not possible). Furthermore, when modelling on a catchment scale, fetch length and transition zones from the one geomorphic unit to the other should be incorporated into the model. The above conclusions account not only for Sahelian situations. McTainsh *et al.*, (1999) showed that average wind erosion rates vary on different land types at their research site in the Simpson Desert Channel Country in Australia. Furthermore they indicated that event-based dust load models could significantly be improved using an erodibility index for different land types.

Conclusion

Mass transport rates at the dune, valley and the degraded plot were measured with MWAC-catchers. Highest sediment fluxes were measured at the plot on the dune and least mass transport was measured at the degraded plot. Differences in intensity of mass transport between the three geomorphologic units were, apart from a different vegetation cover, most probably related to the sediment availability at and in the surroundings of the research plots.

To obtain an indication of the spatial variability in mass transport at a single geomorphologic unit, maps of wind-blown mass transport were produced for each plot from 17 observations per event with conditional simulation. Conditional simulation requires information about the spatial structure of mass transport, which was modelled with a variogram model. To have sufficient data for variogram modelling, data from the 11 events were treated as independent temporal replicates. The variogram model of the valley showed only noise, and the high nugget/sill ratio for the dune plot and the degraded plot indicates that variation due to spatially non-correlated sources is rather large at our plots. Cross-validation of the variograms was good for the degraded plot and less well for the dune and the valley. These results are also shown in the correlation coefficients of 10 simulations for each plot and each event. So even though we were able to produce some maps with the spatial variation of mass transport, the weak variograms of the dune and the valley and the low correlation values of the valley indicated that 17 observations is not always enough for a full characterisation of a wind-blown mass transport in the Sahel. Therefore we suggest that for relatively complex fields more samplers and a stratified sampling scheme as suggested by Chappel *et al.* (2003) should be used.

The maps produced by conditional stochastic simulation reproduce the statistical properties of the observations and emphasize the spatial variability in mass transport. Due to the large spatial variation in mass transport it is concluded that in the Sahel it will be more useful to distinguish erosion and deposition areas in the field than describing soil loss per unit area. An important consequence of this conclusion is that a wind erosion model that is applied at a Sahelian field should at least have a spatial component. Furthermore differences in intension of sediment transport between geomorphologic units indicate that the user should have information about the geomorphologic settings of the field to be able to set the boundary conditions. When modelling at the catchment scale the effects of fetch length and transition zones from the one geomorphologic unit to the other should be incorporated into the model.

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Chapter 5

Wind erosion modelling in a Sahelian environment

S.M. Visser, G. Sterk and D. Karssenberg

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Wind erosion modelling in a Sahelian environment

Abstract

In the Sahel field observations of wind-blown mass transport often show considerable spatial variation related to the spatial variation of the wind erosion controlling parameters e.g. soil crust and vegetation cover. A model, used to predict spatial variation in wind erosion and deposition is a useful tool in the implementation of wind erosion control measures in the Sahel. The aim of this paper was to test two existing wind erosion models on spatial predictions of aeolian mass transport for Sahelian conditions. Field data from Burkina Faso were used to test an empirical (RWEQ) and a deterministic (WEPS) model.

The Revised Wind Erosion Equation (RWEQ) poorly predicted maximum mass transport and so spatial predictions of mass transport were underestimated. Major constraints of RWEQ for application in the Sahel were the required non-eroding boundary and the fact that RWEQ assumes a more or less homogeneous field. It was concluded that RWEQ in its current state was not suitable for application in a Sahelian environment.

Provided with the correct roughness length (*Z0*), WEPS correctly predicted friction velocity and initiation and cessation of mass transport. Furthermore, the model gave a reasonable prediction of the spatial distribution of mass transport at the research sites. It was concluded that WEPS in PCRaster is suitable for prediction of wind erosion in a Sahelian environment. A constraint of WEPS in PCRaster is that WEPS' predictions of spatial variation in sediment transport are closely linked to the spatial variation in the input parameters. A good estimation of the spatial variation of the input parameters was required. Obtaining these might be an expensive exercise and could make its use in the Sahel difficult.

Software availability

RWEQ
First release: June 1998
Contact: Dr. Ted Zobeck
USDA-ARS
3810 4th st
Lubbock Texas, USA
Free download from: http://ww.csrl.ars.usda.gov/wewc/rweq/rweq.htm
Works in DOS environment
WEPS
First release 1995
Contac: USDA-ARS, NPA
Wind Erosion Research Unit
1515 College Avenue
Kansas State University
Manhattan, KS. 66600
Free download from: http://www.weru.ksu.edu/new_weru/weps/weps.html
Works under UNIX and Windows
PCRASTER
First release: 1991
Contact: PCRaster Environmental Software
PO Box 427
3500 AK Utrecht; The Netherlands

Free download from: http://www.pcraster.nl
Works under DOS, Windows and LUNIX

Introduction

Approximately 90% of the inhabitants of the Sahelian zone of Africa (a zone of approximately 200-400 km wide, centred on latitude 15°N) live in small villages and depend on subsistence agriculture for a living (Thiombiano, 2000). Due to rapid population growth, the cropping area has expanded to more marginal lands and the fallow period has been shortened or even abandoned (Thiombiano, 2000). Consequently, the combination of continuous soil erosion and the overexploitation has resulted in large scale degradation of soil productivity (Dregne, 1990). The already low fertile Sahelian soils have in general a sandy or sandy loam texture and are prone to wind erosion, especially early in the rainy season, when soils are bare and unprotected (Bielders *et al.*, 2001; Boiffin and Bresson, 1987; Casenave and Valentin, 1989; Michels *et al.*, 1995; Sterk, 1997, 2003; Thiombiano, 2000). The semi-arid climate of the Sahel has a long dry season from October until May and a short rainy season from June until September. In the early rainy season, when rainfall occurs in heavy thunderstorms, strong dust storms may develop. These events are usually short-lived, but may transport large amounts of sediment (Bielders *et al.*, 2002; Michels *et al.*, 1995; Sterk *et al.*, 1996; Sterk and Stein, 1997; Visser *et al.*, 2004). Wind erosion contributes to soil degradation by removal of the nutrient rich topsoil (Lal, 1988). Furthermore, crop seedlings suffer from abrasion or burial by sand during these early rainy season events (Michels *et al.*, 1995; Sterk, 1997). The damage to crops ranges from reduced or delayed growth to its complete destruction. In order to prevent large-scale famine, it is of the utmost importance to control crop damage and soil degradation by wind erosion in the Sahel. However, in the Sahel soil conservation possibilities are limited. A wind erosion model can be a useful tool in the battle against wind erosion since it can predict wind erosion risk under various land management practices. Then the best wind erosion preventing practices can be selected, tested and finally applied in the field.

Several researchers have shown that soil degradation by wind erosion in the Sahel can't be defined as a total soil loss per hectare due to a large spatial variation in erosion and deposition at the scale of a field (Bielders *et al.*, 2001; Sterk and Stein, 1997; Visser *et al.*, 2004). However, most available wind erosion models do predict erosion in terms of total soil loss per hectare. Especially in a Sahelian environment, factors that determine the erodibility of the soil for wind erosion (e.g. vegetation cover, land management and crust type) are distributed over the area, resulting in a spatial variation of erosion and deposition even when measuring at the scale of a field. Therefore, a wind erosion model, suitable for the Sahelian situation, should at least have a spatial component to be able to deal with the spatial variation in input parameters and to predict the spatial pattern of erosion and deposition.

In the Sahel, crust or crust-like surfaces are omni-present characteristics of the soils (D'Herbes and Valentin, 1992). Their type and structure are not only determined by soil texture but also by erosion and deposition by wind and water and by vegetation. Their distribution in the field further depends on terrain position and micro relief (Graef and Stahr, 2000). Each crust type has unique characteristics for thickness, resistance and availability of loose material and so has an unique influence on the wind erosion process. The following example illustrates the key-role of crust development in wind erosion. Consider e.g. the first rainfall on a freshly tilled Sahelian field. This usually leads to the formation of a structural sieving crust consisting of a plasmic seal overlain by loose sand (Valentin and Bresson, 1992). This loose sand is available for transport by wind, leaving the plasmic layer uncovered, resulting in an erosion crust. The sediment under this erosion crust is excluded from the wind erosion processes and only becomes available when the crust is broken. Therefore, wind erosion models applicable in a semi-arid environment like the Sahel should account more for the distribution of the various crust types (Valentin, 1995). The aim of this paper was to test two existing wind erosion models, an empirical and a physical model, on their spatial predictions of aeolian mass transport at the scale of a field under Sahelian conditions. The performance of the two models will be tested with field data from the 2001 wind erosion measurement campaign in the Katchari catchment, northern Burkina Faso.

Materials and methods

RWEQ

The USDA-Agricultural Research Service first released the Revised Wind Erosion Equation (RWEQ) in 1998 (Stout, 2003). Here only the key processes and equations of the RWEQ model are given, for a detailed description of the model and the measurement techniques of the different input parameters the reader is referred to Fryrear *et al.* (1998b). RWEQ makes estimates of soil eroded and transported by wind between the soil surface and a height of 2 m for specified periods based on a single-event wind erosion model.

Fine sediment is generally transported as suspended load and travels over much larger distances than the coarse sediment, which is generally transported in creep or saltation mode. RWEQ is best applicable for predicting erosion at field scale but also provides information on erosion rates within the field (Fryrear *et al.*, 1998a). The simulation area is a circular or rectangular field bounded by a non-eroding boundary. The model calculates aeolian mass transport within the field from the balance between wind erosivity and soil erodibility. For this the following equation is used (Fryrear *et al.*, 1998b):

$$Q(x) = Q_{\max p}\left[1 - \exp^{-\left[\frac{x}{s_p}\right]^2}\right] \qquad \text{(eq. 1)}$$

Where: x (m) is the downwind distance from the non-eroding boundary, Q_{maxp} (kg m^{-1}) is the transport capacity and s_p (m) is the distance where 63% of the maximum transport capacity is reached, called the critical field length (Fig.1). The assumption of a non-eroding boundary around the field implies that the highest soil losses will occur in the zone just downwind of the non-eroding boundary.

The transport capacity ($Q_{max\,p}$) and the critical field length (s_p) are determined by several factors; weather (WF), single soil roughness (K’), combined crop (COG), crust (CF) and the erodible fraction of the soil (EF) (Fig. 2).

The WF is a function of the wind factor (Wf), soil wetness (SW) and snow depth (SD) (Fig. 2). The wind factor is calculated from wind speed measurements at a height of 2m and soil wetness is a function of rainfall history and solar radiation. K’ is a function of oriented and random roughness, measured with the chain of Saleh (1993) and the COG is determined by the dead, lying and standing vegetation cover and the living crop cover.

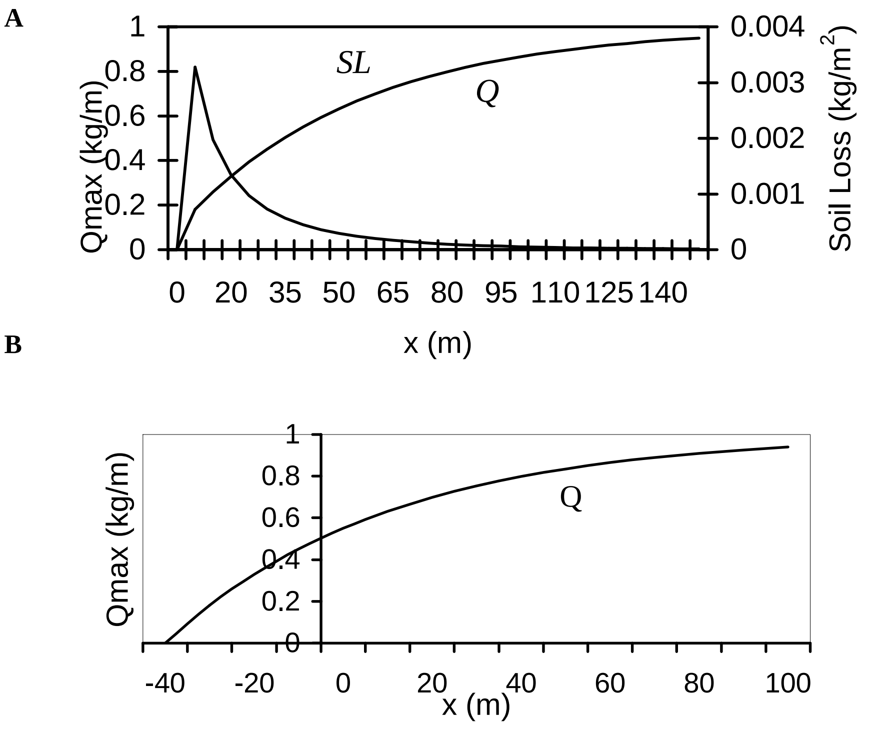

Figure 1A) Relationship between mass transport (Q) and soil loss (SL) from RWEQ using critical field length (s) = 50 m and maximum mass transport (Qmax) = 1 (kg m^{-1}) (Fryrear et al., 1998b). B) Relationship between mass transport and field length, the curve is transposed over distance α=50m using equation 9.

The erodible fraction (EF) of the soil was calculated using eq. 2 (Fryrear *et al.*, 1998b):

$$EF = \frac{29.09 + 0.31SA + 0.17Si + 0.33\dfrac{SA}{CL} - 2.59OM - 0.95CaCO_3}{100} \qquad \text{(eq.2)}$$

Where: SA is the sand content (%), Si is the silt content (%), SA/CL is the sand to clay ratio, OM is the organic matter content (%) of the soil and $CaCO_3$ is the calcium carbonate content (%).

The soil crust factor (SCF) was defined as a function of per cent clay (CL) and organic matter content, using eq. 3 (Fryrear *et al.*, 1998b):

$$SCF = \frac{1}{1 + 0.0066(CL)^2 + 0.021(OM)^2} \qquad \text{(eq. 3)}$$

The range of values in the calibration data set of the RWEQ model is given in table 1; equations 2 and 3 have not been verified for values outside these ranges.

All the factors are combined in equations 4 and 5 to calculate values for $Q_{\max}$ and s.

$$Q_{\max p} = 109.8(WF \cdot EF \cdot SCF \cdot K' \cdot COG) \qquad \text{(eq. 4)}$$

$$s_p = 150.7(WF \cdot EF \cdot SCF \cdot K' \cdot COG)^{-0.317} \qquad \text{(eq. 5)}$$

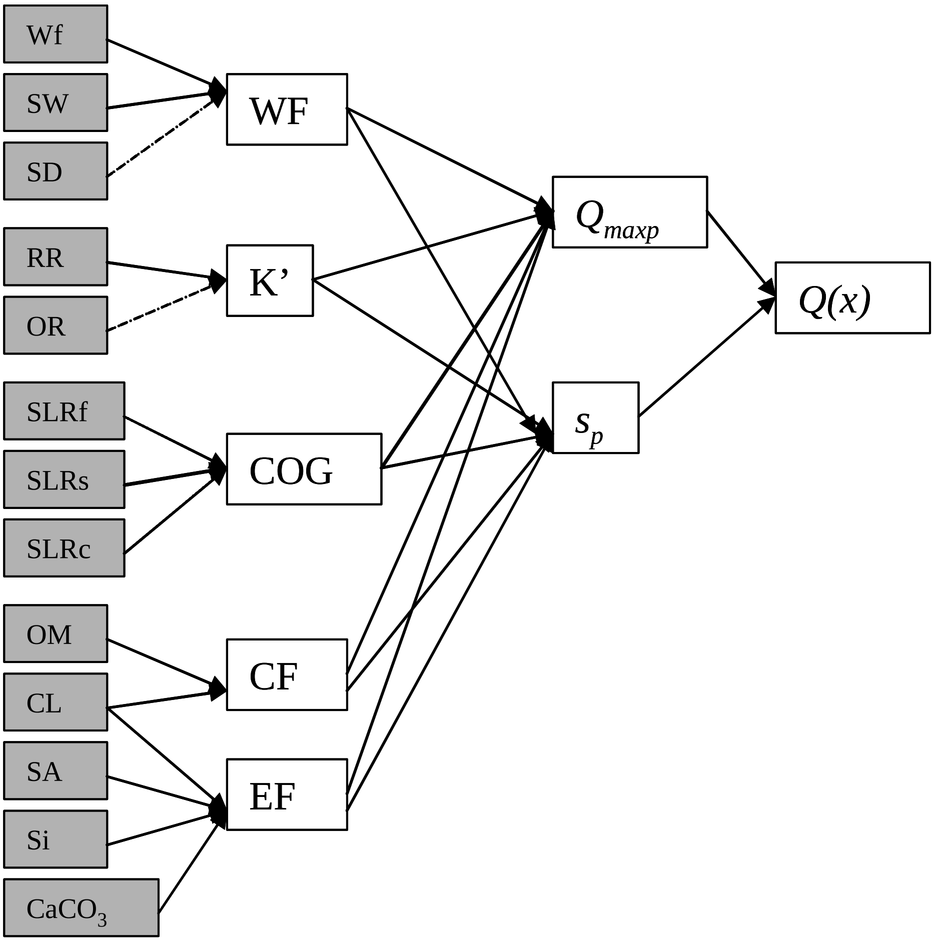

Figure 2) Schematic overview of the calculation procedure for mass transport in the RWEQ model. Grey boxes are the input parameters. Parameters in dashed boxes are not included for application in this research. WF, weather factor; Wf, wind factor; SW, soil wetness; SD, snow depth; K', single soil roughness factor; RR, random roughness; OR, orientated roughness; COG, combined crop factors; SLRf, -s and –c, flat residue, standing residue and crop cover; CF, crust factor; EF, erodible fraction; OM, organic matter; CL, Clay content; SA, sand content, Si, silt content and $CaCO_3$, calcium carbonate content.

Table 1) Range of values in calibration data set of RWEQ. Outside these ranges equations 2 and 3 have not been verified. SA; sand content, Si; silt content, CL; clay content, OM; organic matter content and $CaCO_3$; calcium carbonate content (Fryrear et al., 1998b).

	SA (%)	**Si** (%)	**CL** (%)	$\frac{SA}{CL}$	**OM** (%)	**$CaCO_3$** (%)
Range	5.5-93.6	0.5-69.5	5.0-39.3	1.2-53.0	0.18-4.79	0.0-25.2

WEPS

The USDA-ARS first released a Beta version of the Wind Erosion Prediction System (WEPS) in 1995 (USDA-ARS, 1999). Since then the model has had several updates. WEPS is a process-based, daily time-step computer model that predicts soil erosion through simulation of the physical processes that control wind erosion (Hagen, 1991). Here only the key processes and equations of the WEPS model are given, for a detailed description of the model and the measurement techniques of the input

parameters the reader is referred to Hagen (1996a). WEPS has a modular structure, including a weather simulator, and simulates apart from the basic wind erosion processes, surface condition, crop growth, residue decomposition, soil aggregates and crust status, hydrology and management. When wind speed exceeds the threshold for erosion, the erosion sub-model simulates erosion on a sub-hourly basis. Whereas the full model is more suitable for wind erosion predictions on larger time scales, the stand-alone erosion sub-model is suitable for the erosion modelling at the scale of an event (i.e. daily). The erosion sub-model considers the simulation area to be a rectangular field, composed of one or more sub-regions with different surface conditions for soil, management or cropping. The simulation field is divided into grid cells; each grid cell needs to contain information about the following surface conditions: 1) Surface roughness; random and oriented roughness below the biomass canopy, 2) Soil cover; flat, random biomass cover, crust with loose erodible particles, aggregated soil and rock cover, 3) Surface soil moisture and 4) Standing biomass.
The erosion sub-model is divided into several major functional components to accomplish the following simulation objectives (Fig. 3): to calculate the friction velocities for each cell (U^*), to calculate threshold friction velocities for each cell (*Wust*) and if sediment transport occurs ($U^*/Wust>1$) to compute soil loss/deposition in each cell and finally to update surface variables changed by erosion and output the selected information files. The driving force of the WEPS model is the excess of friction velocity (U^*) above the threshold friction velocity (*Wust*) (Fig. 3). The friction velocity at the weather station is calculated using (Hagen, 1996a):

$$U_w^* = \frac{0.4WS}{\ln\left(\frac{hWS}{Z0_w}\right)} \qquad \text{(eq. 6)}$$

Where: U_w^* is the friction velocity at the weather station (m/s); WS is the wind speed (m s^{-1}); hWS is the height of wind speed measurements (mm) and $Z0_w$ is the roughness length at the weather station.
If the weather station is not situated at the simulation field, the friction velocity at the simulation field is calculated with (Hagen, 1996a):

$$U_p^* = U_w^*\left(\frac{Z0_p}{Z0_w}\right)^{0.067} \qquad \text{(eq. 7)}$$

Where: U_p^* is the friction velocity at the simulation field (m s^{-1}) and $Z0_p$ is the roughness length at the simulation field (mm). The friction velocity at the simulation field is further influenced by the presence of windbreaks. The roughness length at the simulation field is calculated based on aerodynamic roughness of ridges, random roughness and standing biomass canopy (Fig. 3).
WEPS calculates two different values for the threshold friction velocity, one for entrainment (*Wust*) and one for transport (*Wusp*) based on Bagnold's theory on fluid and impact threshold (Bagnold, 1941). For soils with a sandy texture, the impact threshold velocity is generally lower than the fluid threshold velocity. WEPS calculates the threshold friction velocities based on input parameters for the fraction of bare emitting soil surface, flat biomass cover, soil wetness and aggregate size and density. For erosion to occur, U^* needs to become larger than $Wust(U^*/Wust > 1)$.

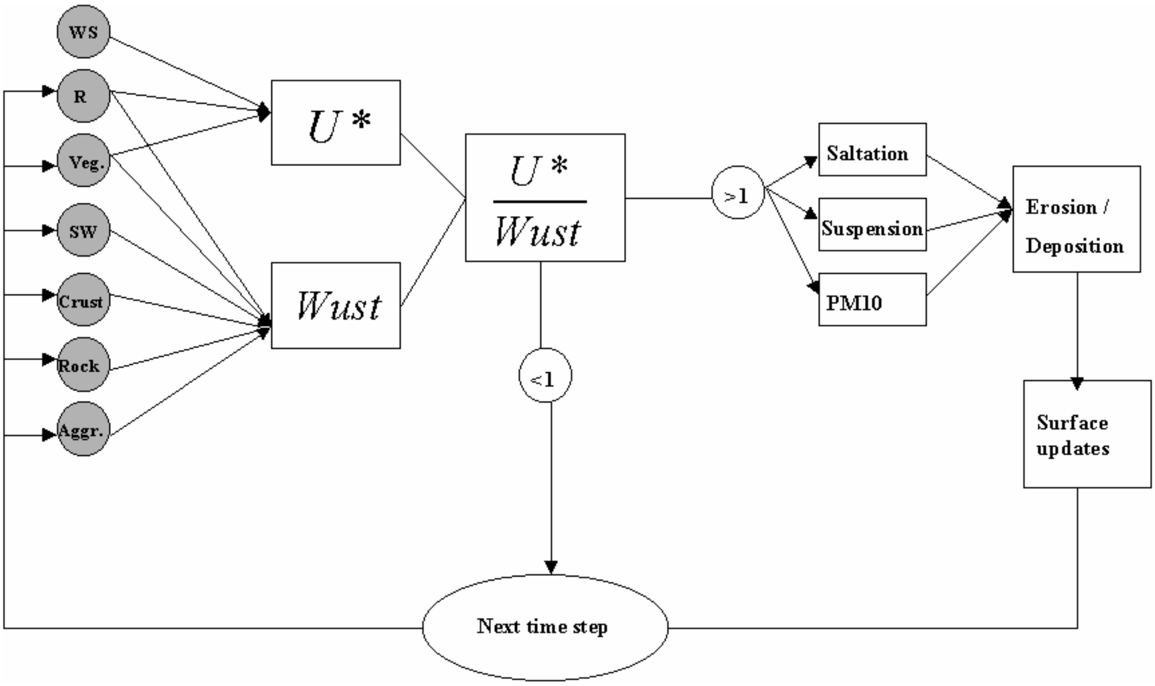

Figure 3) Schematic overview of the calculation procedure for mass transport in the WEPS model. Grey boxes are the input parameters. After an erosive time step, all input parameters, except wind speed are updated based on the net erosion/deposition in a grid cell. WS; Wind Speed (m s^{-1}*), R; roughness parameters, including random and oriented roughness, Veg; vegetation coverage including flat and standing biomass (*m^2 m^{-2}*), SW; soil wetness (kg* kg^{-1}*), Crust; crust parameters, including soil fraction crusted and fraction loose erodible particles, Rock; fraction of rock coverage, Aggr; aggregate parameters, including aggregate strength (Ln (J* kg^{-1}*) and size (µm),* U^**; friction velocity (m* s^{-1}*), Wust; threshold friction velocity for entrainment (m* s^{-1}*) and PM10; particle matter <10 µm.*

Later when wind speeds drop, but U^* is larger than $Wusp(U^*/Wusp > 1)$, theoretically transport is still possible.However, in WEPS, if a grid cell is not erosive $(U^*/Wust < 1)$ and transport is possible $(U^*/Wusp > 1)$, sediment flowing into the cell is first deposed and in the next time step this deposited, loose sediment can be eroded. The model developers used this strategy to enhance model speed. When time steps are sufficient small (< 1 sec), this strategy should not result in errors in prediction of sediment transport.

When it is established that erosion is possible, the transport capacity using the emission threshold capacity (*qen*) and the transport threshold capacity (*qcp*) are calculated as follows (Hagen, 1996ba):

$$qen = CS \cdot U*^2 \cdot (U* - Wust) \qquad \text{(eq. 8a)}$$

$$qcp = CS \cdot U*^2 \, (U* - Wusp) \qquad \text{(eq. 8b)}$$

Where: qen is the transport capacity using the emission threshold capacity (kg m^{-1} s^{-1}); qcp is the transport capacity using the transport capacity threshold (kg m^{-1} s^{-1}); CS is the saltation transport coefficient (kg s^2 m^{-4}), fixed at 0.3.The transport capacities are later used to calculate the input and output sediment fluxes of the grid cells. WEPS separately calculates the saltation/creep, suspension and PM10 (particle size ≤ 10 µm) components of the eroding material, based on the size distribution of the topsoil and the soil surface characteristics. From the in- and outgoing sediment fluxes, net erosion or deposition in the grid cell is calculated. Finally the surface variables changed by erosion and deposition are updated.

Field measurements

During the early rainy season of 2001 field data for wind erosion events were collected at three sites in the Katchari catchment in northern Burkina Faso (14˚00”N, 0˚00”W). The Katchari catchment covers an area of 12 km^2 and is situated in the province of Seno, 11 km West from Dori, the provincial capital. The climate is characterised by a short rainy season of 3-4 months. Mean annual precipitation is 480 mm, but highly variable from year to year. Temperatures are high all year round. Generally, the first rains come from the East. Those rains are often preceded by windstorms, which may cause severe wind erosion.

The research sites were chosen so that they each had a different geomorphologic setting: a degraded site, a valley floor and a dune (Table 2). The degraded site is characterised by its lack of vegetation and a strong gravel crust (Valentin and Bresson, 1992). The south-eastern part of the research plot at the degraded site is bordered by a dry streambed, with a depth of approximately 20 cm and a width of 1.5 m. The valley floor is incised by a river, which is dry in the dry season and may flood during the wet season. The research site at the valley floor is cultivated with millet in the wet season and characterised by fast development of erosion and still depositional crusts (Valentin and Bresson, 1992). Natural vegetation (trees and herbs) are scattered over the field. Annual herbs are removed by hoeing twice in the wet season. The borders of the field at the dune are demarcated with trees; however these trees do not form a continuous row as in a wind barrier. Several shrubs can be found inside the dune site and, similar to the valley floor, annual herbs are removed twice a year and the field is cultivated with millet. The dune is part of an old and flattened dune band that belongs to an extensive sand dune system, which is more than 40.000 years old (Courell, 1977). The loamy, sandy soils of this dune complex are prone to crusting, with structural and erosion crusts being the most common (Valentin and Bresson, 1992).

Table 2) Surface soil characteristics of the dune site, the site at the valley floor and the degraded site in the Katchari catchment, Burkina Faso. All parameters are determined following a procedure as suggested by Fryrear *et al.* (1998b).

Location	Texture	Sand	Silt	Clay	Organic Matter	Calcium Carbonate
		--------	--------	--------%	--------	--------
Dune	Loamy sand	84	13	3	0.2	0.2
Valley floor	Loamy sand	79	16	5	0.5	7
Degraded site	Clay loam	59	19	22	0.3	8

All fields are characterised by an undulating topography. Maximum height differences within the site on the dune were approximately 0.5 m. At the valley floor and the degraded site, the distances between depressions and crests ranged from 10 to 40 m with maximum height differences of approximately 1 m.

At each site a plot of 80 x 80 m was selected and instrumented with 17 Modified Wilson and Cook (MWAC) sediment catchers. The catchers were regularly distributed in circles so that in each of the main wind directions a line of 5 catchers was formed. In one line the catchers were 15 m apart. For each site and each event, total mass transport was determined by sampling mass flux densities at 5 heights (0.05, 0.12, 0.19, 0.26 and 0.75 m) and integrating over the height. Sterk and Raats (1996) gave a description of the MWAC-catchers and a method for quantifying total mass transport (kg m^{-1}) from the trapped material. The research was set up to measure actual sediment transport in farmers’ fields, so the vegetation was not removed before the placement of the catchers. Clear, non-eroding boundaries could not be identified in the selected sites, and thus saltation and creep particles could freely enter the sites. At the dune and the degraded site, weather stations were installed. Since the research plot at the valley was situated less than 500 m from the degraded site, weather data from the degraded site was used for the valley. Wind speed and wind direction were measured at one-minute intervals at a height of 2 m. At the degraded site a wind profile was measured at 0.5, 1, 2 and 3 m. All meteorological equipment was set up in such a way that easterly winds were non-disturbed by obstacles. Soil wetness was measured at five-minute intervals with a water content reflectometer (Campbell, 1999), placed horizontally at a depth of approximately 2 cm. Moments of initiation and cessation of mass transport were determined with saltiphones, which is an acoustic saltation sensor that records particle impacts with a microphone (Spaan and Van den Abeele, 1991).

In the dry period the input parameters, roughness and vegetation characteristics, were determined once a month, in the wet period once a week. The input parameters were measured according the methods advised by Fryrear *et al.* (1998b) and Hagen (1996a). For each of these input parameters 15 measurements points were randomly distributed over the research plot. In a circle of 2 meters around a measurement point, five measurements for each parameter were made. Inverse distance interpolation was used to prepare maps of the necessary input parameters.

Additional data for testing WEPS

The values for U_m^* and $Z0_m$ were calculated from a measured wind profile following a procedure described in Stull (2001). A wind profile was measured only at the degraded site (with anemometers at heights of 0.5, 1.0, 2.0 and 3.0 m). To prevent basing conclusions on data from one research site only, the capability of WEPS (implemented in a spatial modelling language) to correctly predict U_p^*, $Z0_p$ as well as moments of initiation and cessation of wind-blown mass transport were further tested with wind profiles and erosion data from other sites in the Sahel (Sterk, 1993 and Leenders, unpubl., 2002). The research site of Sterk (1993) was situated at the International Crops Research Institute for the Semi-Arid Tropics (ICRISAT) Sahelian Centre at Sadore, in Niger, 40 km south of the capital Niamey. The wind field at this site was not disturbed by obstacles like wind breaks and buildings. The research site had a mulch cover of 5% and no living vegetation.

Additional wind profile data came from two research plots of Leenders that are situated at traditionally cultivated fields near the village Windou, in Burkina Faso, 8 km west of the province capital Dori. The meteorological equipment was set up in such a way that easterly winds were non-disturbed. Windou-bare was a bare field and Windou-mulch had a mulch cover of 0-3%. Natural vegetation was present at both fields and Windou-mulch was used for cropping with pearl millet (sowing date 4 June 2002).

In this paper, parameters measured in the field or calculated from field measurements are indicated with $_m$, whereas model results are indicated with $_p$.

Model adaptations

RWEQ

For the USA, weather data files are available, which describe wind with the monthly Weibull cumulative probability distribution, using coefficients k (shape) and c (Weibull scale) and per cent calm (Skidmore and Tatarko, 1990). Using this information, the RWEQ program simulates wind speeds for the simulation site. For the Sahelian region extended weather data files are not available. The RWEQ model does not directly give output information on mass transport over the field. So, to obtain this information and to be able to work with measured wind speed data during one event as input, an EXCEL worksheet, containing all RWEQ equations was created.

For determination of Q_{maxp} and $s_{p,}$ snow depth (SD) and oriented roughness (OR) were left out of consideration since these parameters were not present (Fig. 2). Furthermore, in the Sahel, fields are not surrounded by non-erodible boundaries. A single tree, a path or rocks often indicate the edges of the fields. None of our research plots had a non-erodible boundary, so we do not know exactly at which point in the predicted plot (Fig. 1 A) the measurements were made. Therefore eq. 1 was adjusted to fit the available data by transposing the sigmoid curve over distance α (eq. 9).

$$Q(x) = Q_{\max m}\left[1 - e^{-(\frac{x+\alpha}{s_m})^2}\right] \qquad \text{(eq. 9)}$$

The curve will cross the y-axis at point (0, Q), the first field measurement, and cross the x-axis at point (-α, 0) (Fig. 1 B). Following a procedure suggested by Zobeck *et al.* (2001), Q_{maxm}, s_m and α are calculated from the field measurements by performing least squares, non-linear regression analysis using eq. 9. Based on the wind direction, mass flux data of 5 sediment catchers were selected from the available sediment catchers.

The measured (using eq. 9) and predicted (using equations 4 and 5) values of Q_{max} and s are compared to see if the RWEQ is applicable to the Sahelian situation. If a good correlation between predicted and measured values is reached, mass transport (Q) in the field can be estimated using eq. 9 and compared with the measured mass transport values of the selected catchers in the field.

WEPS

The current version of WEPS (1.0) can only handle a single homogeneous sub-region (Wagner, 2002). To account for the spatial variation of the input parameters in a Sahelian environment, the programming code of WEPS 1.0 was translated into the dynamic modelling language of PCRaster (De Jong, 1997), which is an environmental modelling language embedded in a GIS (Karssenberg, 2002). Another advantage of incorporating WEPS into PCRaster is the relatively open data structure of PCRaster, which permits the user to closely follow the erosion simulation.

Here we tested the WEPS in PCRaster on the correct prediction of three parameters, which are important in determining the total erosion/deposition on a field. First the model was tested on the prediction of the friction velocity, since this parameter was crucial in the model equations. For several events and different measurement fields the U_m^* and $Z0_m$ were determined from the measured wind profile and these were compared with the $Z0_p$ and the average U_p^* predicted by WEPS. Since the measured $Z0_m$ is based on the average roughness of the soil surface upwind from the weather station, we compared the measured value with the average $Z0_p$ of the field till 80 m (field length of the research site) upwind from the weather station. The U_m^* is an average for the whole event and is therefore compared with the average U_p^* of the event.

Furthermore, we tested whether the model correctly predicted the moment of initiation and cessation of sediment transport. These are important moments since the total duration of a wind erosion event is one of the key parameters in the calculation of total sediment transport.

To see whether WEPS correctly predicted moments of initiation and cessation of mass transport we compared the ratio of $U_p^*(t)/Wust$ with measured saltiphone data. If the ratio was larger than one, sediment entrainment is possible and should correspond with the saltiphone data. Since the saltiphone gives an indication of the intensity of mass transport at one point in the field while mass transport is a spatial variable in the field, average values of 4 x 5 m upwind from the position of the saltiphone for U_p^* and *Wust* were used for the comparison. We chose this 4 x 5 m to account for the influence of roughness elements in the upwind direction.

Finally the model was tested on the correct prediction of the spatial distribution of mass transport. Field measurements of total mass transport (kg m^{-1}) were compared with WEPS output mass transport in kg m^{-1}. For the prediction of mass transport some adjustments to the WEPS erosion sub-model were made in the PCRaster script. First of all, since no non-eroding boundaries were present, input of sediment was a necessary boundary condition. To meet this boundary condition, the simulation area was placed in the centre of an area three times its size. Soil and soil cover characteristics of the boundary area were set to the average of the simulation area. To avoid sediment depletion, sediment flowing out at the down-wind boundary of the larger area at one time step, was blown in at the up-wind boundary of the larger area in the next time step. The main advantage of re-using sediment over a constant input of sediment is that because wind speed was variable, transport capacity was variable and so a better estimation of incoming sediment was obtained.

Furthermore, the assumption of WEPS that saltation transport is only possible when erosion can occur (U_p^*(t)/Wust > 1 and qen > 0 (eq. 8a)) is adjusted. The grid size in original WEPS is sufficiently large to justify this assumption. This is because saltation transport becomes less and less intense when no new saltation particles are added to the sediment stream (Livingstone and Warren, 1996). However, during this study grid size was 1 m^2. So when at a certain grid cell no erosion was possible (U_p^*(t)/Wust <1), the incoming sediment flux could be transported if U_p^*(t)/Wusp >1. In this case the outgoing sediment flux was at its maximum equal to the transport capacity, qcp (eq. 8b).

Results and discussion

In the 2001 rainy season 11 wind erosion events occurred in the Katchari catchment and three of them were followed by heavy rainfall. In general, the first thunderstorms move from east to west, hence wind direction during a wind erosion event is easterly, but it can be variable depending on the site location relative to the centre of the storm (Sterk and Stein, 1997). The wind direction of the 11 sampled events varied from North to South, average wind speed ranged from 7 to 11.9 m/s, and the total duration of the events ranged from 220 to 2760 s (Table 3). During the event of May 20 the catchers of the degraded sited were malfunctioning; therefore these data were not used for modelling. Generally, most sediment transport occurred at the dune site and least sediment transport occurred at the degraded site. This was explained by the higher sediment availability and the higher average wind speeds at the dune site. For all events the range in mass transport (difference between minimum and maximum mass transport) was large in comparison to the mean (Table 3), indicating that mass transport is variable in space. This large spatial variability in sediment transport was explained by the spatial variation in the presence of vegetation, mulch coverage and soil crusts. These parameters have a large influence on the transport capacity of the wind and the erodibility of the soil (Hagen, 1996a; Molion and Moore, 1983; Rice *et al.*, 1997).

Revised Wind Erosion Equation (RWEQ)

Fryrear *et al.* (1998a) and Zobeck *et al.* (2001) performed a validation of RWEQ over a wide range of soil types and climates in the USA. They found correlations between observed and predicted Q_{max} of 0.82 (Fryrear *et al.*, 1998a) and 0,70 (Zobeck *et al.*, 2001) though no correlation between measured and predicted s values was observed. This suggests that RWEQ predicts only Q_{max} well under soil and climate conditions for which RWEQ was initially developed and s is poorly predicted in these circumstances.

Since RWEQ is an empirical based model, the model can only be used with input parameters, which fall inside the test range of the model. In the RWEQ manual only for equations 2 (EF) and 3 (SCF) test ranges are given (Table 1) (Fryrear *et al.*, 1998b). Table 1 and 2 show that all input parameters of the sites fall within the validation range of the formulas, with the exception of the organic matter of the dune, which is low. Further, RWEQ is supposed to be applicable throughout the USA and so for a wide range of climates. Convective wind erosion events comparable with the convective storms in the Sahel do occur in the USA (e.g. Dogget et al., 2003). Therefore it is assumed that atmospheric conditions during a Sahelian wind erosion event will fall inside the test range of RWEQ. Since almost all input parameters fall inside the test range, it is assumed that equations 4 (Q_{maxp}) and 5 (s_p) are also valid for the Sahelian situation.

Initially it was intended to incorporate the spatial variation in the input parameters of RWEQ, for simulation of wind erosion in the Katchari catchment. However, due to the structure of equations 1 and 9 (Q(x) depends on Q_{max} and s), this became difficult. With a spatial variable s, it is difficult to determine x and so Q(x) (Fig. 1A and B).

Therefore, to determine Q_{maxp} and $s_{p,}$ initially no spatial variation in the input parameters was taken into account. Average field values for all input parameters were used. Furthermore, the influence of scattered vegetation and topography were not taken into account because these parameters were not included in the model. These influences should not have had any effect on the predictions at the degraded site, but scattered vegetation surely acted on mass transport at the valley. So for the valley site an overestimation of mass transport was expected.

Table 3) Date, duration (D), average wind speed (WS) at 2 m, wind direction (wdir) and average and range of mass transport at the degraded plot and the dune and average and range of mass transport at the valley in the Katchari catchment, Burkina Faso, 2001 rainy season.

	Dune					Degraded plot					Valley	
Date	*D*	*WS*	*wdir*	*Q*	*range*	*D*	*WS*	*wdir*	*Q*	*range*	*Q*	*range*
	S	*m s⁻¹*		*kg m⁻¹*	*kg m⁻¹*	*S*	*m s⁻¹*		*kg m⁻¹*	*kg m⁻¹*	*kg m⁻¹*	*kg m⁻¹*
20 May	1680	8.3	N	49.6	4-57.7	1620	7.7	N	-	-	32.6	4.6-75.6
22 May	1740	8.1	S	72.9	31.1-120.9	1560	8.6	S	13.6	4.9-25.8	88.3	20-169.9
3 June	2280	7.2	SE	59.4	26.6-59.4	840	7	SE	4.6	1.6-16.3	20.5	1.4-47.9
9 June	2160	8.8	NE	119.1	52.7-206.2	1260	9.3	ENE	12.2	5.5-29.8	54.8	19-122.9
19 June	2760	9.0	E	136.3	47.1-269.4	2400	8.5	E	50.6	21.7-109.1	43.8	13-129.3
22 June	1260	9.2	E	100.7	8.1-182.8	1140	11.8	E	43.4	9.8-96.2	56.1	15-157.8
29 June	220	7.5	N	53.6	12.9-74.2	220	8.6	N	10.6	2.1-38.4	17.8	5.3-43.1
3 July	1200	7.4	N	40.7	8.5-87.7	1140	7.5	N	15.9	4.0-34.7	51.0	17.2-84.2
10 July	1500	9.0	SE	69.3	44.5-113.8	1320	9.5	SE	28.6	6.6-103.3	51.0	14-141.2
11 July	2580	8.4	NE	36.1	5.8-77.9	2280	9.5	NE	13.7	6.7-32.5	8.4	1.3-16.9
13 July	1560	8.2	NE	40.9	9.4-69.2	1500	9.9	NE	49.2	19.5-96.1	47.3	14-102.8

Table 4) Modelling results of RWEQ compared with field measurements of maximum mass transport (Q_{max}) and critical field length (s) for 11 wind erosion events at 3 research plots in the Katchari catchment in Burkina Faso. $_m$, measured; $_p$, predicted; -, no measurements available.

	Degraded Site				Valley				Dune			
	Q_{maxm}	Q_{maxp}[!!]	s_m	s_p[Δ]	Q_{maxm}	Q_{maxp}[!!]	s_m	s_p[Δ]	Q_{maxm}	Q_{maxp}[!!]	s_m	s_p[Δ]
	kg m⁻¹		*m*		*kg m⁻¹*		*m*		*kg m⁻¹*		*m*	
20 May	-	-	-	-	41.7	20.6	912	1004	49.4	43.4	1059	978
22 May	34.9	5.5	2102	1875	253.7	22.7	1280	1125	204.7	30.0	1090	1014
3 June	5.7	13	1364	1402	18.0	11.9	760	844	123.4	66.1	829	790
9 June	13.2	10.9	1936	2169	42.4	42.4	1309	1309	215.9	90.6	1600	1557
12 June	12.3	3.9	2537	2371	241.2	9.9	1378	1679	56.8	13.5	1592	1466
19 June	51.8	11.1	1419	1621	294.0	42.7	1566	980	417.8	56.5	932	883
22 June	52.2	4.26	2470	2300	138.3	11.9	1280	1221	196.3	28.7	2699	2561
29 June	40.0	0.0	1279	1968	48.9	9.8	1195	1026	468.1	23.7	1255	1145
3 July	238	9.3	1586	1588	46.9	27.6	562	797	485.5	37.1	206	715
10 July	90.7	3.6	1545	1374	163.9	14.1	891	828	52.2	52.2	1189	1204
11 July	20.3	8.1	1476	1672	15.5	7.8	1699	1687	683.3	3.1	2853	2940
13 July	30.4	1.7	3562	3962	95.3	6.8	2564	2387	60.2	10.5	4639	5111

[!!] Q_{maxp} is the sum of all predictions of Q_{maxp} for each minute that sediment transport was possible

[Δ] s_p is the average of all predictions of s_p for each minute that sediment transport was possible

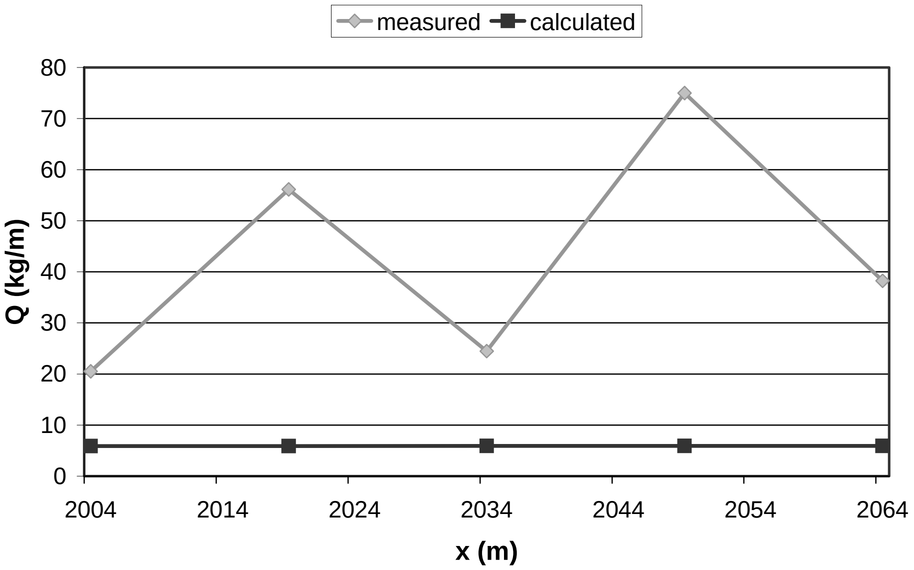

Figure 4) Measured and RWEQ predicted mass transport for an event at the valley, 13 July 2001, Katchari catchment Burkina Faso. α = 1994 m

Table 4 shows the results of RWEQ model simulations in the Katchari catchment. Q_{maxp} is the sum of all predictions of Q_{maxp} for each minute that sediment transport was possible and s_p is the average of all predictions of s_p for each minute that sediment transport was possible. At the dune s_p values are generally underestimated with an average of 7% from the s_m values, with one over-prediction of 246% for the event of 3 July. For the valley s_p values are generally underestimated with 14% and for the degraded site with 13%.

For the dune site Q_{maxp} was generally underestimated with an average of 68.3 %, at the valley site with 66.9% and at the degraded site with 79.9 %. So RWEQ gave acceptable predictions of the s_p values; though failed to predict $Q_{maxp.}$ With a poor prediction of Q_{maxp}, a good prediction of s_p is not very meaningful. It is no use to know where a maximum mass transport might occur, knowing that predictions of this amount are inaccurate. Furthermore, due to the poor prediction of Q_{maxp}, $Q(x)_p$ can't be expected to be well predicted. Figure 4 shows the measured and predicted mass fluxes (Q(x) in kg m^{-1}) at the valley at 13 July 2001, with Q_{maxp}= 6.8 kg m^{-1}, α = 1994 m and s_p = 2387.5 m (Table 4). From figure 4 it is clear that Q(x) is highly under predicted. The apparent inability of the model to predict spatial variation in mass transport can here be explained by the fact that average field values were used for determination of Q_{maxp} and $s_{p.}$ Were the field average Q_{maxp} and Q_{maxm} in the same order of magnitude, this could be overcome by pursuing the following procedure. First calculate $Q(x)_p$ based on the average field values, then determine the specific Q_{maxp} and s_p for that point and multiply $Q(x)_p$ by a factor based on the relation between the average field value for Q_{maxp} and the specific point value for $Q_{maxp.}$ However, the field average Q_{maxp} was not in the same order of magnitude as the field average Q_{maxm}, so this procedure could not lead to better results.

At our sites the random roughness was very low, (roughness values measured with the chain method (Saleh, 1993) ranged from 0.93 at the degraded site to 4.5 at the valley floor) and no oriented roughness (caused by cultivation) was present. Therefore, the parameter K' had hardly any influence on the prediction of Q_{maxp} and $s_{p.}$ The same accounts for the parameter COG; average soil cover by dead and living crops ranged from 0 till 5 percent for all sites. So at our sites, the weather factor (WF), the crust factor (SCF) and the erodible fraction (EF) were the most important factors in determining Q_{maxp} and s_p. Saltiphone data were used to make sure that the wind factor, and therefore the WF, were correctly predicted. Soil wetness was very low (< 5%) and had no influence on the WF. Despite high wind speeds low values for maximum mass transport were predicted. Apparently the model predicted transport to be sediment limited and only the EF and the SCF, calculated with equations 2 and 3, could have caused the low prediction of Q_{maxp}. Both the EF and the SCF were calculated based on textural characteristics of the soil. In the Sahel crust development is apart from textural characteristics determined by rainfall kinetic energy and topography. Furthermore, crust type highly influence sediment availability. The equations for EF and SCF do not represent the Sahelian situation and modifications should be considered.

Even though the Sahelian soils are prone to crusting, it is clear from the field measurements that sediment was available for transport. In RWEQ the erodible fraction (EF) seems to be the most limiting factor for a correct prediction of Q_{maxp} (EF dune, 0.66; EF valley, 0.53 and EF degraded, 0.43). A possible explanation for these low values is that crust type (sediment availability) and abrasion of the crust by saltating particles are not taken into account in the prediction of EF.

Parameters, which might be considered to be used for determination of the soil crust factor (SCF) (SCF dune, 0.94; SCF valley, 0.85 and SCF degraded, 0.24) are topography and rainfall intensity and amount since last tillage. With these parameters it might be possible to predict the spatial distribution of crust type and strength, which could then be used to modify the prediction of EF.

Apart from the weak performances of RWEQ in determining Q_{maxp}, the model has some constraints because of its structure. First of all, it assumes a non-eroding boundary around the field, which is hardly ever present in the Sahel. We tried to circumvent this boundary condition by the introduction of α in equation 9. However, this equation needs to be tested to determine if its use is justified. Furthermore, the model assumes a more or less homogeneous field for soil management, soil crusting, and vegetation cover. Only the distance from the non-eroding boundary determines variation in mass transport over the field. In the Sahel, the fields are seldom homogeneous for the above-described parameters. Therefore, the model structure should be drastically changed before it can be applied in the Sahel. For the RWEQ in its current state, we see no future application to traditionally cultivated fields in the Sahel.

WEPS

The WEPS erosion sub-model was tested both inside the USA (Hagen, 2001; Van Donk and Skidmore, 2001) and outside the USA (Funk *et al.,* 2002). The results for total soil loss for an event and the temporal changes in transport capacity were considered satisfying by the authors.

The wind field could be assumed non-disturbed for the events of 9 June and 11 and 13 July since the wind came from northeast (Table 3). Both the degraded site and the Windou-bare site had no vegetation cover and no oriented roughness caused by cultivation practices. So according to WEPS, the roughness length ($Z0_p$) for these sites is only determined by the random roughness. The sites Windou-mulch and Sadore had a mulch cover of approximately 5 per cent. Furthermore, at Windou-mulch a small crop with a height of 20 cm was present during the event of 13 July 2002.

Table 5 presents the values for measured U^*_m and $Z0_m$ and predicted U^*_p and $Z0_p$. As can be seen in this table $Z0_p$ and U^*_{p1} are only well predicted for Sadore. For all other sites $Z0_p$ is highly underestimated and so is U^*_{p1}. A possible explanation is that around both the degraded site and the sites in Windou natural vegetation was present.

Table 5) Values for measured ($_m$) (using a wind profile) and predicted ($_P$) (by WEPS in PCRaster) roughness length (Z0) and friction velocity (U^*) for four research sites, Sadore in Niger, Degraded site in the Katchari catchment, Burkina Faso and Windou-bare and Windou-mulch in the Windou catchment in Burkina Faso.

Site	Date	$Z0_m$ *(mm)*	$Z0_p$ *(mm)*	U^*_m *(m/s)*	U^*_{p1} *(m/s)*	U^*_{p2} *(m/s)*
Sadore	26 June ‘93	0.2	0.56	0.45	0.37	-
	30 June ‘93	7.0	0.56	0.50	0.43	-
	3 July ‘93	0.5	0.56	0.54	0.48	-
Degraded site	9 June ‘01	2.15	0.36	0.51	0.40	0.50
	11 July ‘01	3.78	0.36	0.52	0.38	0.52
	13 July ‘01	4.82	0.36	0.53	0.37	0.53
Windou-bare	3 June ‘02	5.41	0.19	0.58	0.38	0.59
	13 July ‘02	8.80	0.265	0.73	0.45	0.74
Windou-mulch	3 June ‘02	0.65	0.36	0.46	0.36	0.46
	14 June ‘02	1.47	0.36	0.50	0.36	0.50
	13 July ‘02	1.74	0.44	0.54	0.44	0.54

Even though we tried to set up the measurement equipment so that obstacles did not directly hamper the measured wind profile, it was possible that the scattered vegetation in the area influenced the wind field and increased $Z0_m$. Wolfe and Nickling (1993) state that in sparsely vegetated areas a logarithmic wind profile may exist, but that the effect of individual roughness elements should be considered. Vegetation interacts with the mean flow of wind by extracting momentum from the wind; producing turbulence and breaking down large scale, turbulent eddies into smaller scale motions, and this might result in a larger $Z0_m$.

Since WEPS only accounts for uniform vegetation and does not take the effect of the scattered vegetation within and around the research site into account, the model was run with $Z0_m$ as an input parameter. Now the predicted friction velocity (U^*_{p2}) was correctly predicted for all sites (Table 5).

In order to determine the time of initiation and cessation of sediment transport, we used U^*_{p2} for the ratio between shear velocity and the threshold shear velocity ($U^*_p(t)/Wust$) for the degraded site and the Windou sites. For the Sadore site we used U^*_{p1}. After the first calculations, WEPS appeared to be extremely sensitive to soil wetness. Even at the sandy soils of Windou-bare with low water content (< 5%) in the top two cm soil, the ratio $U^*_p(t)/Wust$ was smaller than 1 for all events, so no mass transport could occur. From field observations it was clear that soil wetness was not a limiting factor for wind erosion, so we set the input parameter soil wetness to 0 for all events at all sites. Then WEPS estimated time of initiation and cessation of mass transport very well for the Sadore and Windou sites. Figure 5A shows the ratio $U^*_p(t)/Wust$ and the saltiphone data for the event of July 3, 1993 at the Sadore site. It is clear that as soon as $U^*_p(t)/Wust$ becomes larger than 1, saltation transport is recorded and as soon as the ratio drops below 1 transport is no longer registered. For the degraded site WEPS rarely predicted ratios larger than 1 (Fig. 5B). This is reasonable taking the soil surface conditions at the degraded site into account (a crusted soil with gravel embedded and on top of the crust). However the saltiphone did record some saltation transport. Therefore the threshold for transport ($Wusp$) and the ratio $U^*_p(t)/Wusp$ were calculated. Figure 5B shows both ratios ($U^*_p(t)/Wust$ and $U^*_p(t)/Wusp$) and measured saltation transport for the wind erosion event at 9 June 2001 at the degraded site. The ratio $U^*_p(t)/Wust$ is only once larger than 1, but at moments saltation transport was registered with the saltiphone the ratio $U^*_p(t)/Wust$ was indeed larger than 1. Apparently the measured saltation fluxes derived from sediment input to the research site.

The mass transport by wind was simulated with WEPS in PCRaster for the research sites at the dune, the valley floor, and the degraded site. The roughness length ($Z0_m$), calculated from the measured wind profile at the degraded site, was used to predict U^*_p using equation 6. $Z0_p$ for the valley and dune were estimated based on measurements on the roughness elements and a comparison with the roughnes elements at the degraded site. Equation 7 was used to predict U^*_p at the dune and the valley. Figures 6, 7, and 8 show the main input maps and the maps of predicted mass transport for the event of 11 July at the dune, the valley and the degraded site respectively.

Figures 6, 7, and 8 show the main input maps and the maps of predicted mass transport for the event of 11 July at the dune, the valley and the degraded site respectively.

Comparing the maps of crop coverage, roughness and crust type at the dune with the map with predicted mass transport (Fig. 6), it becomes clear that here crop coverage is the most important wind erosion controlling parameter. Large amounts of mass transport are predicted at bare areas. The higher vegetation coverage combined with the lack of transportable sediment on the erosion crust results in lower mass transport rates at the south-western part of the field. Though sediment input is high, the amount of mass transport is in the same order of magnitude and the pattern of erosion and deposition agrees reasonably well with the measured pattern. Only the highest peak of sediment transport is predicted too early over the transect. A possible explanation for this is that the vegetation map is created with inverse distance interpolation based on 15 x 5 measurement points. Making aerial pictures with kite-photography and digitising these photos might be a more precise procedure for obtaining maps with vegetation coverage.

Due to a lack of crop cover and the presence of a combined structural/erosion crust, large amounts of mass transport are predicted and measured at the north-eastern part of the valley (Fig. 7). The low mass transport values in the north-western part of the field are explained by the presence of an erosion crust and so a lack of transportable sediment. Though not measured, a large decline in mass transport was predicted in the centre of the field. This can be explained by the presence of an area of approximately 8 x 8 m with a dense mulch cover. Due to the used interpolation technique the input map with vegetation cover was not correct. This emphasizes the importance of reliable information of the distribution of the input parameters.

Due to the lack of vegetation, mass transport at the degraded site is only determined by the distribution of the crust types (Fig. 8). The moment wind-blown sediment arrives at the gravel crust the sediment is entrapped by the loose gravel. Behind the gravel crust erosion occurs. The predicted large amounts of mass transport over the structural crust

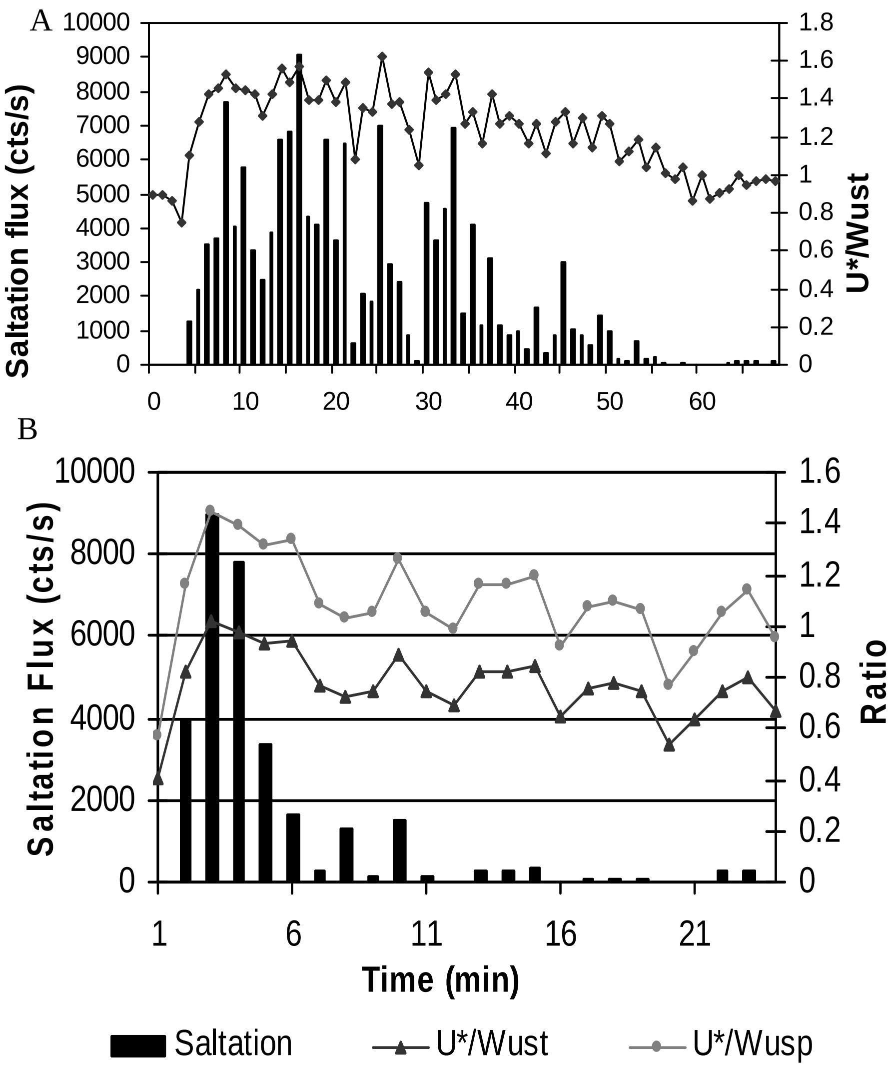

Figure 5A) Measured saltation flux versus ratio of the friction velocity (U^{*}) and the threshold friction velocity for entrainment (Wust) as predicted by WEPS for a wind erosion event at 3 July, 1993, Sadore, Niger. B) Measured saltation flux versus ratio of the friction velocity (U^{*}) and threshold friction velocity for entrainment (Wust) and the ratio of the friction velocity (U^{*}) and the threshold friction velocity for transport (Wusp) for a wind erosion event at 9 July 2001, at the degraded site, Katchari catchment, Burkina Faso.

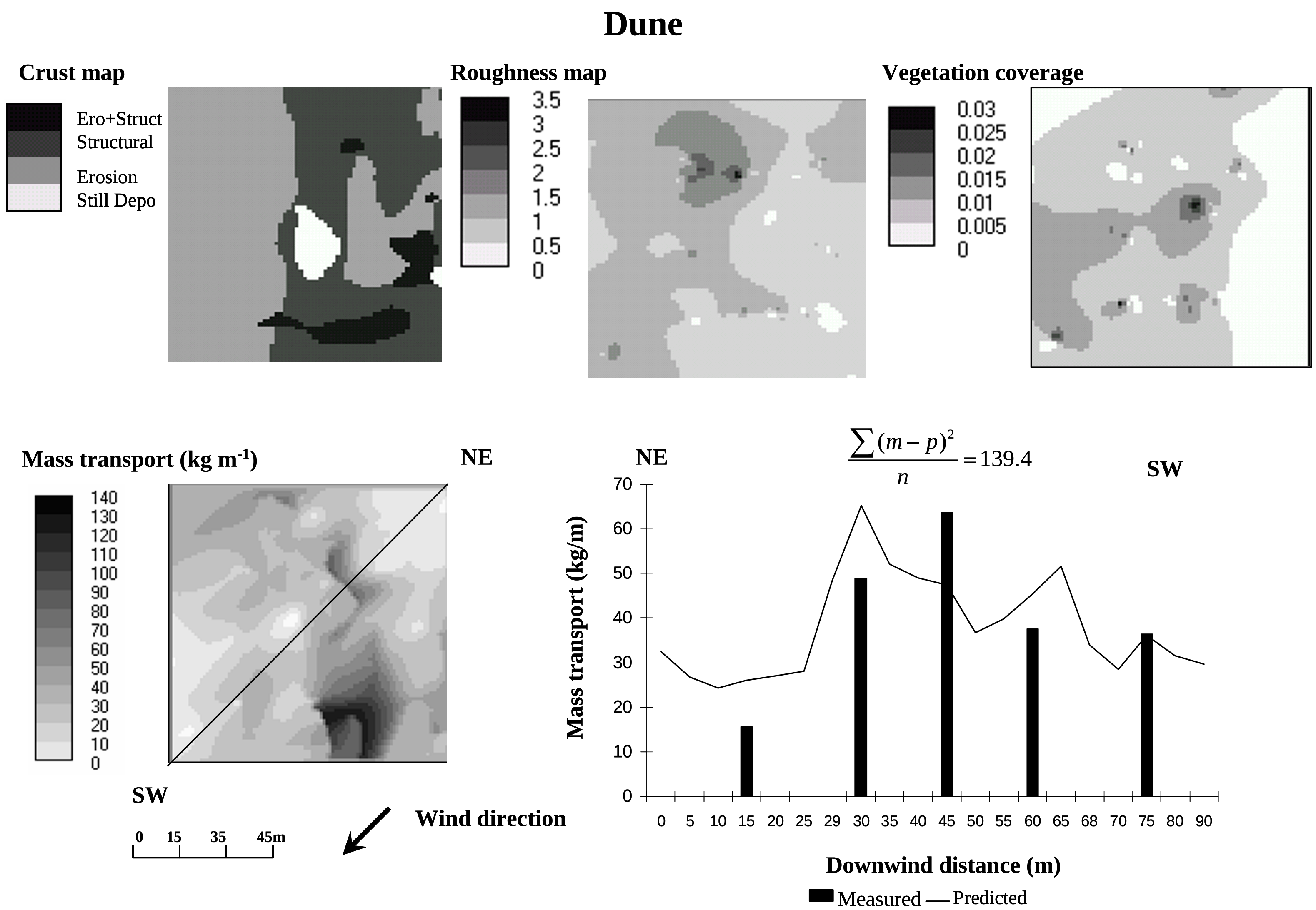

Figure 6) Distribution of the crust types, roughness, vegetation cover and predicted mass transport and transect of predicted and measured mass transport for the wind erosion event of 11 July 2001 at the dune in the Katchari catchment. The black line indicates the position of the transect. The transect should be read along the wind direction, positive gradients indicating erosion, negative gradients indicating deposition. Ero+struct; combined erosion and structural crust, structural; structural crust, erosion; erosion crust, Still Depo; still depositional crust (Valentin and Bresson, 1992).

Valley

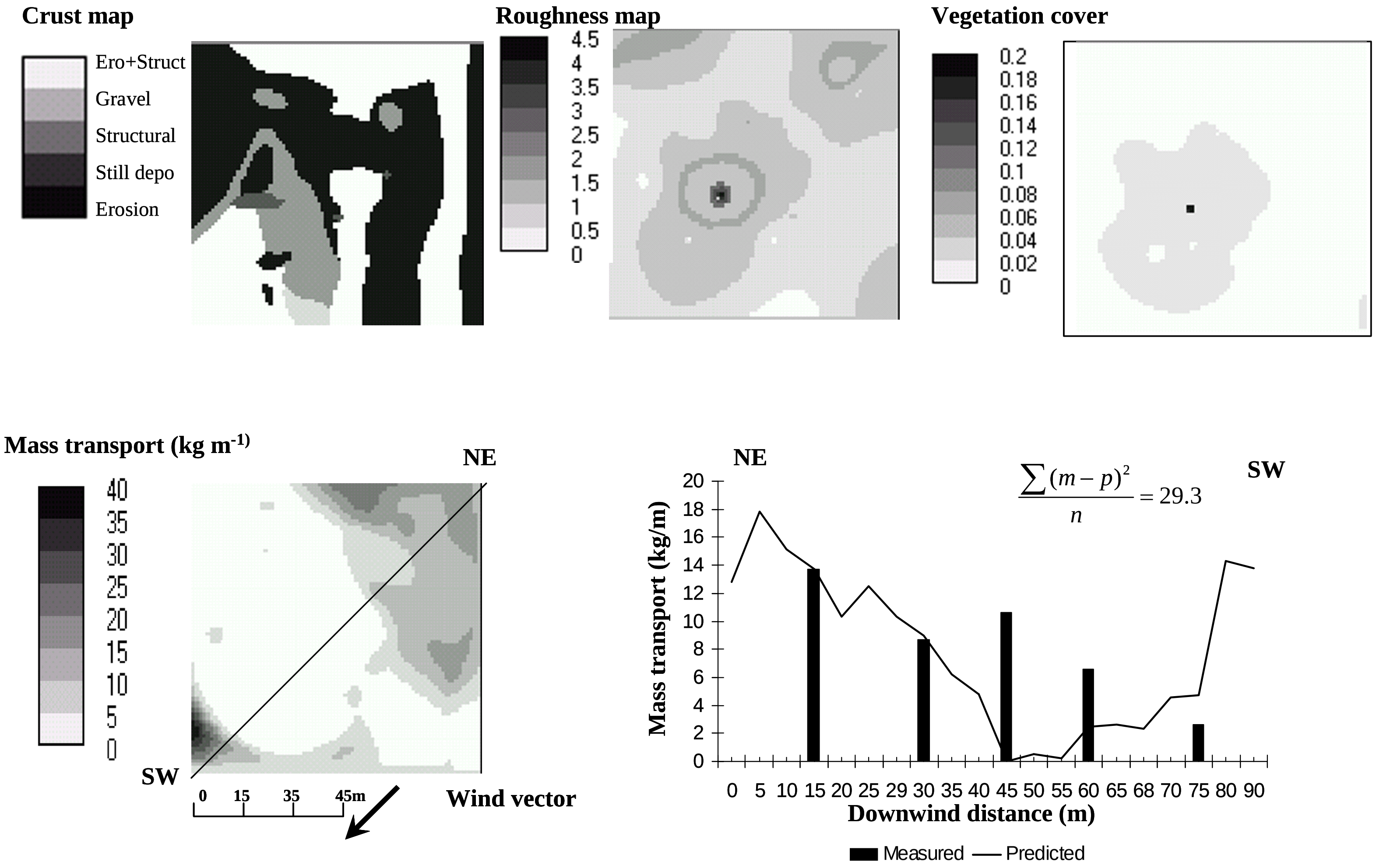

Figure 7) Distribution of the crust types, roughness, vegetation cover and predicted mass transport and transect of predicted and measured mass transport for the wind erosion event of 11 July 2001 at the valley in the Katchari catchment. The black line indicates the position of the transect. The transect should be read along the wind direction, positive gradients indicating erosion, negative gradients indicating deposition. Ero+struct; combined erosion and structural crust, structural; structural crust, erosion; erosion crust, Still Depo; still depositional crust (Valentin and Bresson, 1992).

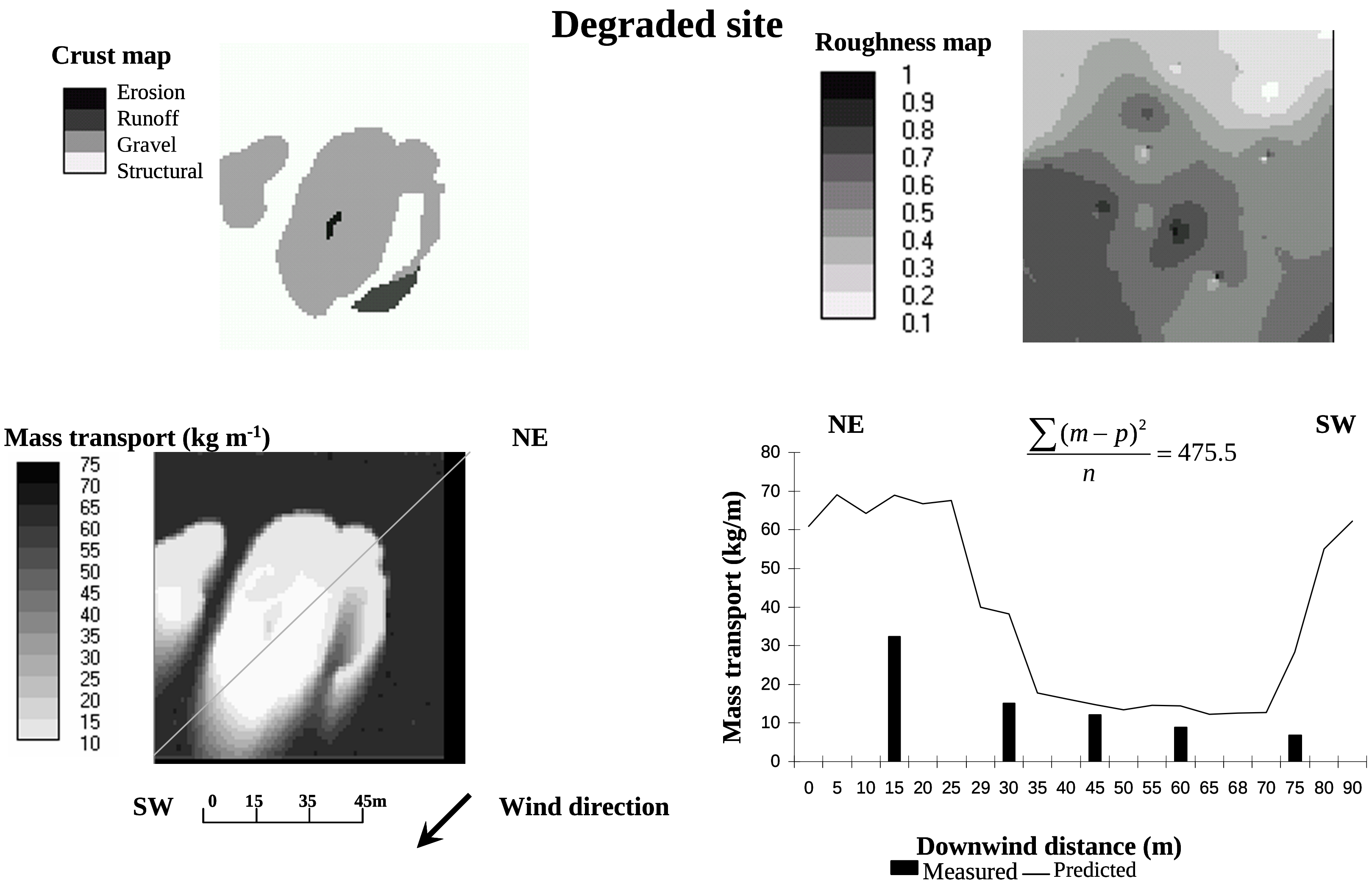

Figure 8) Distribution of the crust types, roughness, vegetation cover and predicted mass transport and transect of predicted and measured mass transport for the wind erosion event of 11 July 2001 at the degraded in the Katchari catchment. The black line indicates the position of the transect. The transect should be read along the wind direction, positive gradients indicating erosion, negative gradients indicating deposition. Erosion; erosion crust runoff; runoff depositional crust, gravel; gravel crust, structural; structural crust (Valentin and Bresson, 1992)

were not measured. A possible explanation for this is that WEPS initially assumes that the loose material at the crust has the same size distribution as the soil under the crust. However here the loose material on top of the crust is merely a lag deposit of rough sand (Fig. 9), which will generally be transported in creep mode. Here it might have been better to use the size distribution of the loose material on top of the crust as an input parameter.

Figure 9) Combined structural and erosion crust at the degraded site

Conclusion

After testing the Revised Wind Erosion Equation (RWEQ) and the Wind Erosion Prediction System (WEPS) on their spatial predictions of wind-blown mass transport at three geomorphic units in the Katchari catchment in northern Burkina Faso it was concluded that RWEQ is not suitable and WEPS in PCRaster is suitable for application in the Sahel.

RWEQ gave a good estimation of the critical field length (s_p) but poorly predicted maximum mass transport (Q_{maxp}). Furthermore, due to the poor prediction of Q_{maxp}, $Q(x)_p$, which depends strongly on Q_{maxp} and s_p, was also under-predicted. At our site little soil cover by dead or living vegetation was present. Hence the most important factors in determining Q_{maxp} were the crust factor (SCF) and the erodible fraction (EF). For successful application of RWEQ in the Sahel it appears necessary to adjust the formulas calculating SCF and EF. In addition, the structure of RWEQ may limit its successful application. First of all the required non-eroding boundary is seldom present at Sahelian fields. Application of eq. 9 might circumvent this problem. However, there are still uncertainties about eq. 9 because this formula is not yet tested. RWEQ further assumes a field that is more or less homogeneous for vegetation cover, management and roughness. But such fields are seldom found in the Sahel. Therefore, despite some good results in the USA, it is concluded that RWEQ as it is, is not suitable for application in a Sahelian environment.

WEPS only gave a good estimation of the roughness length on a non-cultivated field without natural vegetation and low mulch cover. For fields with natural vegetation at and around the research plot, the roughness length was underestimated. But when provided with a good estimate for the roughness length, WEPS gave, in all cases, a good estimation of the friction velocity and correctly predicted time of initiation and cessation of transport assuming a dry soil surface (Fig. 5). Furthermore the model gave an acceptable prediction of the spatial distribution of mass transport at the research sites. Therefore it is concluded that WEPS in PCRaster is suitable for prediction of wind erosion in a Sahelian environment. To obtain even better predictions, the effect of sparse, scattered vegetation should be included in the model. A constraint for using WEPS in the Sahel is that a WEPS prediction of spatial variation in sediment transport is closely linked to the spatial variation in the input parameters. Therefore, one needs accurate estimations of the spatial variation of all input parameters, and this might be an expensive assignment.

Acknowledgments

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Chapter 6

Water erosion modelling in a Sahelian environment

“application of a physically based model on a gentle sloping area”

S.M. Visser, G. Sterk and D. Karssenberg

Submitted to: Earth Surface Processes and Landforms

Water erosion modelling in a Sahelian environment
“application of a physical model on a gentle sloping area”

Abstract

Water is a major limiting factor in arid and semi-arid agriculture. In the Sahelian zone of Africa, it is not always the limited amount of annual rainfall that constraints crop production, but rather the proportion of rainfall that enters the root zone and becomes plant-available soil moisture. Maximizing the rain-use efficiency and therefore limiting overland flow is an important issue for farmers. Apart from carrying away the valuable water, once runoff is generated, it causes erosion and is the transporting agent for dislodged soil particles and plant nutrients. The objectives of this research were to model the processes of infiltration, runoff and subsequent erosion in a Sahelian environment and to study the spatial distribution of overland flow and soil erosion.

A wide variety of water erosion models exist. These models are generally developed for catchments where rill and gully flow are the main eroding processes. Furthermore, though applied on Sahelian situations these models were not developed for the Sahel and so do not include the unique Sahelian processes.

The topography of the Sahelian agricultural lands in northern Burkina Faso is such that slopes at farmers’ fields are generally low (0-5 degrees) and overland flow mostly occurs in the form of sheet flow. Despite the low sediment transport capacity of sheet flow, this type of flow might transport relatively large amounts of fine, nutrient rich particles, resulting in a degradation of the nutrient content of the topsoil. Furthermore, pool formation occurs in the fields, limiting overland flow and causing resettlement of sediment resulting in the development of a surface crust.

The EUROSEM model was rewritten to the dynamic modelling code of PCRaster and extended to account for the pool formation and soil crusts. The modelling results were calibrated with field data from the 2001 rainy season in the Katchari catchment in northern Burkina Faso. It is concluded that the adapted version of EUROSEM for the Sahel is a fully dynamic erosion model, able to simulate infiltration, runoff routing, pool formation, sediment transport and erosion and deposition by inter rill processes over the land surface in individual storms at the scale of runoff plots and fields. A good agreement is obtained between simulated and measured amounts of runoff and sediment discharge. However, since crust development in the Sahel has large influences on infiltration capacity and sediment detachment, crust development during the simulated event should be incorporated in a water erosion model.

Introduction

Approximately 90% of the population in the Sahelian zone of Burkina Faso lives from self-sustaining agriculture (Thiombiano, 2000). The sedentary farmers often combine animal husbandry with rain fed crop production. The principal crop is pearl millet (*Pennisetum glaucum*), which is often intercropped with cowpea (*Vigna unguiculata*) or groundnut (*Arachides hypogaea*) (Spencer and Sivakumar, 1987). Rapid population growth has resulted in the expansion of the cropped area onto more marginal land, which was previously used as communal grazing land. The use of the fallow systems, traditionally used for restoring soil fertility, has been dramatically reduced till the point the system is no longer used in certain areas (Ramaswamy and Sanders, 1992; Thiombiano, 2000). Consequently, larger areas are stripped from their vegetation and left bare and vulnerable for erosion by both wind and water in the early rainy season.

The Sahelian soils, which have generally a sandy to sandy loam texture, are characterised by a low organic matter content and low soil fertility. The soils are prone to crusting and have low water holding capacities (Valentin, 1995). In addition the climatic conditions are harsh. In the early rainy season the rainfall comes with short highly intense events and is often preceded by wind erosion events. Furthermore, Sahelian rainfall has a large variation both within a year and between years. Generally annual rainfall decreases from South to North, but the coefficient of variation in yearly average rainfall increases from South to North. So with decreasing average rainfall the variation increases. The combination of the highly variable rain, the high temperatures, a potential evapo-transpiration exceeding precipitation for most of the year and poor soils make agricultural crop production difficult (Sterk, 2003). Although water is a major limiting factor in the Sahel (Lal, 1988), it is not always the amount of rainfall, but rather the proportion of rainfall that becomes plant available soil moisture that limits crop production (Sivakumar and Wallance, 1991). Due to crust formation, which significantly decreases infiltration rate, large amounts of rainfall are lost in the form of overland flow (generally sheet flow) and evapotranspiration (in the case of stagnating water). Apart from carrying away the valuable water, once overland flow is generated it causes erosion and is the transporting agent for dislodged soil particles and plant nutrients. Generally sheet flow is a thin laminar flow with a low transport capacity. However, combined with intense rainfall, sheet flow becomes turbulent and might transport large amounts of fine, but nutrient rich particles, resulting in a degradation of the nutrient content of the topsoil (Guy *et al.*, 1987). The combination of the limited availability of water and the continuous degradation of the topsoil forms a serious constraint for agricultural production. Furthermore, overland flow might also cause direct damage to the crop. Young plants are damaged by the effect of flowing water and plants die because of the effects of stagnating water. Both processes result in reduced yields (Veihe, 2000). Hence, conservations tools to limit overland flow generation and water erosion are necessary. However, in the Sahel soil conservation possibilities are limited, and it is important to warily manage them.

To be able to use soil and water conservation tools most effectively or to develop new tools for water erosion control a good insight in the erosion processes is necessary. A process-based water erosion model developed for the Sahelian situation would be a useful tool in the battle against erosion since it gives insight in the interaction of the various controlling processes. Furthermore such a model could predict erosion risk under various land management practices.

Present water erosion models are mostly developed for application on sloping areas in western, modern agricultural systems. Whereas these models include specific processes such as e.g. the limited infiltration in wheel tracks, they lack the specific Sahelian processes. First of all, large cultivated areas in the Sahel have low slopes but are subject to water erosion. Whereas specific water erosion processes, such as rill and gully formation do not occur, overland flow does occur in the form of a turbulent sheet flow. The transport capacity of this flow is increased by the impact of wind-driven rainfall. Hence sheet flow in this area can transport large amounts of fine, but nutrient rich particles.

Due to the small topographic differences pool formation occurs, resulting in reduced overland flow discharge, but also in dying crops due to stagnating water and crust development. Crust development in the Sahel has large influences on infiltration rate and sediment availability. Therefore preferably crust development but at least the spatial distribution of crust types in the field should be incorporated in a Sahelian water erosion model. Furthermore, pool formation traps large amounts of water and sediment, limiting total runoff. This process should be incorporated in a water erosion model applied in the Sahel.

In the present study a physically-based model that incorporates all water erosion controlling processes in a Sahelian environment is developed. The model is calibrated and tested with field data from the 2001 rainy season in the Katchari catchment in northern Burkina Faso.

Model description

General structure of the model

The European Soil Erosion model (EUROSEM) (Morgan, 1995; Morgan *et al.*, 1992) was rewritten to make it applicable for the Sahelian situation. EUROSEM was previously applied outside Europe, and though the model needed calibration for individual catchments, the results were promising (Veihe *et al.*, 2001).

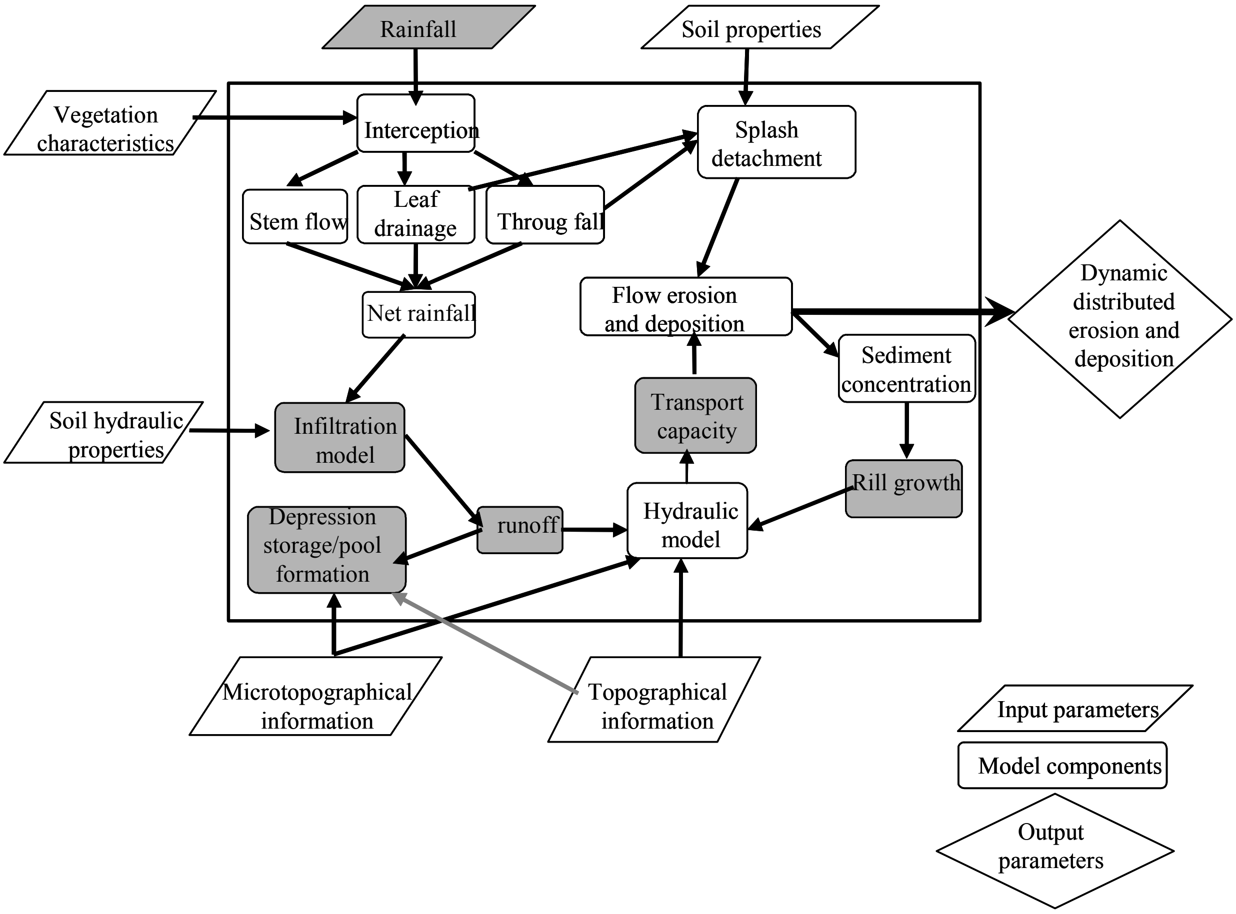

Figure 1) Flow chart of the European Soil Erosion Model (EUROSEM) (Morgan et al.*, 1992). Grey boxes indicate the modules, which are adapted for Sahelian environments.*

EUROSEM is the result of a collaborative research programme involving scientists from ten European countries and the USA. Considering that erosion is dominated by only a few events per year, which are characterised by a highly dynamic behaviour, EUROSEM is developed as an event-based model designed to operate for successive short (e.g. one minute) time steps within a storm. The model simulates erosion on a single plane or segment. Each segment is assumed to have uniform properties. Linking various segments with different properties account for the spatial variability in input parameters at a hill slope. By joining these hill slopes with channel elements, small catchments can be represented.

EUROSEM has a modular structure (Fig. 1). The grey boxes in Figure 1 indicate the modules, which are adapted for Sahelian environments. Most key equations of the model are given in Table 1.

Table 1) Operating equations of the European Soil Erosion Model as used in this research (for brevity some equations have been excluded).

No	Model subroutine and key equation	Definition of terms	Source
I	Interception: $I_c = RP_c$	R; depth of rainfall (mm); P_c; percentage of canopy cover expressed as a ratio	Merriam (1973)
II	Interception storage: $I_{cs} = I_x(1-e^{(R_c-I_x)})$	I_{cs} ; interception storage (mm), R_c ; cumulative rainfall (mm), I_x ; maximum interception storage (mm)	Van Elewijck (1989)
III	Surface runoff continuity equation; $q_{(x,t)} = \left(\frac{\delta h}{\delta t}\right) - \left(\frac{\delta Q}{\delta x}\right)$	$q_{(x,,t)}$; lateral inflow rate ($m^3 s^{-1}$), t; time step (s)	Woolhiser *et al.* (1990)
IV	Soil detachment by rain; $D_s = kK_e \exp^{-bh}$	k; detachability of the soil ($g J^{-1}$), K_e; kinetic energy of the rain ($J m^{-1}$ per mm of rainfall), b; exponent (1 to 3), h; water depth at the soil surface (m)	Brandt (1989)
V	Kinetic energy leaf drainage; $K_e(LD) = (15.8P_h^{0.5}) - 5.87$	K_e(LD); kinetic energy ($J m^{-2}$ per mm of leaf drainage), P_h; height of the plant canopy (m)	Brandt (1989)
VI	Soil detachment by flow; $D_F = \beta\Omega v_s(C_m - C)$	C_m; equilibrium sediment concentration in the flow ($g m^{-3}$), C; actual sediment concentration ($g m^{-3}$), β; resistance of the soil to detachment (kPa), Ω ; stream power ($g cm^{-1} s^{-1}$), v_s; settling velocity of the soil particle (m/s)	Smith *et al.* (1995)
VII	where; $\Omega = uS$	u; mean flow velocity (cm/s), S; slope (deg)	Govers (1990)
VIII	$TC = \frac{b}{\rho_s q}\left((\Omega - \Omega_c)^{0.7/n} - 1\right)^n$	TC; transport capacity ($kg m^{-3}$), b; function of particle size (m), Ω; stream power ($g cm^{-1} s^{-1}$), Ω_s; effective stream power ($g cm^{-1} s^{-1}$), n; 5	Morgan *et al.* (1992)
IX	Sediment continuity equation; $q_s(x,t) = \frac{\delta(AC)}{\delta t} + \frac{\delta(QC)}{\delta x} - e(x,t)$	q_s; lateral input or extraction of sediment per unit length of flow ($m^3 s^{-1}$), A; cross sectional area of the flow (m^2), Q; discharge ($m^3 s^{-1}$), e; net pickup rate of sediment from the bed per unit length of flow ($m^3 s^{-1}$), x; horizontal distance (m)	Bennet (1974) Kirkby (1980) Woolhiser *et al.* (1990)

EUROSEM deals with the interception of rainfall by the plant cover; the volume of rainfall that reaches the ground as direct through fall and leaf drainage; the volume of depression storage caused by random roughness; the detachment of the soil by rainfall and overland flow; the transport capacity of the overland flow; and deposition of sediment (Fig.1, Table 1). Overland flow is routed over the soil surface using the kinematic wave equation (Eq. III, Table 1). Soil loss is computed as a sediment discharge, defined as the product of the volume of overland flow and the sediment concentration in the flow to give a volume of sediment passing a given point in a given time period. The computation is based on the dynamic mass balance equation (Eq. IX, Table 1). Soil erodibility is represented through the use of soil cohesion and an index expressing its detachability by raindrop impact. Rill and interrill processes are modelled explicitly with water and sediment routed from the interrill to the rill area. Vegetation or crop cover are incorporated into the model by their effect on: the volume and energy of the rain reaching the ground surface, infiltration, roughness imparted to the flow and reinforcement of soil cohesion by the root system. By describing the soil, micro topography and vegetation conditions associated with each soil conservation practice, soil conservation measures can be simulated.

Table 2) Parameters and input variables of the adapted EUROSEM model and measurement methods.

Parameter	Description	Method	Reference
DEM	Digital Elevation Model (m).	Height measured with a level in a 2 x 2 grid.	
Crust	Map with the distribution of soil crusts.	Description of crust type in two transects and at 17 fixed positions in the research site.	Valentin and Bresson (1992)
LDD	Map with local drain direction.	Calculated by PCRaster based on DEM and pool position (*see section pool formation).*	De Jong (1997)
Rain	Table with rain fall per minute (mm).	Field measurements with tipping bucket.	
Wind Speed	Table with wind speed per minute (m/s).	Field measurement with Vector wind anemometer.	
Wind Dir	Table with wind direction per minute (deg).	Field measurement with Vector wind vane.	
K_e	Saturated conductivity (cm/h).	Based on rainfall simulations and crust development.	Horstman (2003)
ψ	Wetting front suction head (cm).	Literature.	Chow *et al.* (1988)
θ_k	Residual moisture content.	PF-curve/literature.	Chow *et al.* (1988)
θ_e	Effective porosity.	PF-curve/literature.	Chow *et al.* (1988)
θ_I	Initial moisture content.	Field measurements with theta probe.	
Cover	Map with fractions of surface coverage by vegetation.	1m^2 square with wire mesh at 10 cm intervals, measurements made at 17 points in the research plot	Morgan *et al.* (1992)
LAI	Map with leaf area index.	Based on cover map and literature.	Morgan *et al.* (1992)
Crop Height	Average crop height (m).	Measured in the field with regular time intervals.	
Pool Map	Various maps for prediction of pool formation.	Base don DEM (*see section pool formation)*.	
SLRR	Random roughness	Saleh's chain method.	Saleh (1993)
N	Manning's N	Literature	Morgan *et al.* (1992)
K	Index of soil detachability.	Splash cups.	Poesen (1985)
D_{50}	Median grain size (cm)		
ρ_s	Particle density (kg m^{-3})	Literature	Kutilek and Nielsen (1994)
ρ_w	Water density (kg m^{-3})	Literature	Kutilek and Nielsen (1994)
Coh	Table with cohesion values of bare crust (kPa)	Thorvane measurements over the season.	Morgan *et al.* (1992)
AddCoh	Map with additional cohesion by vegetation roots	Based on cover map and literature.	Morgan *et al.* (1992)

Adaptation for the Sahel

The EUROSEM modules for precipitation, infiltration and overland flow routing were adapted for the Sahelian situation. Further a pool formation module was added to the model. These adaptations will be discussed in the following sections. The PCRaster version of EUROSEM (Van Dijck and Karssenberg, 2000) was used in this study. This version of EUROSEM mainly differs from the original version in that it is raster based and written in the environmental modelling language PCRaster (De Jong, 1997). The used version included only the water components of EUROSEM, but was extended here with the erosion components based on the work of Van der Perk and Slavik (2003). One of the main advantages of incorporating EUROSEM in PCRaster is the relatively open data structure of PCRaster, which allows the model builder to closely follow the erosion simulation and to relatively easily make model adaptations. Due to its physical character the model requires a large amount of input parameters. Table 2 shows all input parameters required for the model application in the Sahel and the measurement methods. In the following sections the main adaptations of the model and the field measurements are discussed.

Rainfall

In the early rainy season in the Sahel, rainfall comes with heavy thunderstorms that move westward through the Sahel. As a result of the strong winds the raindrops have a significant horizontal velocity, which increases their resultant impact velocity (Umback and Lembke, 1966). Furthermore, the distribution and intensity of rain on sloping surfaces is altered depending on wind direction and velocity.

Simple geometric relations were used to express the relation between the amount of rainwater intercepted in a rain gauge and the amount of rainwater reaching the soil surface (Fig. 2). The amount of water intercepted by a horizontally positioned rain gauge depends, besides *i* (angle of incidence (deg)), on the area X (m^2) of the gauge with diameter d_0 (m) (Fig. 2a and b).

When rain reaches the gauge with an angle $i \neq 0$, the effective area changes and the cross section of the column of rain intercepted by the gauge is elliptical, with area *Xcos(i)*. Hence the real rainfall intensity R (m/h) is related to the intensity intercepted by the gauge by (Sharon, 1980):

$$R = \frac{I}{\cos(i)} \qquad \text{(Eq. 1)}$$

where R is the intensity of rainfall in respect to a plane normal to the storm vector (m h^{-1}) and I is the intensity of rainfall measured with a horizontally placed gauge (m h^{-1}). In the case of a sloping surface, rain intensity can become higher or lower, depending on the slope aspect with respect to the wind direction (Fig. 2c and d). Hence the intensity at the slope surface is:

$$I_s = R\cos(i \pm \alpha) \qquad \text{(Eq. 2)}$$

where I_s is the rain intensity at the soil surface (m h^{-1}) and α; slope (deg).

To determine the angle of incidence the following equation was used (Sharon, 1980):

$$i = -0.2070\sqrt{\bar{u}} + 7.1378\bar{u} \qquad \text{(Eq. 3)}$$

where $\bar{u}$ is the wind speed (m s^{-1}).

The kinetic energy of a raindrop hitting the soil surface is an important parameter in determining the amount of splash detachment. A raindrop hitting the soil surface under an angle will exert a different energy to the soil surface as a raindrop hitting the soil surface from the vertical. The kinetic energy (J m^{-2} per mm of rainfall) of the wind-driven rain directly reaching the soil surface (direct through fall in EUROSEM) is given by (Pedersen and Hasholt, 1995):

$$KE = \gamma_1 \exp^{\beta_1 \bar{u}} \ln(I) + \gamma_2 \exp^{\beta_2 \bar{u}} \qquad \text{(Eq. 4)}$$

where γ_1 is 5.27, γ_2 is 10.61, β_1 is 0.07 and β_2 is 0.12.

Infiltration

The formation of a seal and crust at the soil surface alters the way water is partitioned at the surface, resulting in a decreased infiltration and an increased overland flow and erosion (Bristow *et al.*, 1994). The reduction depends upon the soil type, surface conditions and the rainfall's kinetic energy, intensity and duration. Even very sandy soils (90% sand) can experience reduced infiltration due to crust formation (Hoogmoed and Stroosnijder, 1984). Despite several studies there are still real difficulties in predicting the behaviour of crusts and in particular their effect on infiltration and overland flow. The mechanisms involved in the formation of the soil crust and the interactive effects of hydrological processes, the wind erosion processes and the development of a soil crust are not yet fully understood, especially in terms of the changes in pore structure and hence hydraulic properties with time. The generally, sandy, Sahelian soils are prone to crusting. Five main crust types can be identified: the structural crust, the erosion crust, the gravel crust, the runoff and the still depositional crust (Valentin and Bresson, 1992). The coarse pavement crust is generally found on degraded zones whereas all other crust types can also be found within cultivated fields.

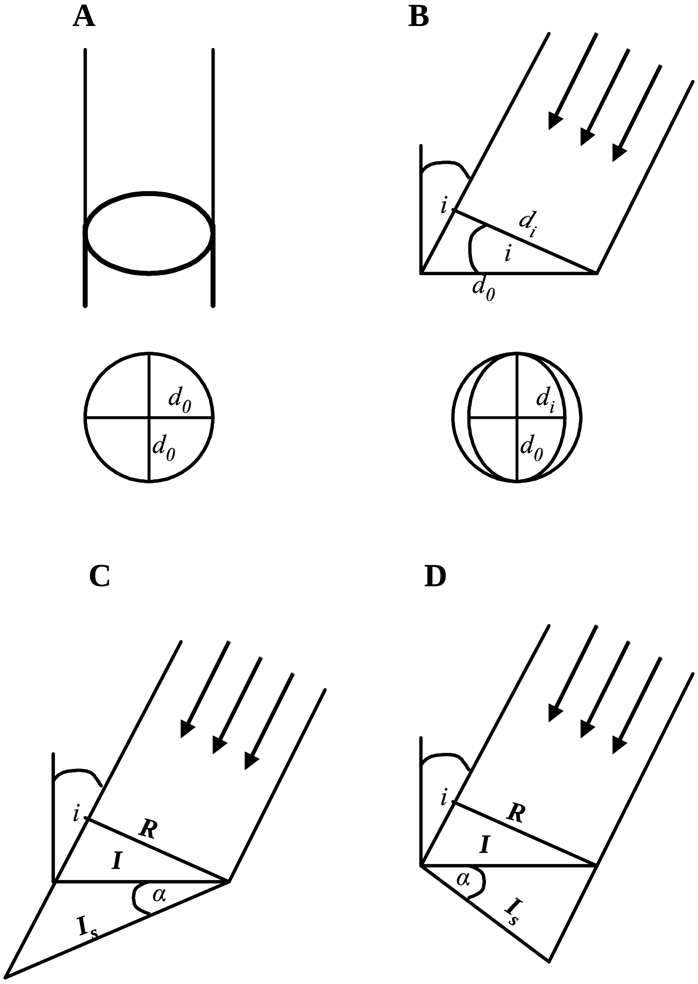

Figure 2) The effective area of the receiving area of a rain gauge relative to incoming rainfall: A) when i = 0*; and B) when* i ≠ 0*. The effective rain intensity at the soil surface of a sloping surface with aspect C) leeward from wind direction and D) windward from wind direction.* d_0;*diameter (m) of interception area when rain is falling vertical,* d_i; *diameter (m) of interception area when rain is falling under angel* i *(deg),* R*; intensity of rainfall in respect to a plane normal to the storm vector (m* h^{-1}*),* I*; intensity of rainfall measured with a horizontally placed gauge (m* h^{-1}*),* I_s*; Rain intensity at the soil surface (m* h^{-1}*) and α; slope (deg).*

A structural crust typically consists of two layers; at a depth of a few millimetres a plasmic layer is formed by the clay and silt particles that are washed out from the top layer by raindrops.This plasmic layer is covered by loose cohesionless sand, which can easily be transported by wind or water. When this loose layer is removed and the plasmic layer is exposed, the crust is called an erosion crust. The coarse pavement crust resembles the structural crust in that it has two layers, with one being a generally further

developed plasmic layer. This layer is overlain by coarse fragments, which are partly embedded in the plasmic layer. The still depositional crust develops in standing water and is characterised by a vertical particle size distribution with coarse particles at the bottom and the finer particles at the top. When this crust dries up, it often breaks up into curled-up plates. Runoff depositional crusts develop in flowing water and are characterised by a microbedded layer (Boiffin and Bresson, 1987). Runoff and disjunction between fine and coarse particles induce alternating sub-millimetric microbeds, which are more or less contrasted in texture and unconformable with the underlying soil. A structural crust often overlies this type of crust.

A two or three layered Green and Ampt approach to simulate infiltration into the crusted soil would be a straightforward approach. However, using this approach, detailed information about the crust thickness and the hydraulic conductivity of the crust and the undisturbed soil underneath is needed. These parameters are already difficult to determine in the laboratory, but in the field this becomes an unfeasible operation. Therefore, here a one layered Green and Ampt model is used using an effective hydraulic conductivity K_e (cm/s), which is a combination of the hydraulic conductivity of the soil crust and the underlying soil and has to be measured in the field.

Prior to ponding ($t<t_p$), rainfall intensity is less than or equal to the potential infiltration rate. In this period infiltration rate *f* is equal to the rain intensity I_s. Cumulative infiltration is calculated as:

$$F_t = F_{t-1} + I_s \Delta t \qquad \text{(Eq. 5)}$$

where F_t is the cumulative infiltration at the current time step (cm), F_{t-1} is the cumulative infiltration at the previous time step (cm), I_s is rain intensity at the soil surface (cm h^{-1}) and Δt is the duration of the time step (h).

Ponding begins when the rainfall intensity exceeds the potential infiltration rate ($t=t_p$). As rainfall continues ($t>t_p$), the saturated zone extends deeper into the soil and overland flow occurs from the ponded water. After ponding the cumulative infiltration is (Chow *et al.*, 1988):

$$F_t = F_{t-1} + K_e \Delta t + \psi \Delta\theta \ln\left[\frac{F_t + \psi\Delta\theta}{F_{t-1} + \psi\Delta\theta}\right] \qquad \text{(Eq. 6)}$$

Equation 6 is solved by the method of successive approximation to give F_t.

In the Green and Ampt equation the infiltration rate *f* (cm h^{-1}) and the cumulative infiltration *F* are related by (Chow *et al.*, 1988):

$$f_t = K_e\left(\frac{\psi\Delta\theta}{F_t} + 1\right) \qquad \text{(Eq. 7)}$$

where ψ is the wetting front capillary pressure head, $\Delta\theta$ is the difference between the initial and the final moisture contents of the soil (-).

Determination of ponding time under rainfall of variable intensity is done by the following approach (Chow *et al.*, 1988). Cumulative infiltration is calculated from rainfall as a function of time using equation 5. A potential infiltration rate can be calculated from the cumulative infiltration using the Green and Ampt infiltration equation (Eq. 7). Whenever rainfall intensity is greater than the potential infiltration rate ponding occurs, for the next time step equation 6 should be used for calculating the cumulative infiltration. When rain intensity drops again below the potential infiltration rate, equation 5 is used again to calculate cumulative infiltration.

Overland flow

Due to the small differences in topography, concentration of flow hardly occurs and overland flow generally occurs in the form of sheet flow. Traditionally, the rill and inter-rill processes are modelled in such a way that detachment by flow occurs only in the rill area and splash erosion detachment occurs only in the inter-rill area.

Since rill erosion does not occur in the described research areas and to enhance model speed, the rill erosion formulas are left out of consideration in this model. However, it is acknowledged that transport capacity of sheet flow will become higher due to the effect of rainfall.

The following equation for the raindrop impact contribution to the transport capacity of sheet flow is used (Guy *et al.*, 1987):

$$TC_r = 4.909 * 10^6 I_S^{2.014} S^{0.865} \qquad \text{(eq. 8)}$$

where TC_r is the additional transport capacity (kg m^{-1} s^{-1}), I_s is the rainfall intensity (m s^{-1}), S is the slope (m m^{-1}).

Total transport capacity of the sheet flow will be equal to transport capacity (TC) as calculated by EUROSEM (eq. VIII, Table 1) plus the additional transport capacity (TC_r).

Deposition will occur when the sediment load becomes higher than the transport capacity. The rate of deposition depends on the distance the sediment has travelled and the settling velocity. The following equation is used to determine the settling velocity (Marshall and Holmes, 1979):

$$v_s = 2(\rho_s - \rho_w) g \frac{\sqrt{D50/2000000}}{9\upsilon_w} \qquad \text{(eq. 10)}$$

where v_s is the settling velocity (m s^{-1}), ρ_s is the particle density (kg m^{-3}) ρw is the density of water (kg m^{-3}), g is the acceleration of gravity, $D50$ is the median grain size (cm) and υ_w is the viscosity of water.

Pool formation

Due to the small height differences in the topography in the Sahelian zone of northern Burkina Faso, pool formation occurs, limiting overland flow discharge and causing resettlement of sediments. These pools generally have a depth of several centimetres, but might extend over several tens of meters. Infiltration in these pools is often low due to the development of a still depositional crust. Due to low infiltration capacity and the large surface, most of the water evaporates fast in the hours after the rainfall event.

The input parameters necessary for simulation of pool formation are calculated on basis of information of a Digital Elevation Model (DEM) of the terrain. Based on this DEM a Local Drain Direction map (LDD) can be created. A LDD gives for each cell the stream direction of water and sediment flowing through that cell. Cells that do not border on lower situated cells form pits. Pits are cells without a flow direction. In the

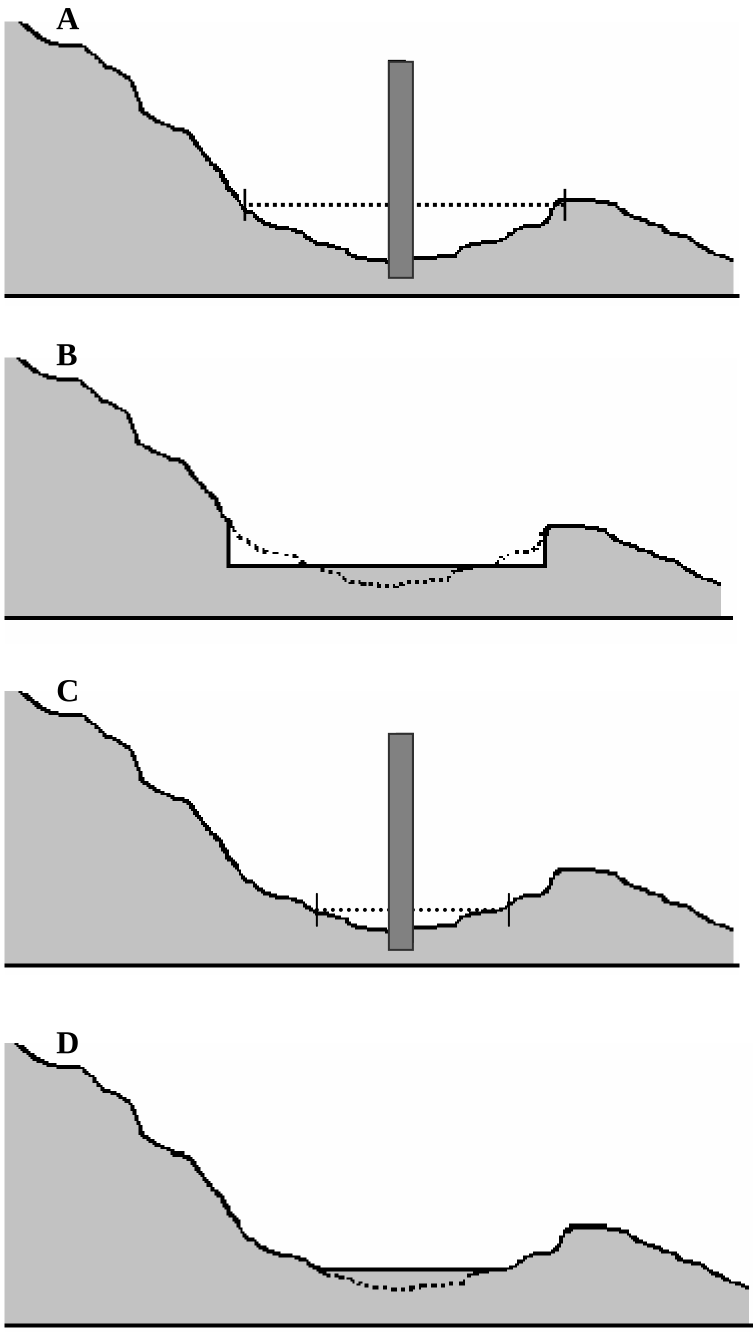

Figure 3A) Cross-section of the DEM with at the pool pit the available amount of water for pool formation. The dashed line indicates the area with the maximal pool extension. B) Cross-section of the DEM after mediation of the available water with the maximal extension area of the pool. The dashed line indicates the original form of the DEM. C) Cross-section of the DEM, with at the pool pit the available amount of water for pool formation. The dashed line indicates the area where the pool will be calculated the second time. D) Final cross-section of the DEM after the pool area and water mirror have been calculated.

case of pool formation pits are created at the deepest point in the pool. The map with the location of the deepest points of the pools is an input map of the model.

For each pit its sub-catchment is determined. Then by using information of the DEM, the position and altitude of the points where the pool will overflow can be determined. The map with the locations of the overflow points is input for the model. Based on the height of the overflow points, the maximal extension and volume of the pools can be calculated, which are also input parameters. Finally the LDD should be adapted so that the water will be directed towards the outflow point instead of to the pool pit. This is achieved by adding the maximum height of water (m per cell size) to the original DEM and calculating a new LDD based on the “full” DEM. This LDD map will also be input to the model.

Simulation of pool formation is based on a method described by Van der Plank (2002) and simulated as follows. All the water that has reached the outflow point, plus the rain in the pool, plus the water already in the pool is directed to the pool pit, which results in a water tower in this cell. This water tower map is at all points equal to the original DEM (m) except at the pool pits, where all the available water (m) is added to the DEM (Fig. 3A). If the water tower at the pit contains a larger volume of water than the maximal volume of water that can be stored in the pool, the remainder is directed to the outflow point and will be regarded as water added to the stream flow in the downstream cell.

The amount of water in the water tower should be spread over the pool area. Since the pool bottom is not flat, it is not exactly known over which area the available water should be spread. To determine the exact pool area the model starts with the assumption that the pool has its maximum extension (which is an input parameter in the model). The available amount of water in the water tower will be averaged over the pool area. This results in an area, which is partly lower than the original DEM (Fig. 3B). The water level in the lower parts is actually lower than the water level should be since also the higher areas of the DEM, which actually are outside the pool area, are included.

Because the water level can’t be lower than the height of the original DEM, the cut-line between the original DEM and the calculated water level can be seen as the new maximal extension of the pool. When mediation of the water over this smaller area is performed, the calculated area of the water level will become more precise (Fig. 3C). Even now there will be an area lower than the original DEM, but this area will be substantial smaller than that after the first mediation. Theoretically, after each mediation the height of the water mirror and the maximum extension of the pool will become more precise, but the perfect height and extension will never be reached. However, the error will become smaller after each mediation and after a certain number of repetitions become nil or fall within the resolution of the raster (Fig. 3D).

After the water height in the pool is determined, infiltration occurs over the whole pool area. In the next time step new water can be added to the pool.

In nature the flow direction of water in and to a pool changes with pool development. At the onset of pool formation all water streams in the direction of the lowest point. As soon as the pool is full the flow direction changes towards the point where the pool overflows.

In order to avoid problems with working with several LDD’s (starting with the original one directing water to the pool pits and ending with the “full pool” LDD) it was decided to work only with the “full pool” LDD. All water that reaches the outflow point of the pool is redirected to the pool pit till the maximum pool volume is reached. This solution works well for the water part of the model; however for the sediment part another scenario has been developed. As soon as the overland flow reaches the pool area, the transport capacity will become zero and deposition will occur. However, since we do take the settlement velocity into account, not al sediment is deposited at the pools borders, but deposition will decline towards the outflow point.

This solution will create a small error in the area where the actual drain direction is opposite to the overall drain direction of the “full pool” LDD. It is assumed that these slopes do not contribute much to the sediment budget of the pool since they will be covered with water in an early stage of the rainfall event. Detachment in this area will be greatly limited. Furthermore, these slopes do not have a large sediment contributing area.

Research area

In the Sahelian zone of northern Burkina Faso five main geomorphologic units can be distinguished. The gentle sloping pediplanes are interrupted by the smoothened ancient dune complexes, temporally flooded rivers, young dunes, which might still be active, and by small hills, which pop up in the landscape as anthills (Zerbo, 1993). The hills are geologic remnants and have a height of 100-200 m covering only small part of the landscape. When stabilised, the young dunes are often cultivated. The young dunes generally have steep slopes and high infiltration capacities. The ephemeral rivers are deeply incised and carry water only during and shortly after heavy rainfall events. The rivers are often bordered by a band of dense vegetation up till 50 m from the riverbed. The area directly next to this band of vegetation is often cultivated. Approximately 90 % of the ancient dune is cultivated and the pediplanes are generally used as grazing zone. At the ancient dunes, the area next the rivers and at the pediplane slopes are generally low (0-5 degrees) and runoff mostly occurs in the form of sheet flow. Due to the small height differences, pool formation occurs, limiting runoff discharge and causing resettlement of sediment.

The Katchari catchment is situated in the Seno province in northern Burkina Faso (14˚00”, 0˚00”W), 11 km West from Dori, the province capital. The climate is characterised by a short rainy season of 3-4 months starting in May- June. The mean annual precipitation is approximately 480 mm, but can be highly variable from year to year. Generally the first rains come from the East. Over the season rainfall depth and occurrence can be highly variable as can be seen from Figure 4 A and B. Temperatures are high all year round, but two hot periods can be distinguished; the first starts in April and lasts till the beginning of the rainy season, the second immediately follows the rainy season (September) and lasts till the onset of the Harmattan winds in November-December.

Measurements were performed at three different geomorphologic settings; a degraded site, a cultivated field next to the ephemeral river (from now on referred to as valley) and a field at an old dune complex. The degraded site is characterised by its lack of vegetation and a well-developed coarse pavement crust, which covers approximately 75% of the research plot. The coarse pavement crust consists of a well-developed erosion crust, with gravel embedded and overlain by loose gravel with a coverage of 30-70%. An erosion crust with significantly less embedded gravel covers the other 25% of the research plot. The research site at the valley floor is cultivated with millet in the wet season and characterised by a fast development of erosion and still depositional crusts (Valentin and Bresson, 1992). Natural vegetation (trees and herbs) is scattered over the field. Annual herbs are removed by hoeing twice in the wet season. At the southern-centre part of the research plot a still deposition crust had developed. At this part of the field no millet was sown nor was it tilled during the research period. The dune site is part of an old and flattened dune band that belongs to an extensive sand dune system, which is more than 40.000 years old (Courel, 1977). The loamy, sandy soils of this dune complex are prone to crusting, with structural and erosion crusts being the most common. Also at the dune site natural vegetation is present; however trees and shrubs are more used to demarcate fields. Within the cultivated fields trees are rarely found.

All fields are characterised by an undulating topography. Maximum height differences within the site on the dune were approximately 0.5 m. At the valley floor and the degraded site the distances between depressions and crests ranged from 10 to 40 m with maximum height differences of approximately 1m.

Measurements

During the rainy season of 2000 and 2001 field data of water erosion events were collected at the three sites in the Katchari catchment. The degraded site and the dune site were equipped with a complete weather station continuously measuring average wind speed and direction, average temperature and total rainfall at one-minute intervals. Average soil moisture content and total solar energy were continuously measured at five-minute intervals. Since the research site at the valley was situated less than 500 m from the degraded site, weather data from the degraded site was used for the valley during the 2000 rainy season. During the 2001 rainy season the valley site was equipped with an automatic rain gauge, which measured rainfall amounts at one-minute intervals.

At each site three runoff plots were installed; one with an area of 1 m^2 (1x1 m) and two with an area of 20 m^2 (10 m length, 2m width). Each plot was closed at its upper boundary so that run-on was not possible. The positions of the plots in the research site were chosen so that they were representative for the whole site with regard to the slope, crop coverage and crust type.

Under the 1-m^2 plots an automatic tipping bucket was installed, which recorded overland flow intensity at one-minute intervals. These measurements were used to compare measured time to ponding and peak discharge of overland flow with model predictions of these variables. Time to ponding is defined as the moment of first measurement of overland flow since to onset of rainfall. Furthermore, total measured overland flow at the 1-m^2 plots was compared with the model predictions. The field measurements at the 1-m^2 plots were used to calibrate the model.

Overland flow and sediment load from the 20-m^2 plots was captured in four oil-barrels at the end of the plot. The oil barrels could trap a maximum of 600 litres of water, which was similar to 30 mm of overland flow. After a rainfall event total collected overland flow was measured with a precision of 0.5 l. All water and sediment of the first two oil barrels was deposed into two large buckets and left alone for 48 hours so that resettlement of sediment in suspension could occur. After this time period the water was poured and the sediment was collected, sun-dried for at least 5 hours and weighted. These measurements were used to compare measured total overland flow and total sediment load with model predictions.

The types of crust found in the field are usually related to topography and surface hydrology (Philibert, 2000; Valentin and Bresson, 1992). So, to get an impression of the flow direction and areas of erosion and deposition in the research sites, descriptions of crust development on the research plots were made during the 2001 rainy season. After each event crust development was described for two transects (one from NE to SW and one from NW to SE) and the topography of transects was measured with a level four times trough the rainy season. Furthermore the crust type at 17 fixed positions distributed over the research sit was described after each rainfall event. Comparing crust development as found in the field with the model predictions of the distribution of erosion and deposition in the field will give an indication of the precision of the model. Furthermore, the positions of pool formation could be identified by the occurrence of a still deposition crust and compared with the position of pools based on the DEM.

Input values for the effective hydrologic conductivity (K_e) were based on work of Horstman (2003) who measured the effect of crust development on infiltration characteristics with a disc-infiltrometer in the Katchari catchment. Infiltration values just after ploughing were based on literature (Chow *et al.*, 1988). Since K_e is related to crust type, a non-uniform distribution of the K_e input value over an uniform land use unit is obtained as an input parameter of the model.

The detachability of the soil by raindrop impact (k, Table 2) is expressed as the weight of soil particles per unit of rainfall energy (g J^{-1}). It is measured in the field with splash cups (Poesen, 1985), and corrected for the effect of cup size (Poesen and Torri, 1988). Since crust development causes a further compaction of the topsoil, more energy will be needed to detach the same amount of soil once a crust is formed. Measuring soil detachability with splash cups should be performed at a bare soil (Morgan *et al.*, 1992). After consulting the owner of the fields of the valley and the dune, it was agreed that a part of the field was left uncultivated to be able to perform measurements with splash cups. Though this allowed us to perform measurements through the time, it did not allow us to measure at the various crust types. So soil detachability at one moment in time was taken as uniform for the whole research site, which could lead to errors in model prediction.

Results discussion

In the 2000 rainy season rainfall started at 19 July with a large event of 62 mm within 2½ hours (Fig. 4A). This event was followed by a dry period of 4 weeks, which forced the farmers to re-sow their fields. The third rainfall event at 8 July was once again a large event; this time of 54 mm. Total rainfall in the 2000 rainy season was 382 mm.

In 2001, first rains fell in May, but since these were only small events and early in the season, farmers did not start to sow their field till after the rains of July 10. First and second cultivation occurred on 24 July and 18 August at the dune and at 30 July and 30 August at the valley site. Total rainfall in the 2001 rainy season was 360 mm.

Due to malfunction of equipment in the 2000 rainy season, for the 2001 rainy season a more complete and extended data set was available. Therefore, it was decided to calibrate and run the model for 11 events of the 2001 rainy season. Table 3 shows the total amounts of precipitation and duration of the selected events for each geomorphologic unit. Care was taken to select events that were representative for all events that occurred in 2000 and 2001 both for total amount of rainfall and duration of the event.

Rainfall and overland flow was simulated for all events at three different scales; small runoff plot (1m^2), large runoff plots (20 m^2) and research plot (6400 m^2). For simulation at the scale of both types of runoff plots pool formation was not considered, as the surfaces of these plots were relatively homogeneous, and without major depressions.

Model calibration at 1-m^2 runoff plots

The model was calibrated by varying the effective hydrologic conductivity (K_e) for each site and each crust type. Table 4 gives an overview of the final input parameters for K_e for each crust type.

Horstman (2003) showed that the effective hydrologic conductivity changes over time due to cultivation practices and crust development. Therefore this value changes over the season. Furthermore, Horstman (2003) found that the infiltration characteristics of the well-developed erosion and coarse pavement crusts at the degraded site and the still depositional crust at the valley (which had not been cultivated over 4 years) showed no decrease in infiltration capacity through time. For these crust types, once calibrated, the K_e values were taken as constant over the season (Table 4). Further it was decided to use constant K_e values for the erosion crust at the valley and the dune.

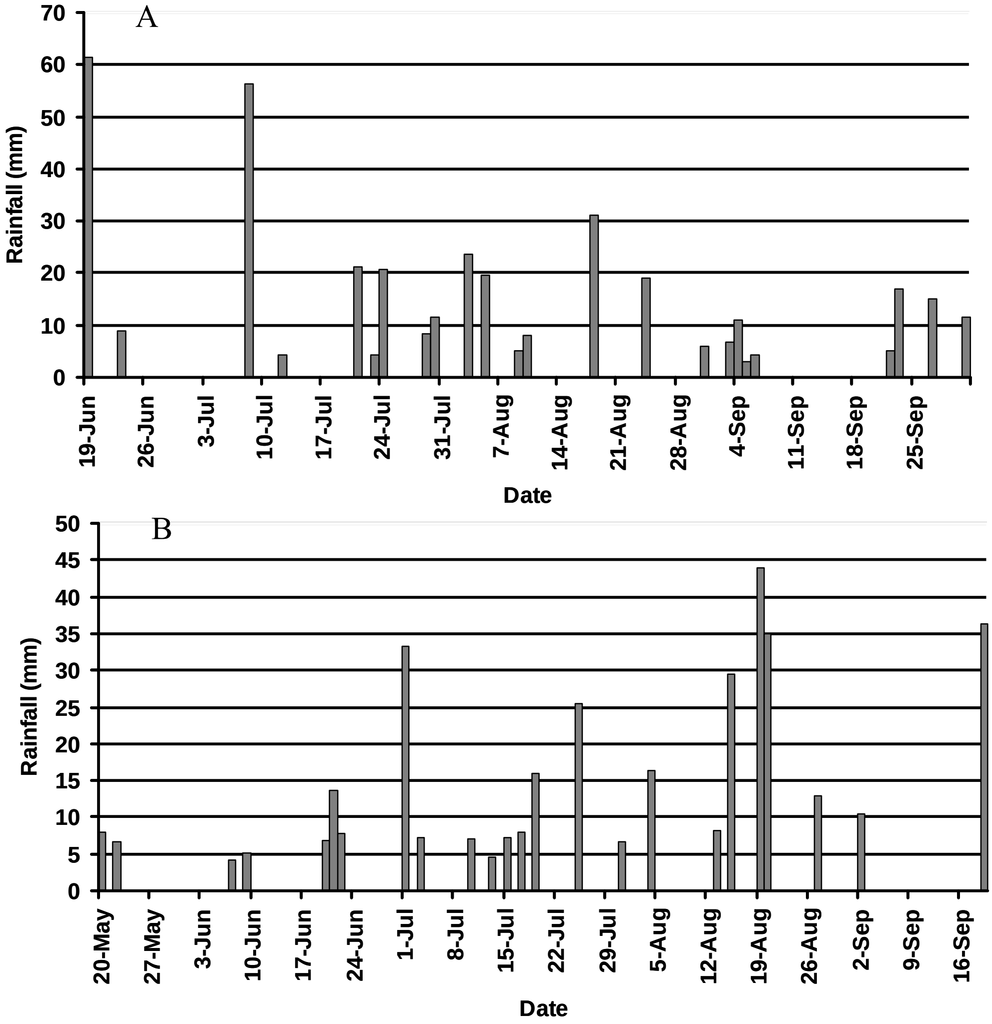

Figure 4) Rainfall at the degraded site in the Katchari catchment for the years 2000 (A) and 2001 (B)

Table 3) Measured and predicted runoff amounts on 1 m^2 plots during the 2001 rainy season. Plots were located at three geomorphologic units in the Katchari catchment , Burkina Faso. Rainfall (P), Duration (D), measured overland flow (R_m) and predicted overland flow (R_p), - = no measurements made.

Date	Valley				Dune				Degraded site			
	P (mm)	D (min)	R_m (mm)	R_p (mm)	P (mm)	D (min)	R_m (mm)	R_p (mm)	P (mm)	D (min)	R_m (mm)	R_p (mm)
June 21	13.2	45	3.8	3.8	13.3	46	-	4.2	13.1	48	10.3	6.1
July 2	17.4	76	-	5.1	30.1	94	-	17.2	30.2	95	-	19.9
July 25	23.5	186	8.1	9.1	23.5	215	6.4	6.2	23.2	215	8.1	11.2
Aug 4	10.5	202	0.0	0.0	11.7	48	0.0	0.0	11.5	49	3.4	4.2
Aug 14	4.9	13	2.2	3.2	6.9	11	2.0	2.3	16.8	11	-	4.7
Aug 15	26.2	194	9.9	9.1	28.6	230	15.4	11.0	28.6	230	15.8	16.2
Aug 19	16.6	193	17.4	16.0	29.3	191	6.9	6.3	43.0	198	-	25.9
Aug 20	34.0	65	26.2	22.8	27.6	62	13.8	13.8	33.8	67	-	24.6
Aug 27	13.0	24	-	7.3	9.5	23	-	3.1	11.8	25	6.4	7.0
Sept 2	9.2	214	-	0.0	8.6	251	-	0.0	8.5	76	2.1	3.5
Sept 19	23.2	250	-	0.15	21.8	198	7.4	4.2	34.6	255	-	17.5

Since the erosion crusts at the valley and the dune were less developed than the erosion crust at the degraded site, these values were significant higher (Table 4). The transition from erosion to structural crust occurs gradually. It is possible to find both erosion and structural crusts within 1 m^2 (the size of a pixel). Rainfall simulations and disc-infiltrometer measurements showed that the effective hydrologic conductivity for these kind of surfaces is significant lower than that of the structural crust alone but higher than that of the erosion crust (Horstman, 2003) (Table 4). However over the season, no significant decrease in K_e for these kinds of surfaces was found, therefore the input value was constant over the season.

Figure 5 shows the correlations between measured and simulated overland flow for the three geomorphologic units after calibration. Correlation was best for the valley and though still acceptable, the degraded site showed the weakest correlation. For the valley and the dune sites, total overland flow was generally slightly underestimated, whereas for the degraded site a general overestimation occurred. Table 3 shows total amounts of measured and simulated overland flow for the 1 m^2 plots at the three research sites. Deviation of the simulated overland flow was generally around 5 - 8 % from the measured overland flow, with the exception of the event on 15 August at the dune, which resulted in an underestimation of 28.5% at the dune. Comparing model predictions of time to ponding and overland flow discharge with the measured values generally showed a good agreement (Fig. 6). For the degraded site simulated ponding generally occurred in the same minute as the first measured overland flow. At both the valley and dune sites a deviation of 1-2 minutes between simulated and measured time to ponding occurred. This deviation could be caused by the model simplification at this scale. Due to the small plot size it is assumed that all water that does not infiltrate in one time step leaves the simulation area. So no routing with the kinematic wave, as for the larger plot sizes, is simulated. Especially at the plots of the valley and the dune, where slopes were lower than these of the degraded site this assumption may lead to small errors in the moment the overland flow reaches the plot outlet.

Table 4) Model input values of the effective infiltration capacity (K_e) of various crust types at the degraded site, the dune and the valley in the Katchari catchment, Burkina Faso. The range values for the structural crust indicates the highest and lowest values used, with the highest values used after the first rain after ploughing.

Site	Crust type	K_e (cm h^{-1})
Degraded site		
	Gravel crust	0.15
	Erosion crust	0.09
Valley site		
	Still Depositional crust	0.15
	Just ploughed	1.1
	Structural	0.43 - 0.61
	Erosion	0.25
	50% structural, 50% erosion	0.28
Dune site		
	Just ploughed	2.9
	Structural	0.34 - 0.50
	Erosion	0.19
	50% structural, 50 erosion	0.26

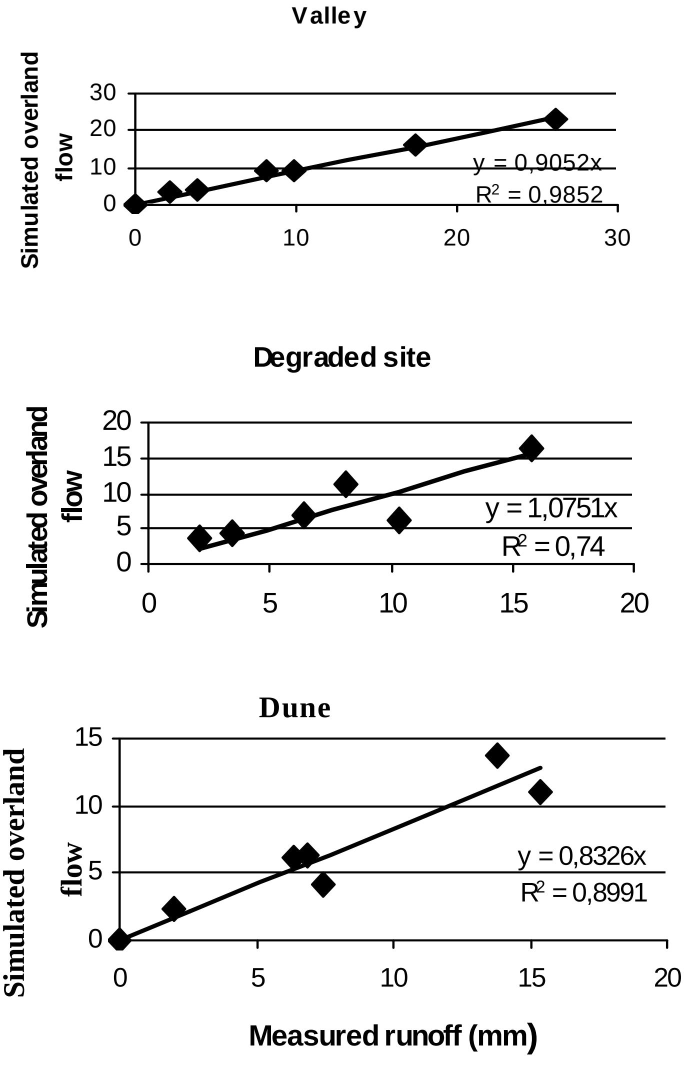

Figure 5) Correlation between measured and simulated over land flow at the valley, the dune and the degraded site in the Katchari catchment, northern Burkina Faso.

Large runoff plot model simulation

Table 5 shows the measured and simulated total overland flow and total sediment discharges for the 20 m^2 runoff plots at the three research sites. The measured values for the overland flow and sediment load are the average values of measurements at the two runoff plots. For all simulations at all sites more sediment was detached than transported. For example for the event of 21 June at the degraded site total detachment (splash detachment + flow detachment) was 17.8 kg, and total deposition was 17.5 kg, resulting in a total soil loss over a 20 m^2 area of 0.3 kg. Furthermore, sediment fluxes ($g\ m^{-3}\ s^{-1}$) were equal to transport capacity ($g\ m^{-3}\ s^{-1}$) indicating that sediment transport was transport capacity limited. The transport capacity is low due to the low slopes and the fact that here sheet flow is the transport process. Most of the detached sediment was directly deposed within the same cell. This indicates that splash detachment was the most important sediment detaching process.

At the degraded site overland flow was generally well predicted. Sediment discharge was well predicted for 5 out of 8 events for which the sediment discharge was measured. At the dune simulated overland flow was generally in the same order of magnitude as the measured overland flow. However, for all simulations overland flow was slightly overestimated. At parts of the runoff plots at the dune ants were active. Ants rework the soil and break up crusts causing larger infiltration capacities (Mando, 1997). At the valley overland flow was well predicted for 8 out of 11 events and sediment discharge was correctly estimated for four out of seven events. At the dune sediment discharge was correctly estimated for 3 out of 5 events. For all sites stand that when sediment discharge was not well predicted, it was underestimated.

A possible explanation for the underestimation of sediment discharge can be found in the calculation of the transport capacity, especially in the effect of rainfall on the transport capacity. In calculating the effect of wind driven rainfall on the interrill transport capacity, Guy *et al.* (1987) did assume vertically falling rainfall. Wind-driven rainfall exerts a larger kinetic energy on the soil surface (Pedersen and Hasholt, 1995) and so also on a water layer. This additional energy creates more turbulence. So the transport capacity of sheet flow in the case of wind driven rain might be larger than that of sheet flow in the case of vertically falling rain with the same intensity. The fact that sediment discharge is more underestimated at the valley and dune sites than at the degraded site can be explained by the differences in slope. At the degraded site the slopes are generally steeper and so the stream velocity of the sheet flow is larger, resulting in higher transport capacities.

Table 5) Measured (R_m) and predicted (R_p) overland flow and sediment discharge (S) for the 20 m^2 runoff plots at three geomorphologic zones in the Katchari catchment, 2001 rainy season.

	Valley				**Dune**				**Degraded site**			
	R_m (mm)	**R_p (mm)**	**S_m (kg)**	**S_p (kg)**	**R_m (mm)**	**R_p (mm)**	**S_m (kg)**	**S_p (kg)**	**R_m (mm)**	**R_p (mm)**	**S_m (kg)**	**S_p (kg)**
June 21	3.5	5.4	0.9	0.2	0.4	2.3	-	0.1	3.9	5.8	-	0.3
July 2	10.1	7.7	-	0.3	11.7	18.6	1.3	1.2	21.4	21.2	5.6	2.1
July 25	13.5	10.1	0.8	0.4	0.4	0.5	0.0	0.0	23.7	9.9	3.2	0.5
Aug 4	0.1	0.0	-	0.0	0.1	0.0	-	0.0	5.9	4.6	-	0.2
Aug 14	0.2	0.9	-	0.0	0.0	0.6	-	0.1	4.1	4.4	-	0.4
Aug 15	2.9	6.9	0.6	0.2	10.3	9.8	0.7	0.2	18.2	14.7	1.9	0.7
Aug 19	11.3	11.3	1.7	0.3	1.0	2.0	0.6	0.1	26.6	25.8	1.5	1.8
Aug 20	24.2	22.8	1.8	1.6	8.3	12.7	0.4	0.7	24.2	25.7	1.5	2.1
Aug 27	1.5	0.9	0.2	0.1	0.1	2.5	-	0.1	6.3	7.5	1.4	1.1
Sept 2	0.0	0.1	0	0.0	0	0.0	-	0.0	0.1	0.0	0.1	0.0
Sept 19	2.3	4.4	0.2	0.0	0.1	0.0	-	0.0	12.8	15.4	0.8	0.6

Probably transport capacity of interrill flow is only significantly affected by wind driven rain when slopes are very low (0-2 deg). The large underestimation of sediment discharge for the event of 25 July at the degraded site can be explained by the fact that wind blown sediment transport occurred during 7 minutes preceding rainfall. It is possible that the gutter of the runoff plot trapped some sediment and that sediment entered the oil barrels through small holes between the cover and the barrel. This led to an overestimation of the measured sediment discharge.

Also overland flow for the event of 25 July is underestimated for the degraded and valley sites (the dune site had just been cultivated so much water could infiltrate). This is most probably due to the character of rainfall; the first 20 minutes a total of 14.6 mm rainfall with intensity up till 78 mm h^{-1} followed by three hours of drizzle rain with a total of 9.8 mm. When measuring drizzle rain with a tipping bucket rain gauge, instead of recording continuous rainfall, it appears that is does not rain for e.g. 5 minutes followed by a minute of rainfall with an intensity of 12 mm h^{-1}. The reason why this large underestimation of overland flow did not show while modelling at a smaller scale lies in the overland flow routing. Whereas overland flow at the small plots is simulated as reaching the outlet within one time step, this does not occur at the larger plots. When rainfall in one time step falls at the upper part of the plot and does not directly infiltrate, it takes, especially with the low slopes, at least 1 to 2 time steps (of 2 seconds) to reach the outlet. During these time steps the flowing water gets the opportunity to infiltrate, which will occur especially when no rain is added. When a continuous, lower intensity rainfall was used as model input, more overland flow would be simulated. Especially a site with low infiltration capacities such as the degraded site is vulnerable for distribution of rainfall input. As can be seen in Table 5 for the valley, this site is less vulnerable for the effects of drizzle rain, most probably due to the larger infiltration capacities. Still an underestimation of overland flow occurred.

Research site model simulation

As can be seen in figure 7 pool formation is well simulated by the model. Pool formation starts at the deepest point in the pool (Fig. 7A), continues till this cell is completely filled up and starts to expand as rainfall continues (Fig. 7B). With decreasing rainfall and continuing infiltration pool size is decreasing again (Fig. 7C). As can be concluded from figure 7, pool formation limits overland flow and, in this case increases infiltration. In case the development of a still depositional crust would have been simulated in the model, pool extension would not decline so fast after the rainfall event. Now the standing pool-water is allowed to infiltrate with an infiltration rate equal to that of the crust type present before the onset of the rainfall event, which was not always a still depositional crust. Furthermore, if the development of a still deposition crust would be simulated during the event, less water would infiltrate in the pool area, resulting in an increased runoff and standing water for a longer period as

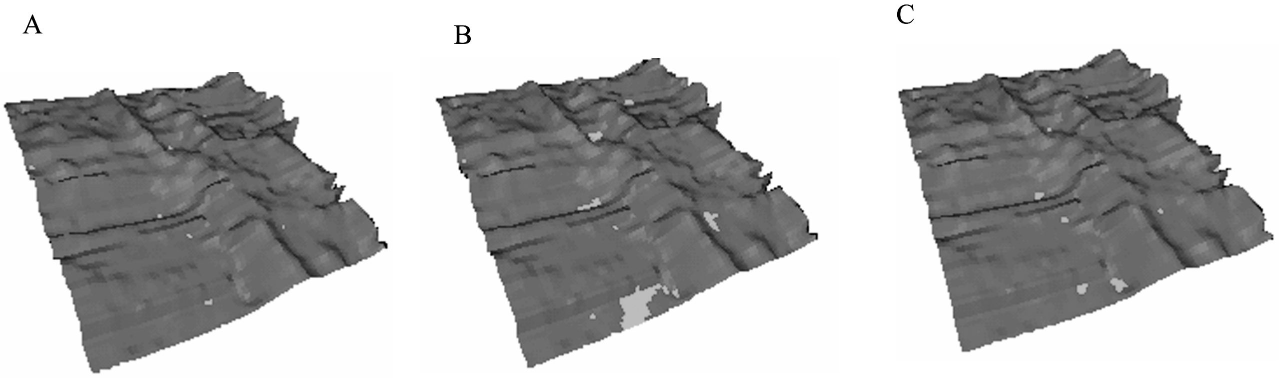

Figure 7) Extension of pools for the rainfall event of 14 August at the valley at 3 (A), 13 (B) and 25 (C) minutes after onset of rainfall. The clear areas indicate the extension of the pool.

was observed in the field.

Table 6 shows for each event the total simulated soil losses from the three geomorphologic zones. Except for the event of 2 July, soil losses were highest at the degraded site. The generally low infiltration capacities at the degraded site cause large amounts of overland flow. From simulation at the scale of the runoff plots it was already clear that sediment transport was transport capacity limited. So more overland flow results in more soil loss since the sediment is available.

For the event of 2 July the highest soil losses were simulated for at the dune site. At this moment the soil at the dune site was for 80% covered with an erosion crust with a low infiltration capacity.

The amount of rainfall at the dune site was almost equal to the amount of rainfall at the degraded site, 30 mm (Table 4), whereas the valley site received only 17 mm. Due to the finer texture of the soil at the dune site (d50 dune 0.0079 cm, d50 degraded site 0.0151 cm), and despite the slightly lower total discharge, more sediment could be transported at the dune than at the degraded site.

Apart from the event of July 2 and August 19, simulated soil losses at the valley and the dune sites generally were in the same order of magnitude. Just before the event of 19 August the site of the dune was cultivated, crusts were removed and the infiltration capacity of the soil became high. So less runoff occurred at the dune site and soil loss was limited.

Comparing total soil loss (kg ha^{-1}) predicted for the site scale with the predicted soil losses at the runoff plots (kg ha^{-1}), we see that predicted soil losses at the runoff plots are higher than predicted soil losses at site scale. For instance predicted soil losses at the scale of a runoff plot for the well predicted event of August 20 were 775 kg ha^{-1} for the valley, 345 kg ha^{-1} for the dune and 1050 kg ha^{-1} for the degraded site. Whereas for the site scale simulated soil losses were 46.6 kg ha^{-1} at the valley, 50.4 kg ha^{-1} at the dune and 872.4 kg ha^{-1} at the degraded site (Table 4 and 6). This difference is partly explained by the fact that at the runoff plots no sediment-loaded water enters the plot. The overland flow in the upstream cells is loaded with sediment till its maximum transport capacity. This causes more erosion in those particular cells than would have occurred when the water streaming into these cells would have had a sediment load. Furthermore, resettlement occurs in areas with smoother slopes, resulting in lower total soil losses at the scale of the research sites.

Figure 8B shows total detachment (kg m^{-2}) for the event of 14 August at the valley site. Comparing this map with the crust map (Fig. 8A) it is clear that detachment is closely related to the crusting pattern. This is the case for al events at the valley site.

Table 6) Total soil loss (kg) and soil loss in kg ha^{-1} from the simulation area at three geomorphologic zones in the Katchari catchment, 2001 rainy season. The total simulation area of the valley and the degraded site was 6400 m^{2} the simulation area of the dune was 5226 m^{2}.

Date	Valley (kg ha^{-1})	Dune (kg ha^{-1})	Degraded site (kg ha^{-1})
June 21	7.4	6.2	16.6
July 2	10.9	66.7	55.8
July 25	1.6	0.4	183.4
Aug 4	1.0	0.0	57.1
Aug 14	0.1	1.5	2.6
Aug 15	6.4	15.3	310.2
Aug 19	393.9	4.5	580.4
Aug 20	46.6	50.4	872.4
Aug 27	0.1	4.1	47.5
Sept 2	0.0	0.0	0.0
Sept 19	0.8	0.1	251.3

Apparently raindrop detachment is the most important process; but at the somewhat steeper slopes additional detachment by flow occurs. Comparing figure 8B with the net erosion and deposition map (kg m^{-2}) (Fig. 8C), it becomes clear that sediment transport is transport capacity limited.

Almost all detached sediment is directly deposited, resulting in only small amounts of erosion.

When comparing the net erosion and deposition map with the crust-transect (Fig. 9), we find that at the locations where the net effect is almost zero and where pool formation is simulated, a still depositional crust is formed. In the slightly steeper areas, where most erosion occurs, a runoff crust is formed and in the areas where alternating smaller amounts of erosion and deposition occur, a mixture of structural and erosion crusts had developed.

The previously mentioned conclusion, that sediment transport at the valley site is transport capacity limited, accounts also for both the dune site and the degraded site. The large amounts of sediment that were detached by rain drop impact, remain behind

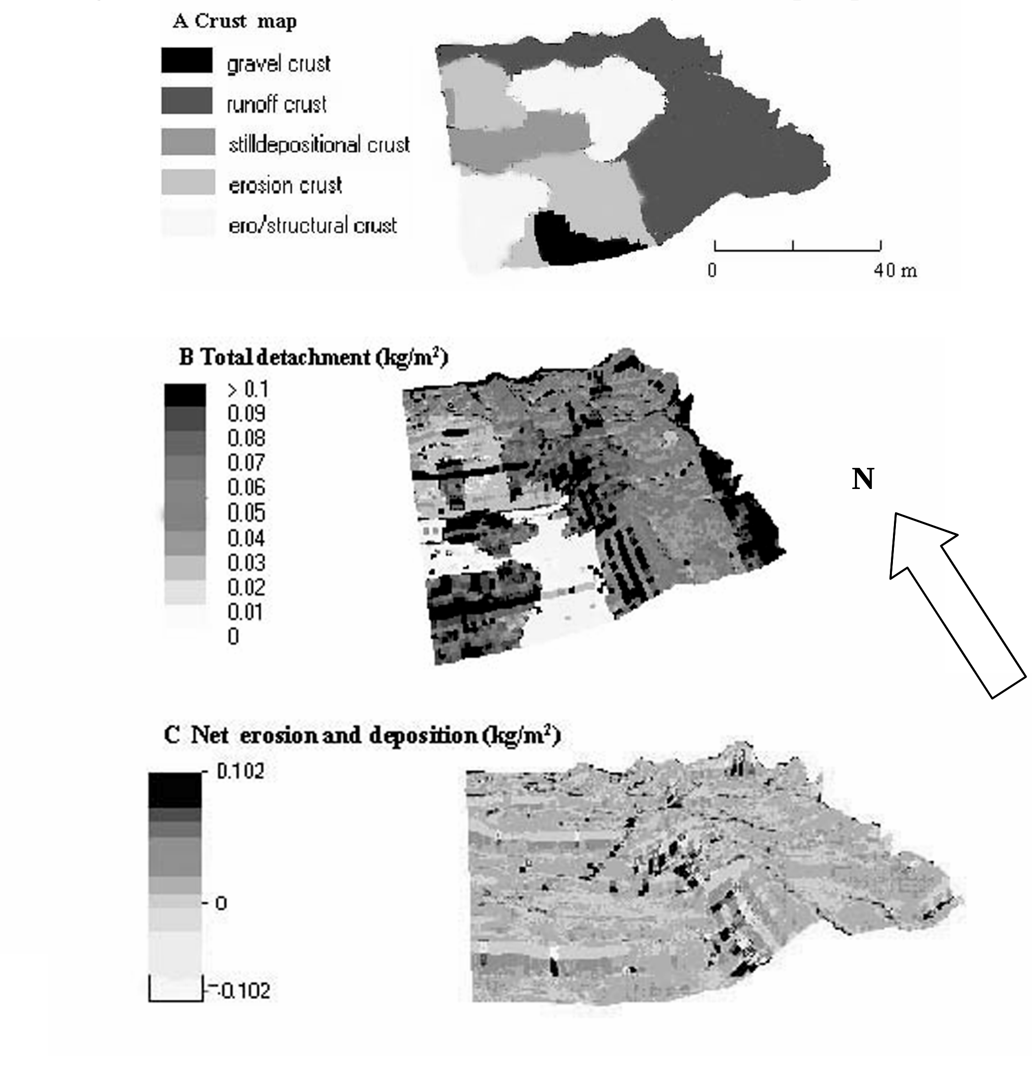

Figure 8A) Distribution of crust types at the valley before the event of 14 August. B) Total detachment (kg/m^2) during the event of 14 August 2001 C) Net erosion and deposition after the event of 14 August at the valley. Positive numbers indicate deposition and negative numbers indicate erosion. The white line indicates the position of the transect of Figure 9.

as loose particles available for transport by future wind erosion events, which regularly develop in this area in the early rainy season (Sterk, 1997). In the literature a wide variety of references stating negative sediment balances for farmers fields in this areas can be found (Albergel *et al.*, 2000; Collinet and Valentin, 1985; Joly *et al.*, 1991). However, taking into account the low erosion rates found (Table 6), it has to be concluded that, in the current research area, it is not water erosion alone, but rather the interaction between wind and water erosion that causes these large negative balances. In this interaction water erosion is seen as the sediment delivery process, whereas wind erosion is the transporting process. This conclusion is also confirmed by the description of the crusts over time.

Whereas in the early rainy season, erosion crusts cover the largest part of the field, later in the season the structural and runoff crusts cover the largest parts of the field. The fact that soil crusting has such a large influence on soil erosion by water; both in detachment and infiltration, implies that model performance in the Sahel could be improved by including crust development during the event; as was already stated by (Valentin, 1995).

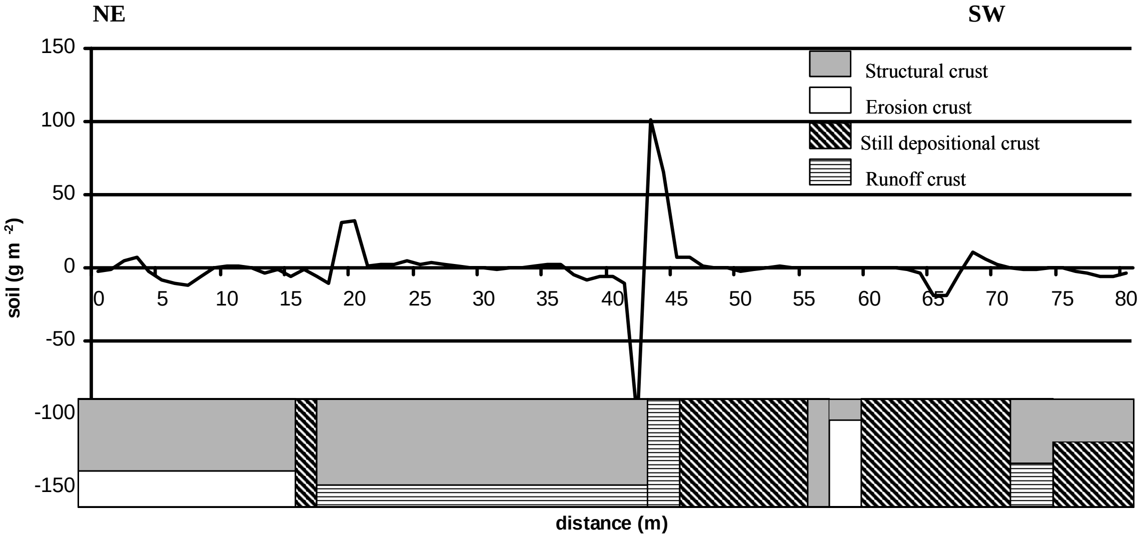

Figure 9) Erosion and deposition (g m^{-2}) versus crust type at the valley over a NE-SW transect after the event of 14 August 2001. The transect is measured along the white line from Figure 8. When two crust types occur at the same place, it is meant that both curst types occur side by side. Negative values indicate erosion and positive values indicate deposition

Conclusion

The rewritten version of EUROSEM for the Sahel, is a fully dynamic erosion model, able to simulate infiltration, overland flow routing, pool formation, sediment transport and erosion and deposition by interrill processes over the land surface for individual storms at the scale of both runoff plots and fields. After calibration a good agreement between measured and simulated overland flow was obtained for simulation at 1m^2 plots. Furthermore, time to ponding and overland flow discharge was predicted well by the model.

At the scale of a 20 m^2 runoff plot the model performed well, total measured and simulated overland flow generally were for all sites in the same order of magnitude. For all sites stand that sediment transport was transport capacity limited. For several events the sediment discharge was underestimated. By incorporating the effect of wind-driven rain on transport capacity, this underestimation could most probably be avoided.

At the scale of the research site, the model performs well in the formation of pools, limiting total overland flow. Due to the fact that development of a still depositional crust is not considered in the model, pool water infiltrates, which was not observed in the field.

The model simulates large amounts of detachment directly followed by deposition, suggesting that transport is transport capacity limited. However the large amounts of detached sediment remain behind as loose particles, available for transport by a future wind erosion event. Therefore it is concluded that in this area, it is not water erosion alone, but rather the interaction between wind and water erosion that causes negative nutrient and sediment balances.

Clearly crust development has large influence on soil erosion by water in the Sahel, both on infiltration and detachment. So far we are only working with crust-related input parameters, which are fixed during the event. Since during the event the largest part of crust development occurs, incorporating crust development would probably largely enhance model performance.

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Chapter 7

Modelling nutrient losses by wind and water erosion in a Sahelian environment

S.M. Visser, L. Stroosnijder and W. Chardon

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Abstract

In the Sahelian zone of West-Africa, erosion by both wind and water causes a serious decline in fertility of the already low fertile soils. Despite the fact that the flow of nutrients has been intensively investigated by the use of nutrient balances, little attention has been paid to the contribution of the soil erosion to the nutrient balance. Two physically based models (WEPS and EUROSEM, both written in PCRaster) were extended with nutrient modules to investigate the combined role of wind and water erosion in the loss and gain of nutrients at the scale of a Sahelian field. The models are applied at three geomorphic units in the Katcheri catchment in northern Burkina Faso.

WEPS can predict spatial patterns of erosion and deposition due to wind-blown particle transport. Depending on wind direction, crusting and vegetation cover net erosion or deposition can occur. When erosion occurs considerable amounts of nutrients are lost, but when deposition occurs, most of these nutrients can be regained. Soil loss by water erosion is closely related to the crust type present, which regulates infiltration and thus runoff. Nutrient losses by water erosion are small compared with those by wind erosion, but are forever lost for the area and mount up over large timescales.

Sediment transport by wind in saltation mode results in the largest soil and nutrient losses at the time scale of an event, but when there is a correct balance between cultivated and fallow land in a region, the largest amounts of nutrient losses over a larger time scale (e.g. 50 years) are the result of soil losses related to runoff.

Introduction

Ever since the 1960s, rainfall in the Sahel has shown a general decline. Since the 1980s the rainfall has been below the long-term mean for most of Africa (Nicoleson, 2001). Due to rapid population growth, the cropped area has been expanded to include more marginal lands and the fallow period has been shortened or even abandoned (Thiombiano, 2000). Consequently, the combination of drought and overexploitation has resulted in large-scale land degradation. In 1994 Williams and Balling estimated that 332 million hectares of the African drylands were prone to soil degradation. The land degradation process includes erosion by both wind and water and deposition elsewhere, a long-term reduction in the amount and diversity of natural vegetation, and the salinisation of soils (Dregne *et al.*, 1991).

Soil erosion is a particularly serious threat to the sustainable use of soil and water resources in the already low fertile areas of the semi-arid tropics of West Africa. Lal (1998) has suggested that the most important chemical and nutritional constraints for crop growth are low levels of N, P, K and a low cation exchange capacity (CEC), and that these are accentuated by soil erosion. Since the fine particle fraction is often preferentially eroded, a disproportionate loss of the soil nutrients can occur, leading to even greater degradation (Hashim *et al.*, 1998).

In the Sahel, severe wind and water erosion mainly occurs in the first half of the rainy season (May-July). In this period the rain falls in very intense thunderstorms often preceded by violent winds. At this time of the year, the soil is bare and vulnerable to erosion. Already impoverished, the soil loses its fertile topsoil due to transport by the wind (saltation and suspension: Sterk *et al.*, 1996) and by water (dissolved nutrients and sediment suspended in runoff: Stroosnijder, 1995).

Although the flow of nutrients in sub-Saharan African agriculture has been investigated in detail, using nutrient balances (De Jager *et al.*, 1998; Nandwa and Bekunda, 1998; Wortmann and Kaizzi, 1998), little attention has been paid to the contribution of soil erosion to the nutrient balance of this area. Often, calculations of nutrient losses due to soil erosion are based on average soil losses per hectare. Furthermore, precise measurements of nutrient contents of the eroded sediment are not often performed in the Sahel.

To date, the only researchers to have quantified nutrient losses by wind erosion in the Sahel are Bielders *et al.* (2002) and Sterk *et al.* (1996). During their research in a pearl-millet field in southwest Niger Sterk *et al.* (1996) found that the total element (TE) content of wind-blown sediment caught at a height of 0.05 m was similar to the TE content of the topsoil, but at a height of 0.5 m it was approximately three times higher than the TE of the topsoil. Furthermore, they showed that the main mass of nutrients is transported by saltation, even though the sediment suspended in the air is much more nutrient-rich. Sterk *et al.* (1996) reported the following TE losses from a 40 x 60 m experimental plot after two storms: 57.1 kg ha^{-1} K , 79.6 kg ha^{-1} C, 18.3 kg ha^{-1} N and 6.1 kg ha^{-1} P. Bielders *et al.* (2002) performed measurements on wind-blown sediment transport in a conventionally managed cultivated field and a bush fallow in western Niger. Generally, the nutrient content of the wind-blown sediment declined with distance into the cultivated field and increased with distance into the bush fallow. A net deposition of nutrients was measured in the bush fallow and a net loss of nutrients occurred in the cultivated field. In both these studies, although the nutrient losses were low in absolute terms, they were high compared to the average nutrient uptake of a millet crop (Buerkert, 1995).

Similar to the case of wind erosion, not much research has been done on the loss of nutrients by water erosion in the Sahel. In an Alfisol in the semi-arid tropics of India, Cogle *et al.* (2002) found that although values for total soil erosion were low, nutrient losses were large. Due to enrichment ratios larger than 2, annual nutrient losses up to 27 kg N ha^{-1} and 178 kg C ha^{-1} were measured. These results agree with the results of Geelhoed (1995), who investigated the losses of nutrients by water erosion in Burkina Faso. He calculated annual losses of 654 kg C ha^{-1}, 51 kg N ha^{-1} and 8.7 kg P ha^{-1}, concluding that the nutrient losses were large due to the large enrichment ratios in the eroded sediment nutrient. Furthermore it is also known that a large proportion of soluble N was lost in the runoff water. Ribolzi *et al.* (2003) have shown that not only runoff water but also underground flow transports large amounts of solutes.

From the foregoing we can conclude that total nutrient losses due to wind and water erosion are large, especially when compared to the annual uptake by a millet crop. However, several researchers have argued that in Sahelian fields, soil erosion by wind and water has a large spatial variation (Karambiri *et al.*, in press; Lal, 1998; Sterk and Stein, 1997; Visser *et al.*, in 2004-a; Visser *et al.*, 2004-b; Visser *et al.*, 2004-c). From the work of Bielders *et al.* (2002) we learn that when wind erosion occurs in the cultivated fields, the adjacent bush vegetation serves as a sink for sediment and so for nutrients. Depending on the local topography this sediment and the attached nutrients can be returned via water erosion. Furthermore, Visser *et al.* (2004-a) have shown that though large amounts of erosion can be measured in a runoff plot, the total sediment losses from Sahelian fields may be limited and that what occurs is merely a redistribution of the sediment, and hence of the nutrients. This is confirmed by the knowledge of the local farmers, who can point out areas of low and high fertility in their fields (Sterk and Haigis, 1998; Visser *et al.*, 2003).

The objective of the study described in this paper was to evaluate the combined role of wind and water erosion in the loss and gain of nutrients at the scale of a Sahelian field (a Sahelian field may vary in size from 100 m^2 to several ha). This was done by incorporating nutrient modules into physically based models suitable for the Sahelian situation. As wind and water erosion occur almost simultaneously in the early rainy season in the Sahel, a wind erosion model was combined with a water erosion model. In this paper we will discuss the separate and combined effects of the processes of wind and water erosion in three geomorphologic units in the Katchari catchment in northern Burkina Faso.

Materials and methods

Description of the fieldwork area

During the 2000 and 2001 rainy seasons, field experiments on sediment transport by wind and water were conducted in the Katchari catchment in northern Burkina Faso. The Katchari catchment covers an area of 12 km^2 and is situated in Seno province, 11 km west from Dori, the provincial capital. In the first half of the rainy season (May-July) severe wind erosion occurs. In this period, rain falls in intense thunderstorms that are often preceded by violent winds. The prevailing wind direction is northeast. Measurements were performed on three fields in different geomorphologic settings: a degraded site, a valley site and a dune site. At all sites a 80 x 80 m research plot is selected for measurements on wind and water erosion.

All three fields have an undulating topography. The maximum height difference within the dune site is approximately 0.5 m. On the valley floor and in the degraded site the distances between depressions and crests range from 10 to 40 m and the maximum height difference is approximately 1 m.

The degraded site lacks vegetation and has a strong gravel crust over approximately 75% of the soil surface. The remaining 25% of the research plot is covered by a well developed erosion crust (Valentin and Bresson, 1992). The river in the valley dries up in the dry season but may flood during the wet season. The research plot is situated at a farmer’s field, which is cultivated with millet in the wet season. During that season farmers remove the annual herbs twice, by hoeing. Natural vegetation (trees and bushes) is scattered over the experimental field. The soil is characterised by a fast development of erosion and depositional crusts (Valentin and Bresson, 1992) and consists of a layer of 25-30 cm of loamy sandy soil on top of a clay-loam soil. The sandy loam layer has been trapped by branches put down by the farmers who wanted to start cultivating this area. The dune site is part of an old and flattened dune band that belongs to an extensive sand dune system, which is more than 40,000 years old (Courel, 1977). The borders of the field in the dune site are demarcated with single trees. Millet is grown in the field, and annual herbs are removed by hoeing twice a year. The loamy, sandy soils of this dune complex are prone to crusting, with structural and erosion crusts being the most common (Valentin and Bresson, 1992).

Wind erosion measurements

For the measurement of wind-blown mass transport, each research plot was equipped with 17 Modified Wilson and Cooke (MWAC) sediment catchers (Fig.1). Each catcher consists of a vane, which ensures that the catcher always faces the wind, and five traps attached to a central pole at heights of 0.05, 0.12, 0.19, 0.26 and 0.75 m. A trap consists of a small (100 ml) PVC sample bottle, closed with a cap through which inlet and outlet tubes enter the bottle. The glass tubes have an internal diameter of 8 mm. The trapping efficiency (obtained from previous calibration by Sterk and Raats (1996)), defined as the ratio between the measured mass transport rate and the total mass transport rate, is 0.49.

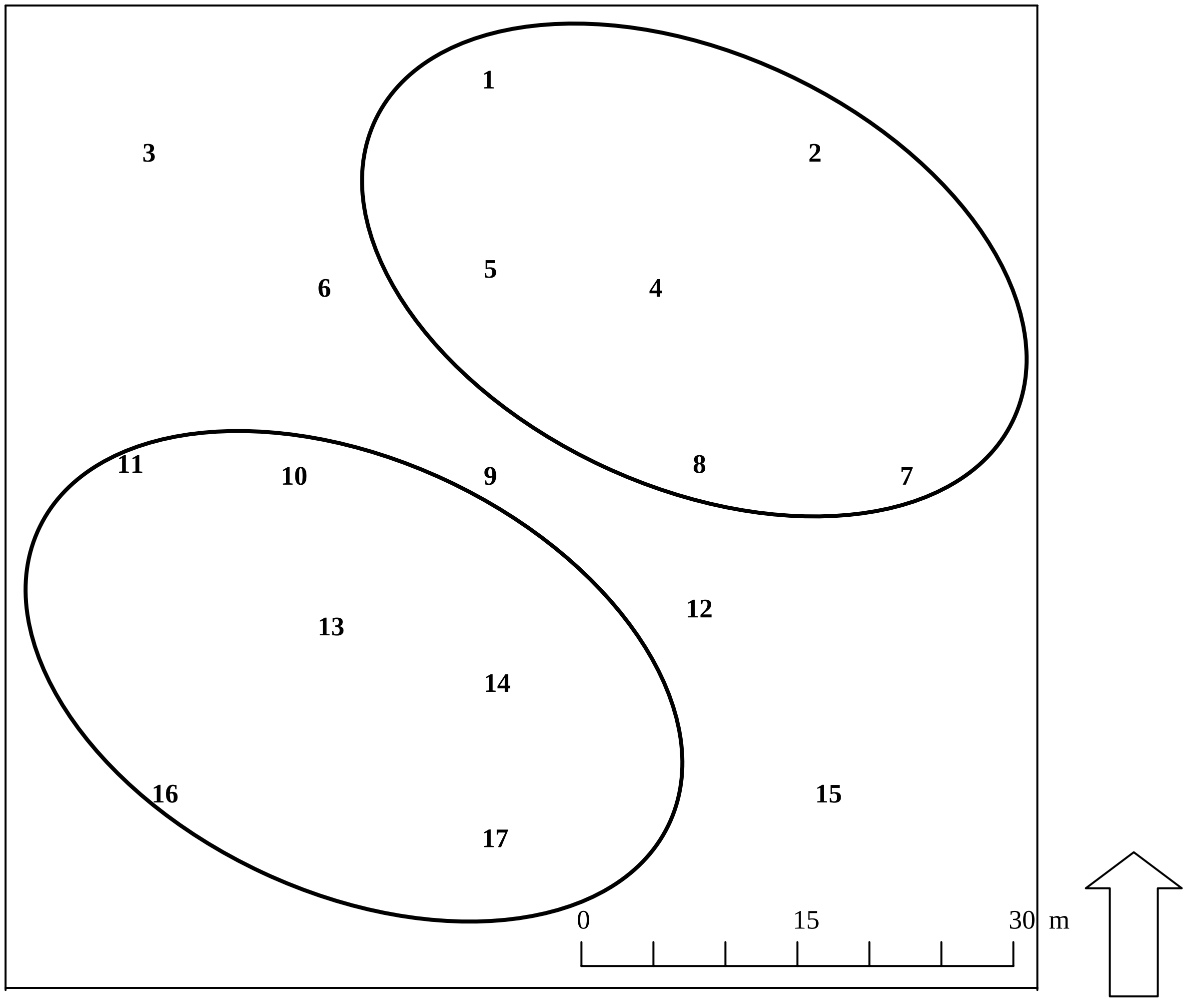


Figure 1) Spatial distribution of MWAC sediment catchers on the degraded site, the valley site and the dune site in the Katchari catchment, Burkina Faso.

From the weight of the trapped sediment and the duration of the event, mean horizontal mass fluxes (q (z); kg m^{-2} s^{-1}) at the sampling height z (m) were calculated. A mass flux model was used to describe the relation between horizontal mass flux and height (Sterk and Raats, 1996):

$$q(z) = a\left(\frac{z}{\alpha}+1\right)^{-b} + c\exp\left(-\frac{z}{\beta}\right) \qquad \text{(Eq.1)}$$

where a, α, b, c and β are regression coefficients. The model describes the vertical profile of horizontal mass flux from the soil surface (z = 0 m) to any height z.

For each event, Eq. 1 was fitted through the measured mass fluxes by non-linear regression (Visser *et al.*, 2004-c). Here Eq. 1 was only used to describe mass fluxes from 0 to 1 m since no observations above this height were available. Integrating Eq. 1 over height resulted in mass transport rate Q (kg m^{-1} s^{-1}) at the sampling point. Total mass transport at each sampling point was obtained by correcting for the overall trapping efficiency of the catcher and multiplying by the duration of the event.

An overview of the spatial distribution of measured mass transport was obtained by following a procedure suggested by Sterk and Stein (1997). Event-based maps of sediment transport were obtained by using the variogram from the measurements and applying stochastic simulation, resulting in acceptable results for the degraded and the dune sites. However, the variogram of the valley showed noise only, and therefore the simulated maps have a low confidence level. A detailed description of this technique and the results can be found in Visser *et al.* (2004-c).

To obtain sufficient sediment for nutrient content measurement, we pooled the material trapped in catchers 1, 2, 4, 5, 7 and 8 and in catchers 10, 11, 13, 14,16 and 17 (Fig. 1). The trapped material had been collected at two height ranges; we pooled the samples of height range from 0.12 to 0.19 m and the samples of height range from 0.26 to 0.75 m. This resulted in 4 samples per event per site. The representative height of each sample was based on the share of the contents of one trap to the total of the two traps.

A total of fifteen soil samples spread over the experimental plot at widely spaced intervals were taken from the topsoil (0-0.02m). Five samples were pooled to give one sample; this resulted in three soil samples for each research site. For all samples, the total element (TE) contents were determined; nitrogen (N) was determined with the Kjeldahl method, carbon (C) with the Walkley and Black method, and total available phosphorus (P) with the Bray II method.

According to Zobeck and Fryrear (1986), the extractable cation contents of wind-eroded material as a function of height can be described by a simple power function:

$$X(z) = pz^q \qquad \text{(Eq. 2)}$$

where X is the extractable cation content (mg kg^{-1}), z is the height (m) and p and q are (positive) regression coefficients. This equation showed good correlations between fitted and measured extractable cation contents of Na, Ca, Mg, K. Later this equation was successfully used by Leys and McTainsh (1994) and Sterk *et al.* (1996). Here Eq. 2 was used as a model for the vertical distribution of the TE content with height. Multiplication of Eq. 1 and Eq. 2 results in an equation that describes the vertical profile of TE mass fluxes:

$$f(z) = pz^q \left[a\left(\frac{z}{\alpha}+1\right)^{-b} + c\exp\left(-\frac{z}{\beta}\right)\right] \qquad \text{(Eq. 3)}$$

where f (z) is the horizontal mass flux (mg m^{-2} s^{-1}) of a certain nutrient at a height z (m). The TE mass flux profiles were numerically integrated from z=0 to z=1 m. The TE transport M_t (mg m^{-1}) was obtained by correcting measured TE mass transport rates for the trapping efficiency and multiplying by the event duration. The average TE content of the transported sediment (mg kg^{-1}) was obtained by dividing the TE transport (mg m^{-1}) by the total sediment transport (kg m^{-1}).

By calculating the ratio of the amount of a particular element in the transported material to the amount of the element that is in the parent soil, average enrichment ratios (ER) were obtained for each site. These ER were the input for the wind erosion model.

Wind erosion modelling

Visser *et al.* (2004-b) rewrote the erosion sub-model of the Wind Erosion Prediction System (WEPS) (Hagen, 1996) in the dynamic modelling language PCRaster (De Jong, 1997). WEPS is a process-based daily time step computer model that predicts soil erosion by simulating the physical processes that control wind erosion (Hagen, 1991). Translating the original WEPS code into PCRaster allows the user to insert spatially varying parameters that control wind erosion e.g. vegetation cover, crust type, and soil roughness. The model calculates the friction velocities and the threshold friction velocities for each grid cell. When the friction velocity is larger than the threshold friction velocity sediment transport is possible, and the model calculates the soil loss or deposition for each grid cell and updates the surface parameters. The original erosion sub-model of WEPS was modified for the Sahel by:

1) allowing sediment to enter the field (no non-eroding boundaries),

2) allowing transport to occur when erosion is no longer possible (friction velocity is still larger than transport threshold but smaller than the erosion threshold) (due to the small grid size),
3) assuming the water content of the topsoil to be 0.
For a detailed description of the WEPS erosion sub-model and the adaptations made for the Sahelian environment see Hagen (1996) and Visser *et al.* (2004-b). For this research the WEPS in PCRaster model is extended with a nutrient module. Nutrient losses were calculated by:

$$EGN = EG * N_{soil} * ERN \qquad \text{(Eq. 4)}$$

where: EGN is total loss (negative) or gain (positive) in nutrients (mg), EG is loss (negative) or gain (positive) of saltation sediment (kg), N_{soil} is the nutrient content of the topsoil (mg kg^{-1}), and ERN is the enrichment coefficient for a specific nutrient. This equation was necessary to be able to calculate the redistribution of nitrogen, phosphorus and carbon.

Water erosion measurements

During the rainy seasons of 2000 and 2001, data on water erosion events were collected at the three sites in the Katchari catchment. The degraded site and the dune site were each equipped with a complete weather station that continuously measured wind speed and direction, temperature, total rainfall, soil moisture content and total solar energy. During the 2001 rainy season the valley site was equipped with an automatic rain gauge, which measured rainfall amounts at one-minute intervals. At each site three runoff plots were installed; one with an area of 1 m^2 (1 x 1 m) and two with an area of 20 m^2 (10 m length, 2 m width). Each plot was closed at its upper boundary so that run-on was not possible. At the end of the 1-m^2 plots an automatic tipping bucket was installed, which recorded overland flow intensity at one-minute intervals. Overland flow and sediment load from the 20-m^2 plots were captured in four oil-barrels at the end of the plot. After a rainfall event the total collected overland flow was measured with a precision of 0.5 l. All the water and sediment from the first two oil barrels was put into two large buckets and left for 48 hours to allow the suspended sediment to resettle. Then the water was poured off and the sediment was collected, dried and weighed.
To determine the nutrient content in runoff water (µg l^{-1}), two 1-litre sample bottles were filled with the runoff water from the first oil barrel before the total overland flow was measured. The N, C and P contents of the eroded sediment were then determined, using the same method as described for wind erosion and the enrichment ratios were calculated. These ER were input into the water erosion model.

Water erosion modelling

Visser *et al.* (2004-a) extended the PCRaster version of EUROSEM (Van Dijck and Karssenberg, 2000) with the erosion and sediment transport modules of EUROSEM (Morgan *et al.*, 1992). EUROSEM is an event-based model designed to operate for successive short time steps. It models the interception of water by the vegetation cover, the volume of rainfall that reaches the soil as direct throughfall and as leaf drainage, the infiltration, the volume of depression storage, the detachment of soil by rainfall and runoff, the transport capacity of the flow, and the deposition of sediment. Runoff discharge is calculated using the kinematic wave equation, routed over the soil surface using a LDD (local drain direction map). Soil loss is computed as a sediment discharge, defined as the product of the volume of overland flow and the sediment concentration passing a certain point at a given time.

The following four modifications were made to the extended version of EUROSEM so that it could be applied to the Sahelian situation:
1) wind-driven rainfall was simulated.
2) infiltration was simulated with a single-layer Green and Ampt infiltration model, using an effective infiltration capacity (K_e) for the combined crust and underlying soil.
3) it was assumed that overland flow only occurs in the form of a turbulent sheet flow, with rain falling in the flow enhancing the transport capacity.
4) allowing pool formation, this occurs due to the small height differnces in the local topography.
For a detailed description of EUROSEM and the version of EUROSEM adapted to the Sahelian environment, see Morgan *et al.* (1992) and Visser *et al.* (2004-a). For this research the EUROSEM in PCRaster model was extended further with a nutrient module. The amount of soluble nutrient loss was computed based on the measured nutrient content in the runoff water (µg l^{-1}) multiplied by the simulated discharge at the field outlets (l s^{-1}). Loss of soluble nutrients by leaching was not measured and thus is not accounted for in the model. The solid nutrient loss was simulated by first multiplying the detached sediment (kg) (either detached by flow or by rainfall) with the nutrient content of the soil and the ER for each nutrient. Finally, total nutrient losses were computed as a nutrient discharge, defined as the product of the volume of overland flow and the nutrient concentration in the flow passing a certain point in a given time period.

Combination of the wind and water erosion models
In order to be able to simulate a wind erosion event that is directly followed by intense rainfall, several assumptions had to be made. First of all it was assumed that as soon as rainfall starts, all material transported by the wind is directly deposited in the grid cell where it is present at that time-step. Furthermore, windblown sediment transport is no longer possible from this moment on, due to the wetness of the soil surface.
Secondly, it was assumed that even when it is windy, splash by raindrops only helps to detach soil particles that are then transported by the runoff, splash distances are not considered here. Therefore splash distances are assumed to be negligible. We are aware that this may lead to an underestimation of erosion and deposition in the field. However, in order to elucidate this process, more research on this topic needs to be done in flat and sloping Sahelian fields.
Finally, it was assumed that the material that is deposited under wind-driven circumstances is enriched with nutrients, which initially, are distributed homogeneously (at least in the uppermost centimetres). In other words, at places where erosion occurred it was assumed that the soil contained its initial concentration of nutrients. These assumptions result in a non-homogeneous distribution of nutrient concentration over the field at the onset of rainfall.
So far the wind erosion model has used input maps with different map attributes (X_{min} Y_{min}, X_{max} Y_{max}) than the water erosion model and has simulated with a larger time-step than that model. Therefore, first the wind erosion model was run, then the input maps for the water model were created and finally the water erosion model was run.

Results and discussion

During the 2001 rainy season there were several wind erosion events, resulting in intense mass transport. Some of these events were followed by rain. For three events not followed by rain (9 June, 22 June and 3 July 2001; see Table 1) the nutrient contents of the wind-blown sediment was determined. These events were used for the simulation of nutrient transport by wind alone.

During both the 2000 and the 2001 rainy seasons there were intense rainfall events that resulted in severe erosion. However, most of the early events were preceded by several minutes of wind-blown sediment transport and the deposits measured in the runoff plots was a mixture of wind-blown sediment and sediment transported by runoff. To be able to measure the nutrient content of sediment that had been transported solely by runoff, the nutrient content of the sediment from events somewhat later in the season was measured. We were absolutely certain that no wind-blown mass transport occurred before the events of 20 July, 15 August and 20 August 2001 (Table 1).

During the early rainy season of 2000, wind-blown mass transport was less intense than during the 2001 season. No rain fell in August 2000, so young millet crops died and the crop cover in the fields was patchy. Therefore saltation under the influence of the wind was still possible during the event of 20 August 2000. This event was used for the combined simulation of wind and water erosion. See table 1 for the characteristics of this event. The texture and nutrient content of the topsoil are shown in Table 2. The P contents are approximately twice those found by Bielders *et al.* (2002), but are very similar to those found by Sterk *et al.* (1996). The organic C content in the dune site and in the degraded site are similar to the values found by Bielders *et al.* (2002) and Sterk *et al.* (1996).

The higher values for organic C in the valley are attributable to input from the droppings of cattle that grazed here during the dry season of 2000/2001. The values for N are similar to those found by Bielders *et al.* (2002) and Sterk *et al.* (1996).

Wind erosion measurements

For each MWAC catcher Eq (1) was fitted through the measured mass fluxes at five heights. Generally the fitted mass flux profiles agreed well with the observations. From the fitted mass flux profiles the total mass fluxes (Qt) were calculated. The average values of all 17 catchers for measured mass transport for each event are given in Table 1.

There were differences between the north-eastern and the south-western parts of the research plots in the nutrient content of the material trapped with the MWAC catchers (Table 3). This indicates a spatial variation, not only in mass transport but also in the nutrient content of the mass transport. Bielders *et al.* (2002) also measured spatial variation in TE content of the material they trapped during their research in Niger. Most probably a decrease in TE content (mg kg^{-1}) is related to a downwind enrichment in sand-sized material, to which fewer nutrients are attached. This results in a decreasing TE content in the downwind direction. However, since our observations were based on only two clustered samples for each event and the wind direction varied between the events we decided that pending further investigation of this phenomenon; we would calculate one ER for each nutrient for each event (Table 4). The ER values used for the event of 20 August 2000 were the average of the ER measured for the three events.

Table 1) Duration (D), wind direction (Dir), average wind speed (WS) at 2 m and average wind-blown mass transport (Q) for 4 wind erosion events. Total precipitation (P), duration, and runoff (R) for 4 rainfall events at the degraded, dune and valley sites in the Katchari catchment, Burkina Faso. Date, duration, direction, average wind speed, total amount of precipitation for a combined wind/water erosion event on 20 August 2000.

	Dune				**Degraded**				**Valley**		
Wind erosion	**D** *(min)*	**Dir**	**WS** *(ms^{-1})*	**Q** *(k/m^{-1})*	**D** *(min)*	**Dir**	**WS** *(ms^{-1})*	**Q** *(kgm^{-1})*	**Q** *(kg m^{-1})*		
Aug 20 2000	10	ESE	13.7	13.1	13	ESE	9.7	16.4	nm*		
June 9 2001	36	NE	8.8	119.1	21	ENE	9.3	12.2	54.8		
June 22 2001	21	E	9.2	100.7	19	E	11.8	43.5	56.1		
July 3 2001	20	N	7.4	40.7	19	N	7.5	4.6	51.0		
Water erosion	**P** *(mm)*	**D** *(min)*	**R** *(mm)*		**P** *(mm)*	**D** *(min)*	**R** *(mm)*		**P** *(mm)*	**D** *(min)*	**R** *(mm)*
Aug 20 2000	19.6	50	1.31		18	50	17.9		18	50	0.8
20 July 2001	16	20	7.6		10	16	8.5		10	16	6.8
Aug 15 2001	26.2	194	10.3		28.6	230	18.2		28.6	230	2.9
Aug 20 2001	34.0	65	24.2		27.6	62	24.2		33.8	67	8.3

Table 2) Characteristics of the top 10 cm of the soil of the dune, the valley and the degraded sites in the Katchari catchment, Burkina Faso. The standard deviations are shown in brackets.

Location	**Texture**	**Sand**	**Silt**	**Clay**	**N**	**C**	**P**
		-------------%-----------			**mg kg^{-1}**	**mg kg^{-1}**	**mg kg^{-1}**
Dune	Loamy sand	84 (3.5)	13 (3.0)	3 (0.9)	160 (7.1)	1590 (196)	100 (3.2)
Valley	Loamy sand	79 (6.5)	16 (6.2)	5 (0.8)	230 (10.6)	2580 (622)	110 (7.8)
Degraded	Clay loam	59 (1.5)	19 (5.0)	22 (3.7)	300 (49.8)	1820 (238)	170 (4.9)

Table 3) Total nitrogen (N), carbon (C) and phosphorus (P) contents of the materials trapped with the 17 MWAC catchers during three wind erosion events, at three geomorphic units in the Katchari catchment. For location of the sample see Figure 1

Date	Site	Location sample	Height m	C mg kg^{-1}	N mg kg^{-1}	P mg kg^{-1}
June 9 2001	**Dune**	NE	0.15	2000	186	54
		NE	0.36	4720	317	92
		SW	0.15	1690	171	59
		SW	0.37	3780	291	78
	Degraded	NE	0.16	4570	309	94
		NE	0.43	8430	353	97
		SW	0.16	1970	194	83
		SW	0.53	3010	243	124
	Valley	NE	0.14	1620	144	45
		NE	0.29	1640	154	50
		SW	0.16	2470	187	49
		SW	0.34	2630	196	59
June 22 2001	**Dune**	NE	0.16	3450	349	84
		NE	0.46	3240	216	105
		SW	0.15	5280	364	152
		SW	0.41	5530	378	172
	Degraded	NE	0.16	5070	201	105
		NE	0.34	6110	329	161
		SW	0.16	4680	202	101
		SW	0.44	5670	198	94
	Valley	NE	0.15	2990	204	102
		NE	0.37	3760	225	112
		SW	0.16	5190	446	137
		SW	0.42	5680	503	146
July 3 2001	**Dune**	NE	0.16	2220	249	124
		NE	0.43	2470	264	71
		SW	0.17	4310	367	130
		SW	0.47	4450	389	139
	Degraded	NE	0.16	1970	195	83
		NE	0.42	3010	243	124
		SW	0.15	1870	156	85
		SW	0.39	2890	176	78
	Valley	NE	0.14	3560	198	77
		NE	0.43	3170	200	82
		SW	0.17	4150	308	89
		SW	0.41	4850	368	98

Comparing the ER found in this study with those of Bielders *et al.* (2002) and Sterk *et al.* (1996), it is clear that the ER values of phosphorus (P) are very low (even below 1 for the degraded site). This may be caused by the presence of iron (Fe) in the soil. Fe binds free P and forms large aggregates (up to 2 mm in diameter) and therefore P is easily not transported by wind. The ER for N and C found in this study agreed well with the ER found by Bielders *et al.* (2002) and Sterk *et al.* (1996). Comparing the ER values with the intensity of mass transport reveals that for all sites the ER values were larger when mass transport was more intense. This suggests that during intense wind erosion events, saltating particles break up the crust, in and under which there are more fine particles with nutrients attached.

Table 4) Enrichment ratios for nitrogen (N), carbon (C) and phosphorus (P) for four wind erosion events at three geomorphic units in the Katchari catchment.

Date	Element	ER Dune	ER Degraded	ER Valley
June 9 2001	N	1.48	1.34	0.81
	C	1.32	1.50	0.87
	P	0.62	0.73	0.44
June 22 2001	N	1.91	0.73	1.80
	C	3.04	2.99	1.86
	P	1.30	0.77	1.19
July 3 2001	N	1.92	0.57	1.12
	C	2.51	1.31	1.35
	P	1.15	0.47	0.73
Average values used for August 20 2000	N	1.77	0.88	1.24
	C	2.29	1.93	1.36
	P	1.02	0.66	0.79

Wind erosion modelling

Visser *et al.* (2004-b) showed that the WEPS in PCRaster could predict the pattern of spatial variation in mass transport. However, they did not give a qualitative indication of the reliability of the model results. Therefore, we calculated the correlation coefficients of the maps of simulated mass transport using conditional simulation based on geostatistics (Visser *et al.*, 2004-c) versus the WEPS predictions of mass transport. Figure 2 shows the correlation between the conditional simulated maps and the WEPS-predicted maps of mass transport for the event of 9 June 2001. The correlations for the dune site and the degraded site are acceptable and the correlation for the valley site is small, as expected. While looking at the results (Fig. 2), the reader should keep in mind that the variogram model of the valley site was weak and that even with the stronger variogram models of the dune and the degraded sites cross correlation of several simulated mass transport maps did not result in correlation coefficients higher that 0.6. Since the low correlation for the valley site is due to the poor quality of the variogram and the correlation of the other sites is in the line of expectations, we concluded that WEPS in PCRaster gave good predictions in spatial variations of wind-blown mass transport, and therefore also in spatial variation of erosion and deposition.

Table 5 shows the results of the simulation of three wind erosion events. The simulation results vary between 115 ton ha^{-1} soil loss on the degraded site and a deposition of 469 ton ha^{-1} on the valley site. For the event of 9 June, net deposition was predicted for all sites, whereas for the other events soil loss was predicted at the dune and the degraded sites. For the valley, deposition was predicted for all events. A possible explanation for the prediction of deposition is that no loose sediment on top of the soil crust was available for entrainment. On 5 June a moderately intense wind erosion event occurred, with the same average wind direction (NE) as the event of 9 June; eroding most available sediment. No rainfall event occurred between 5 and 9 June, so no new sediment was created. Deposition was predicted in and just before cells that had a low transport capacity due to their roughness or vegetation cover. If the wind had come from another direction, the previously deposited sediment would have been available for re-entrainment. The fact that there was deposition on the valley site for all events can be attributed to the scattered cover of trees and shrubs on the site. The dune and degraded sites lack this vegetation cover, and therefore the wind could develop enough force to entrain particles (erosion); as these sites had fewer cells with low transport capacity, less sediment was deposited.

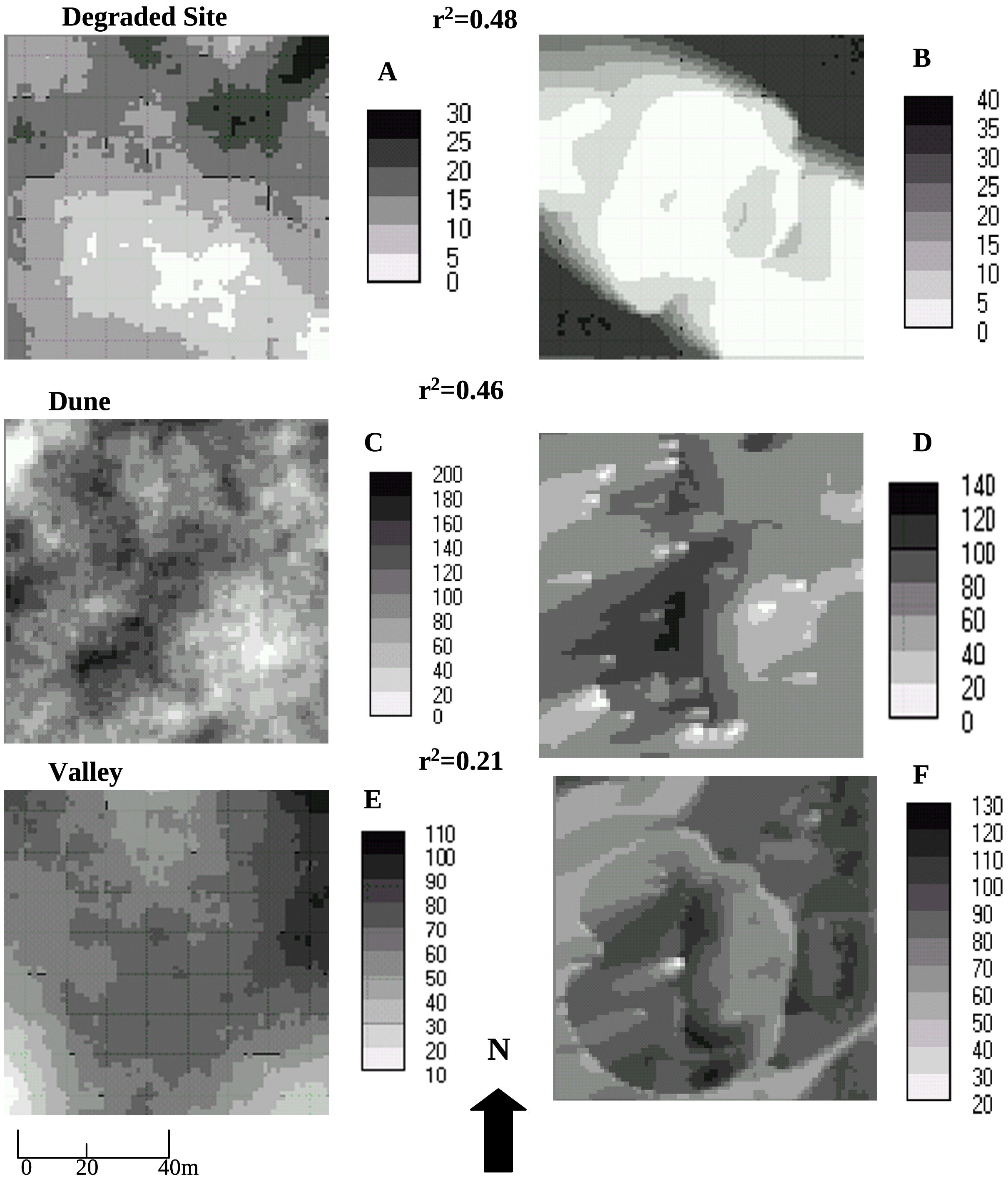


Figure 2) Stochastic simulated and WEPS–predicted maps of mass transport (kg m^{-2}) for a wind erosion event on 9 June 2001 at the degraded site (A and B), the dune site (C and D) and the valley site (E and F) in the Katchari catchment in northern Burkina Faso. r^2 indicates the correlation between the two maps.

Table 5 presents the simulated nutrient gains and losses related to the saltation material. It can be seen that when erosion occurs, considerable amounts of nutrients are lost, and when deposition occurs, large amounts of these lost nutrients can be regained. The reason that the total losses of C, N and P are larger than those found by Bielders *et al.* (2002) and Sterk *et al.* (1996) has to do with the larger soil losses predicted by the model. According to Buerkert and Hiernaux (1998), 15 kg N and 2 kg P ha^{-1} y^{-1} are exported with crop yields from traditionally cultivated fields in the Sahel. Comparing these values with the losses simulated for our research sites, it becomes clear that in one wind erosion event 78% of the N and 100 % of the P needs for crop growth may be removed due to erosion. On the other hand, these nutrients can be gained if deposition occurs.

Table 5) Simulated erosion and deposition (t ha^{-1}) and total N, P and C (kg ha^{-1}) for three wind erosion events at three geomorphologic units in the Katchari catchment in northern Burkina Faso. Positive numbers indicate deposition, negative numbers indicate erosion.

Date		Dune	Degraded	Valley
June 9 2001	Er./Dep.	+ 33	+ 73	+ 469
	N-tot	+ 1.3	+ 9.9	+ 97.7
	P-tot	+ 0.4	+ 3.2	+ 2.5
	C-tot	+ 75.1	+ 9.5	+ 849.7
June 22 2001	Er./Dep.	- 38	- 77	+ 195.8
	N-tot	- 4.6	- 3.1	+ 19.7
	P-tot	- 2.0	- 3.2	+ 5.2
	C-tot	- 74.0	- 78.8	+ 176.8
July 3 2001	Er./Dep.	- 102	- 114.7	+ 5
	N-tot	- 11.6	- 6.8	+ 5.5
	P-tot	- 4.4	- 3.3	+ 1.7
	C-tot	- 153.1	- 98.4	+ 74.3

Water erosion measurements

Table 6 shows the TE content of the sediment caught in the runoff plots. The highest TE contents were found at the valley site. At the dune site, nitrate-N losses were 3-10 times higher than at either the valley site or the degraded site. As permeability is higher at the dune site than in the other sites, there is probably less denitrification here; this results in a larger loss of nitrate-N with the runoff water. Similar results were obtained by Biaou *et al.* (1999) : the nitrate-N values they measured in runoff from very permeable aeolian deposits in a small catchment in northern Burkina Faso were up to 4 times higher than the values in runoff from poorly permeable erosion crusts. The ER values we calculated from the TE content of the trapped material are shown in Table 7. The ER values for the event of 20 August 2000 are the average of all measured ER values.

For each event, the ER values for N and P were highest in the valley site. This was to be expected, since the TE contents of the topsoil were measured before the onset of the rainy season and the new topsoil was already nutrient-rich thanks to the continuous deposition of wind-blown sediment. For these reasons the ER values for the eroded sediment in the valley site were highest in absolute terms. The ER values for C were not the highest (Table 7) though, because the topsoil already had a high C content before the onset of the rainy season as a result from input of C via the dung of the cattle that had been grazing in the valley (Table 1).

The highest ER values for all sites were for the event of 15 August, except for the ER

Table 6) Total carbon (C), nitrogen (N), and phosphorus (P) contents of the sediment caught in the runoff plots and the total soluble N-content of the runoff water for three rainfall events at three geomorphic units in the Katchari catchment. P1 and P2 runoff plots 1 and 2

Date	Site	Plot	C mg kg^{-1}	N mg kg^{-1}	P mg kg^{-1}	Nitrate N µg l^{-1}
July 20 2001	**Dune**	P1	2510	221	54	1900
		P2	8400	570	129	949
	Degraded	P1	2820	378	96	625
		P2	7050	365	68	312
	Valley	P1	4800	448	104	113
		P2	11030	986	120	128
August 15 2001	**Dune**	P1	3330	364	68	1324
		P2	6070	480	123	1308
	Degraded	P1	5190	368	109	287
		P2	7870	397	161	200
	Valley	P1	3160	477	137	139
		P2	7540	904	175	125
August 20 2001	**Dune**	P1	1070	114	119	1277
		P2	2470	243	119	1083
	Degraded	P1	1160	149	125	217
		P2	2050	203	83	219
	Valley	P1	3610	356	107	424
		P2	8170	742	170	532

value for C in the dune site and the ER value for N in the valley site: the highest values for these were reached after the event of 20 July. Although most rainfall was recorded at the valley and dune sites after the event of 20 August, this event resulted in the lowest ER values at all sites. A possible explanation is that during the event of 20 August the highest runoff and the largest amount of sediment transport were measured. More sandy material (not containing any nutrients) was transported, resulting in lower ER values. Alternatively, most nutrients attached to the loose material on top of the crust might already have been removed by previous events. Furthermore, the heavy rain caused sheet flow to develop during the first 5 minutes of the event. When the ground is protected by a sufficiently thick layer of water, rain splash can’t exert large forces on the soil surface and so the crust containing and overlying fine material and nutrients is not broken. The result is that not much fine material and nutrients will be added to the material available for transport.

Table 7) Enrichment ratios (ER) for four water erosion events at three geomorphic units in the Katchari catchment.

Date	Element	Dune	Degraded	Valley
July 20 2001	N	2.4	1.3	3.1
	C	3.4	2.7	1.0
	P	0.9	0.5	0.8
August 15 2001	N	2.6	3.0	3.0
	C	3.0	3.6	1.9
	P	0.9	0.8	1.5
August 20 2001	N	1.1	0.6	2.4
	C	1.1	0.9	1.3
	P	1.0	0.7	0.7
Average values used for August 20 2000	N	2.0	1.6	2.8
	C	2.5	2.4	1.4
	P	0.9	0.7	0.9

Table 8) Simulated erosion (t ha^{-1}) and nutrient losses (kg ha^{-1}) for three rainfall events at three geomorphologic units in the Katchari catchment in northern Burkina Faso.

Date		Dune	Degraded	Valley
July 20 2001	Er./Dep.	0.04	0.21	0.01
	N-tot	0.02	0.08	0.01
	P-tot	0.00	0.02	0.00
	C-tot	0.24	1.05	0.01
	Nitrate-N	$<<10^{-3}$	$<<10^{-3}$	$<<10^{-3}$
August 15 2001	Er./Dep.	0.02	0.32	0.01
	N-tot	0.01	0.95	0.00
	P-tot	0.00	0.04	0.00
	C-tot	0.07	2.07	0.03
	Nitrate-N	$<<10^{-3}$	$<<10^{-3}$	$<<10^{-3}$
August 20 2001	Er./Dep.	0.05	0.87	0.05
	N-tot	0.01	0.14	0.03
	P-tot	0.01	0.13	0.00
	C-tot	0.08	1.09	0.15
	Nitrate-N	$<<10^{-3}$	$<<10^{-3}$	$<<10^{-3}$

Water erosion modelling

Earlier, Visser *et al.* (2004-a) had calibrated and tested the EUROSEM in PCRaster model at the same three research sites as described here and had concluded that it could be applied to the Sahelian situation and predicts total runoff and sediment losses well. Since nutrient losses are closely related to the prediction of runoff (nitrate-N) and sediment (total N, P and C) and both runoff and sediment losses are well predicted, we assume that the model also predicts nutrient losses well.

Table 8 shows the total simulated soil and nutrient losses for the three rainfall events. For all three events the largest soil losses were predicted for the degraded site. These soil losses occurred due to a combination of the presence of a well developed soil crust which limits infiltration and increases runoff, and the absence of a vegetation or mulch cover.

For all sites, the largest soil losses were predicted for the event of 20 August, which was the largest event. The second largest event (of 15 August) did not result in the prediction of large amounts of soil losses in the dune and valley sites. This is related to the cultivation history of the fields: none of the sites had been cultivated before 20 July, and a well developed crust limited infiltration. Infiltration capacity increased after the valley site was hoed on 24 July and the dune site was hoed on 3 August. After the event of 15 August, two large rainfall events occurred, during which the new soil crust could develop further. At the onset of the rainfall event of 20 August, both the dune and valley sites were again covered with a well developed crust.

Nutrient losses were highest in the degraded site, as was expected, given the large sediment losses here. The N losses via the dissolved transport of nitrate were negligible compared with the N losses in the sediment. This finding corresponds with the results reported by Biaou *et al.* (1999) in northern Burkina Faso. They found that N losses in dissolved form represented only 0.3 % of the total N losses. From this it is clear that compared with the nutrients exported with the harvested crops in the Sahel, the nutrient losses from the three simulated rainfall events are small.

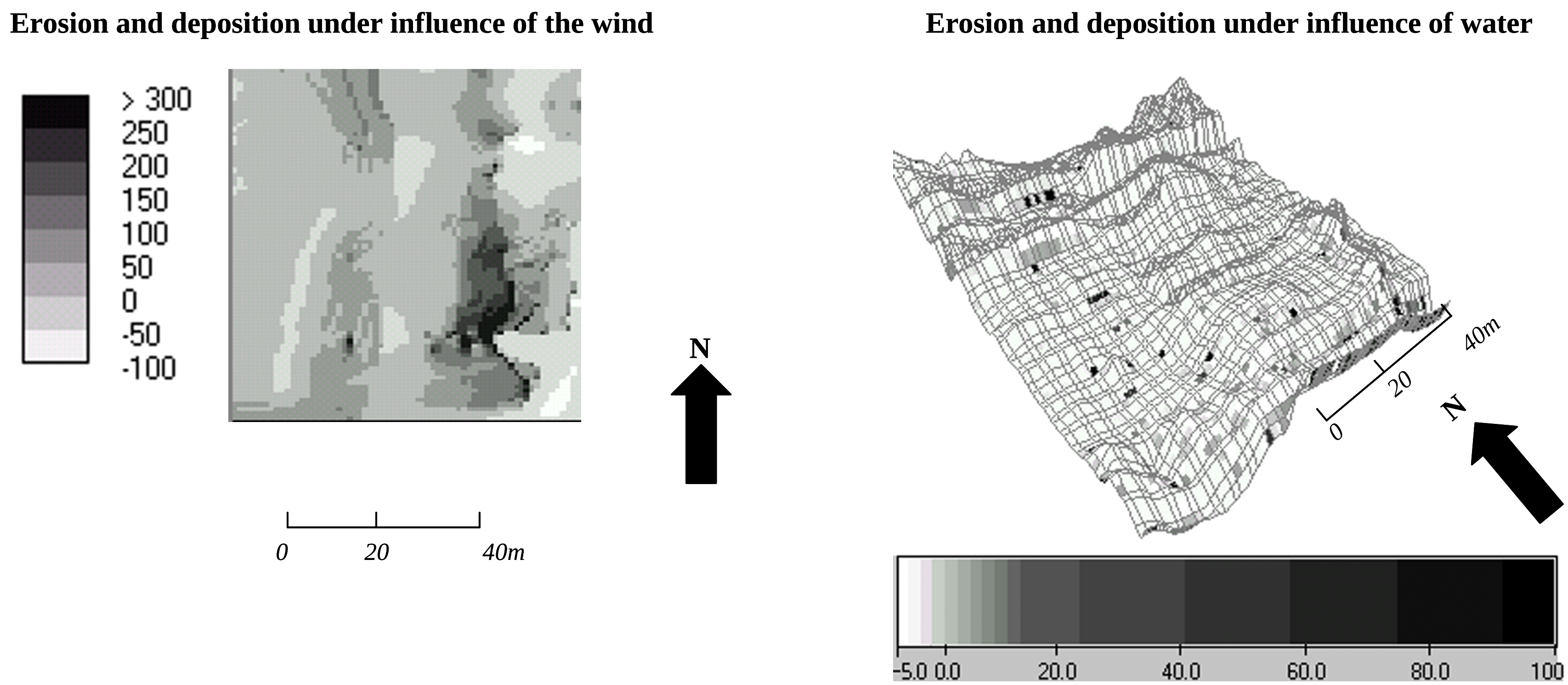
Table 9) Simulated erosion and deposition and nutrient gains and losses by wind and water during the event of 20 August 2000 at three geomorphic units in the Katchari catchment, northern Burkina Faso.

	Dune	Degraded	Valley
Soil *(ton ha^{-1})*			
Wind	+29.85	-23.65	-0.03
Water	-0.01	-0.28	-0.01
Total	*29.84*	*-23.93*	*-0.04*
N *(kg ha^{-1})*			
Wind	+6.27	-8.69	-0.01
Water	-0.01	-0.21	-0.01
Total	*+6.26*	*-8.90*	*-0.02*
P *(kg ha^{-1})*			
Wind	+2.24	-3.80	-0.00
Water	-0.01	-0.05	-0.00
Total	*+2.23*	*-3.85*	*-0.00*
C *(kg ha^{-1})*			
Wind	+171.90	-119.00	-0.11
Water	-0.10	-1.90	-0.06
Total	*+171.80*	*-120.90*	*-0.17*

Combination of wind and water erosion

For the simulation of a combined wind/water erosion event, first the wind erosion event was simulated. As soon as rainfall starts, the wind erosion model was interrupted and all sediment in motion was deposited. Input maps of the spatial distribution of loose sediment and nutrients were prepared and the water erosion model was run. Table 9 shows the results of the simulation of the wind/water erosion event of 20 August 2000. In the dune site there was net deposition of sediment and nutrients under influence of the wind, but water erosion resulted in a net soil loss that is negligible compared with the deposition due to wind-blown mass transport. Figure 3 shows the spatial distribution of erosion and deposition by wind and water in the dune site for the event of 20 August 2000. From this figure it becomes clear that despite a net deposition under influence of the wind in the dune site, there were large areas with net erosion. The deposition generally occurred in concentrated areas. The pattern was similar for water erosion: small amounts of soil were eroded from the slopes and deposited in the down slope area or in the depressions, especially in the pool in the south-eastern part of the field. The map of wind erosion and deposition shows net erosion for this south-eastern area; here, the net effect of wind and water erosion is approximately zero. This demonstrates that although soil losses by water erosion can be negligible at the field scale, they can be significant in smaller areas.

In the degraded site, wind erosion caused most soil loss, whereas in the valley site soil loss by water contributed 17 % of total soil loss (Table 9). At the valley site wind-blown sediment transport occurred in only a small part of the area: in the rest of the area the crop cover hampered wind-blown sediment transport. Therefore, at this site the losses of sediment and nutrient due to the wind were very small and water erosion was relatively more important. Comparing the nutrient losses by wind and water at the degraded and dune sites reveals that wind erosion can cause the largest nutrient losses and that by comparison the losses via water erosion are negligible. And when deposition by wind occurs, the nutrient losses via water erosion are also negligible by comparison with the amounts deposited.



Erosion and deposition under influence of the wind

Erosion and deposition under influence of water

Figure 3) Spatial distribution of erosion (negative) and deposition (positive) (kg m^{-2}) by wind and water at the dune site in the Katchari catchment, northern Burkina Faso for the combined wind and water erosion event of 20 August 2000.

Soil and nutrient losses due to water erosion occur no matter whether the field is cultivated or abandoned and in the long term the cumulative losses due to water erosion may be significant. Furthermore, the runoff carries soil and nutrients to the nearest stream, which transports them out of the area. In this way, nutrients lost by water erosion are lost forever from the catchment.

The average distance travelled by saltating particles ranges from 10 metres to several hundred metres (Bagnold, 1941). Once picked up by the wind, saltating particles are moved in the downwind direction until they reach an obstacle like a tree or bush, against which they are deposited. The saltating particles may leave the field and be deposited in an adjacent field or fallow, or, alternatively, the process results in a redistribution of sediment within the farmers' field (Visser *et al.*, 2004-a). In northern Burkina Faso the landscape can best be described as parkland with trees and bushes scattered over the area, even on cultivated fields. However, cultivated fields generally have a less dense cover of trees and shrubs and therefore serve as a source of sediment and nutrients for wind-blown transport. This sediment is generally deposited in adjacent fallow areas, which have a denser shrub cover and serve as a sink. When farmers abandon their exhausted fields and start cultivating a fallow area the source /sink relation is reversed. Therefore, saltation transport can only result in a local redistribution of soil particles and nutrients. In the long run, the net erosion/deposition of nutrients under influence of saltation transport may be close to zero. However, this crop/fallow system only functions when a sufficiently large area of fallow land is present, otherwise the regional budget of nutrient losses related to saltating particles becomes negative (Sterk *et al.*, 1996). Even if fallow and cultivated land are in balance, wind erosion can be responsible for large losses of nutrients and fine particles in the long run. Though suspension transport by wind was not discussed in this article, its impact should not be overlooked. With each event, suspended dust, rich in nutrients is lifted to a height of several hundred metres and may be carried over long distances. Several authors have reported that dust clouds from West Africa have crossed the Atlantic Ocean (Carlson and Prospero, 1972; Westphal *et al.*, 1988). These nutrients are lost from the area. However, input of dust occurs during the Harmattan. These dust deposits originate from the Sahara desert and are rich in K but poor in P. Whether there is a net loss or gain of dust and nutrients due to suspension transport in the Sahel is unclear (Sterk *et al.*, 1996).

Conclusion

This study confirms that the nutrient content of wind blown sediment is spatially variable. The implication is that when calculations of total nutrient losses are based on the average nutrient contents of the wind-blown sediment of a field, the losses are likely to be under- or overestimated. However, since our observations were based on only two clustered samples for each event, we decided that this phenomenon requires further investigation and so for each event we calculated an average ER for each nutrient. Generally, the ER values were larger when wind-blown sediment transport was more intense. It seems likely that saltating particles break up the crust, in and under which more fine particles and nutrients are present.

We have demonstrated that the physically based model of WEPS in PCRaster can predict patterns of erosion and deposition due to wind-blown sediment transport. Whether net erosion or deposition occurs depends on wind direction, crusting pattern and vegetation cover. When erosion occurs, considerable amounts of nutrients are lost (with one wind erosion event 77.5% of the N and 100 % of the P needs for crop growth may be eroded), but when deposition occurs, most of these lost nutrients can be regained.

The ER values of sediment transported by water are generally higher when more runoff occurs, but they also depend on the availability of fine particles and the moment at which overland flow develops. The deposition of wind-blown sediment results in a topsoil which is enriched in nutrients. When the ER values for water-eroded sediment are calculated based on nutrient contents of soil samples taken before the onset of the rainy season, the ER values will be relatively high. This might lead to the soil degradation being overestimated.

Soil loss by water erosion is closely related to the crust type present, which regulates infiltration and thus runoff. The N loss due to the dissolved transport of nitrate is negligible compared with the N loss due to sediment transport. The three rainfall events we investigated resulted in only 0.7 % of the crop requirements for N and 0.006 % of the crop requirements for P being removed by erosion.

Even though at the scale of the field there is net erosion or deposition by both wind and water erosion, within the field it is possible to identify areas with erosion and areas with deposition. At field scale, soil and nutrient losses by water erosion are negligible in comparison with wind erosion. However, the role of water erosion can be significant in smaller areas within the field. Furthermore, soil and nutrient losses by water flow into the nearest stream and leave the catchment. These nutrients are forever lost for the area and mount up in the long term. Sediment transport by wind in saltation mode results in the largest soil and nutrient loss at the time scale of an event. However, when the cultivated and fallow land in a region are in balance, the largest amounts of nutrient losses over a larger time scale (e.g. 50 years) are the result of soil losses related to runoff. The net, long-term effect of suspension transport by wind is still unclear.

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Chapter 8

Nutrient dynamics by wind and water erosion at village scale in the Sahel

S.M. Visser and G. Sterk

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Nutrient dynamics by wind and water erosion at village scale in the Sahel

Abstract

Numerous model studies based on nutrient budgets predict serious losses of chemical soil fertility and indicate severe soil degradation in the Sahelian zone of West-Africa. The erosion components of these studies generally form a large contribution to the negative part of the balance. However, research on soil erosion was generally performed at plot scale (and thus should not be up-scaled to district scale) and the wind erosion contribution to the total nutrient losses by erosion is often overlooked. In this paper the erosion component of the nutrient balance is critically reviewed based on an intensive literature study.

The loss of nutrients by wind erosion is generally attributed to losses by suspension, since suspension selectively removes the finest particles. However, because the main mass of sediment is moved by saltation during an event, the main mass of nutrients is also moved by saltation. Nutrient losses from one field during one wind erosion event can be as high as 72.5% of the N and 100% of the P needs for crop production. But at village scale the long-term effect of nutrient losses due to saltation can be assumed nil, provided a balance between fallow and cultivated areas. Deposition of suspended dust is generally assumed to be homogenous for a whole area. In the Sahel two types of dust can be distinguished The Harmattan dust is richer in nutrients and regarded as a real input of nutrients whereas the convectional storm dust has a nutrient content comparable with the nutrient content of the dust fraction of the topsoil and can’t be regarded as input of nutrients. From research on nutrient losses by water erosion at plot scale it is concluded that nutrient erosion by water can cause serious losses of the basic plant nutrients. Though at village scale the losses are considerably smaller than at plot scale, these losses should not be overlooked in comparison with wind erosion, since nutrient losses by water are generally transported to the system outlet and forever lost for the area.

After applying a nutrient budget analysis at the area around the village Dangadé it is concluded that this area is especially vulnerable for wind erosion. The role of water erosion and dust deposition is small in comparison with erosion by saltation transport. This indicates that at village scale in the Sahelian environment the effect of wind erosion can’t be ignored.

Introduction

In the Sahelian zone of West Africa ongoing soil degradation and the consequent decrease in soil productivity forms a major concern to the local farmers and the international community (Lal, 1988). According to UNEP (1997) 30% of the West-African Sahel is affected by human induced soil degradation and for about 50% of this area soil degradation is moderate to extreme. A combination of factors including increased population pressure, deforestation caused by firewood and cultivation area demands, lengthening of cultivation period and repeated cycles of drought have caused the soil degradation in the Sahel to become widespread (Kessler *et al.*, 1995; Ramaswamy and Sanders, 1992; Thiombiano, 2000). According to Bationo *et al.* (1998) the low fertility of the soils is the major constraint for the production of food grains and natural vegetation in the Sahelian zone of West-Africa. Furthermore they state that the soil fertility in traditional, but intensified farming systems can only be maintained through integrated plant nutrient management with efficient recycling of organic matter such as crop residue, compost or manure in combination with mineral fertilizers and using rotations with legumes.

Since the late 1980s model studies based on nutrient budgets form an increasingly important source of evidence on soil degradation (Pol, 1992; Smaling, 1993; Stocking, 1996; Stoorvogel and Smaling, 1990). These studies come with alarming conclusions about the farmers in the Sahel and the way they are currently exhausting their soils. As a part of their study at a continental level Stoorvogel and Smaling (1990) give figures for nutrient losses in Burkina Faso, estimating annual losses in the order of 12, 14 and 4 kg ha^{-1} for potassium (K_2O), nitrogen (N) and phosphor (P_2O_5) respectively. Of these losses 43%, 41% and 42% respectively are attributed to soil erosion, which is therefore the main loss term in the budget.

The generally accepted view of ever degrading soils in West-Africa was recently challenged by Mazzucato and Niemeijer (2000) and Stocking (1996) who state that soil productivity has not decreased over the last 50 years.

Decrease in soil productivity is closely related to soil erosion, but this is not the only controlling parameter. Measurements on soil erosion have largely been carried out on experimental sites and not on farmers' fields. For this reason it is doubtful whether such experimental results can actually be used for extrapolation to the watershed level, let alone to the region or country level (Stocking, 1996; Mazzucato and Niemeijer, 2000). Plot level data tends to overestimate erosion because it does not take into account the fact that at watershed level both erosion and deposition occurs. In fact even within single field distinct areas with either erosion or deposition occur (Stocking, 1996; Visser *et al.*, 2004-a).

The Sahelian zone can be defined as the transition zone between the arid Sahara in the North and the more humid Sudan zone the South. These limits correspond roughly with a mean annual rainfall of 200 mm in the North and 600 mm in the South (Le Houérou, 1984). Using this definition for the Sahel it can be stated that in the Sahel the effect of wind-blown sediment transport is often overlooked. Smaling (1993) incorporated nutrient inputs through atmospheric deposition but considered as output only water erosion. Bielders *et al.* (2002), Sterk (1997) and Visser *et al.* (2004-b) showed that wind-blown sediment transport causes considerable soil and nutrient losses at field scale, these losses are some times even larger than soil losses by water erosion (Visser *et al.*, 2004-d). Therefore the role of wind erosion in the nutrient balance for Sahelian areas should not be overlooked. In the more humid Sudan zone, which is often referred to as part of the Sahel, wind erosion is less important.

Finally, one of the reasons that erosion is considered to be so serious is that the valuable nutrient rich topsoil is lost. Smaling (1993) notes that his nutrient budgets are only slightly negative for the semi-arid countries in West Africa because the poor soils have little to loose anyway. Where the soil is deep and poor in fertility, topsoil may not always be that more fertile than the subsoil and productivity does not decrease much as a result of soil erosion.

Despite the numerous uncertainties, erosion is a pronounced factor in the nutrient balance studies. The erosion component is often an estimate because good data on nutrient losses by erosion is lacking. Therefore the erosion component of nutrient balances needs to be critically reviewed. Based on a previous study on modelling nutrient fluxes under influence of wind and water erosion (Visser *et al.*, 2004-d) and a literature review, the dynamics of nutrients under influence of wind and water at village scale in the Sahel are studied. Finally the results will be applied to part of the area belonging to the village Dangadé northern Burkina Faso.

Wind erosion component

Unlike sediment transport by water, wind-blown sediment transport is not confined by topographic boundaries. Sediment is transported in the mean direction of an erosive wind, which can change for successive events. Source material, soil erodibility and non-erodible roughness determine the spatial patterns of erosion and deposition. Furthermore, texture and transportation mode are important parameters in determining the transported distances and the related nutrient losses.

Three different modes of sediment transport can be distinguished: saltation, creep and suspension (Bagnold, 1941). Particles transported in creep mode are mainly set in motion by the bombardment of saltating grains, but are sufficiently large to always keep in contact with the soil surface. Creep is considered not to result in significant nutrient losses because creep mainly transports coarse sand, which is usually poor in plant nutrients (Sterk *et al.*, 1996). Transport distances of sediments moving in creep mode range from several centimetres till several meters (Allen, 1994). Saltating particles bounce over the soil surface and may reache heights until 2 m, but the bulk of saltation transport occurs just above the soil surface. Saltating grains can be transported over a range from several meters to a few hundred meters (Allen, 1994). The finest particles are held high in the air by the wind as suspended dust and may travel up to thousands of kilometres (Allen, 1994; Sterk *et al.*, 1996). Because suspension selectively removes the finest particles, that contain relatively larger proportions of nutrients and organic matter, from the topsoil, the loss of nutrients is usually attributed to losses by suspension (Leys and McTainsh, 1994; Zobeck and Fryrear, 1986). However, Sterk *et al.* (1996) showed that although suspended sediments are generally more enriched in nutrients, the main mass of nutrients is transported in saltation mode simply because the main mass of sediments is moved by saltation during an event. Furthermore, particles can hardly come into suspension if no saltation occurs. Saltating particles often consist of aggregates of finer particles, which are rich in plant nutrients.

In this section we will further describe the contribution of suspension and saltation to the erosion component in the nutrient balance.

Nutrient losses by saltation

So far only Bielders *et al.* (2002), Sterk *et al.* (1996) and Visser *et al.* (2004-d) published work on measured nutrient losses by saltation transport in the Sahel. Sterk *et al.* (1996) calculated a nutrient budget based on incoming and outgoing nutrient fluxes in a pearl millet field in Niger for two wind erosion events. These events eroded a total of 39.3 tons sediment ha^{-1} from the field. The estimated nutrient losses were 3.2% (K), 2.8% (C), 2.8% (N) and 2.6% (P) of the 10 cm topsoil.

Bielders *et al.* (2002) in traditionally managed land in western Niger measured saltation and nutrient fluxes in a transect over a millet field into the adjacent fallow and calculated total loss or gain of nutrients. Total nutrient content in the sediment samples generally declined with distance into the field and rose with distance into the fallow. This was probably due to higher nutrient contents of the soil from which the incoming sediment eroded, a relatively large addition of nutrient poor sediment over the field and finally the rapid deposition of the sand-sized material in the fallow. They state that in absolute terms nutrient losses are low, but for one event measured nutrient losses at the field represent between 3% (K) and 17% (P) of the nutrients taken up by an average millet crop. Most of these nutrients were deposited in the adjacent fallow. Furthermore, they found that nutrient losses by saltation are considerable, but they often remain in the system when the sediment is trapped by vegetation or other obstacles (Bielders *et al.*, 2002).

Visser *et al.* (2004-d) measured nutrient fluxes at three geomorphic units in northern Burkina Faso: a cultivated field in a valley, a cultivated field at an ancient dune and a site in a degraded area. A physically based wind erosion model extended with nutrient modules was used to predict total nutrient erosion or deposition was predicted for three events at three research sites. For each research site maps indicating areas with erosion and deposition were derived. For the valley site, which had a higher cover of vegetation, a net deposition of sediment and nutrients was calculated. The other sites showed alternatively net erosion or deposition depending on the availability of sediment and the mean wind direction. The field at the dune site lost during one wind erosion event 77.5% of the N and 100% of the P needs for crop growth.

From the previously described studies it can be concluded that in traditionally managed fields, saltation may cause severe soil losses. However, from the work of Bielders *et al.* (2002), Visser *et al.* (2004-d) and Sterk *et al.* (2004) we learn that soil losses apply only for a limited part of the field and that despite a net erosion at field scale, areas with deposition may occur within the field. The associated nutrient losses, though low in absolute terms, are large in comparison with the nutrient content of the top soil (Sterk *et al.*, 1996) and in comparison with the average annual uptake of a millet crop (Bielders *et al.*, 2002; Visser *et al.*, 2004-d).

Nutrient losses by suspension

Generally, suspended dust is richer in nutrients than the coarser saltation material owing to a higher percentage of clay and silt (Zobeck and Fryrear, 1986). Dust deposition is variable form season to season. Rajot (2001) measured during a three-year monitoring in southwest Niger broad peaks in deposition fluxes related to the continuous strong winds, which might last for several days during the Harmattan season. These peaks are in the order of 1-1.5 g dust m^{-2} d^{-1}. Apart from these peaks, the average deposition during the Harmattan season (October through March) is also large (approximately 0.1 g dust m^{-2} d^{-1}). During the early rainy season high peaks in deposition fluxes (approximately 3-4.5 g dust m^{-2} d^{-1}) were measured, which were related to local erosion events such as the short duration dust storms occurring just before a convective rainfall event. Finally, considering only the dust particle sizes < 20 μm, Rajot (2001) calculated a total average deposition of 1.0 t dust ha^{-1} yr^{-1} of which 51% is contributed by the Harmattan winds and 49% by the convective events during the rainy season. When considering all trapped mass (also particle sizes > 20 μm), a total average dust deposition of 1.4 t ha^{-1} $y^{-1}$was calculated, of which 42% was contributed by the Harmattan winds and 58% by the convective events.

The dust that is deposed during the Harmattan season should be regarded as real input from remote sources (the Sahara desert). The dust deposed during the early rainy season origins from local sources, is deflated in front of convective rainfall events and is partly deposed with the rainfall that immediately follows the deflation event (Herrmann *et al.*, 1994). It is important to notice that during the early rainy period actually a net loss of dust occurs, which is clear from the high dust concentrations measured above the Atlantic Ocean following a Sahelian convective storm (Prospero, 1999).

Highest dust emission fluxes generally occur during the convective dust storms (Nickling and Gillies, 1993), though some emission occurs also during the Harmattan season. Rajot *et al.* (1994) measured similar dust emission values in southwest Niger. During only one week of measurements vertical dust emission fluxes ranged from 6.0

10^{-10} to 2.0 10^{-7} kg dust m^{-2} s^{-1}. Total dust emission from their site during one week was 2.0 10^{-3} t ha^{-1}. Despite these measured dust emission values it remains uncertain how much of this dust is actually lost from a certain area during the passage of a convective storm since part of this deflated dust is deposed again (Sterk, 2003). Deposed dust has roughly two origins; the Sahara and local sources. Herrmann *et al.* (1994) measured element contents of the Harmattan dust, the convective storm dust and the potential dust fraction of the soil. Potassium (K), sodium (Na), calcium (Ca) and phosphorus (P) content of the Harmattan dust were high (1.58%, 0.46%, 1.91% and 638 mg kg^{-1}, for K, Na, Ca and P respectively) in comparison with the element contents of the convective storm dust (1.03% K, 0.13% Na, 0.38% Na and 389 mg P kg^{-1}) and the potential dust fraction of the topsoil (1.15% K, 0.11% Na, 0.25% Ca and 660 mg P kg^{-1}) and the subsoil (0.55% K, 0.15% Na, 0.05% Ca and 377 mg P kg^{-1}). The high P content of the potential dust fraction of the topsoil is most probably related to measurement errors caused by plant debris (Herrman *et al.*, 1996). The high similarity of K, NA an Ca concentrations in the potential dust fraction of the top soil compared with the convective storm sample shows that the Harmattan dust is a real source of nutrients, whereas the dust from the convective storms origins from local sources and can’t be regarded as an input of nutrients.

The P content of the Harmattan dust is high compared with the P content of the convective storm dust. Wilke *et al.* (1984) stated hat the high P content in the Harmattan dust in northern Niger was one of the primary causes of the fertility of the fields. However in absolute terms P content of the Harmattan dust is low and in combination with the already low P content in the soil, it is clear that P is a limiting factor for plant production in the Sahel (Herrmann *et al.*, 1994).

Assuming that deposition rates in the fallow were equal to the deposition rates for crop land and that no redistribution occurs, Herrmann *et al.* (1994) calculated a nutrient budget. Nutrient uptake in the above ground biomass by the millet crop is 69 kg K ha^{-1}, 9 kg Ca ha^{-1}, 10 kg Mg ha^{-1} and 9.5 kg P ha^{-1}. In the case that the whole biomass would be removed the deposition/export ration would be 0.2, 1.7, 0.5 and 0.008 for K, Ca, Mg and P respectively. This confirms the phosphorus limitation of the system.

Dynamics of wind erosion

Vegetation cover in a bush fallow (Bielders *et al.*, 2002) or in a valley (Visser *et al.*, 2004-d) reduces wind erosion and effectively traps incoming saltation material originating from adjacent fields. Therefore saltation leads to short range transport, with the main source of particles and nutrients being the bare millet fields in the dry and early rainy season. Consequently, saltation transport can only result in a local redistribution of soil particles and nutrients. At village scale, provided a balance between fallow and cultivation area, the long term effect of nutrient losses due to saltation can be assumed nil (Rajot, 2001; Sterk *et al.*, 1996). When too much land is taken under cultivation, the budget of saltating particles and nutrients may become negative at village scale. First indications for such a negative balance were given for the Maradi region in south Niger, were agricultural over-use caused the negative balance (Mainguet and Chemin, 1991)

Tough suspended dust is richer in nutrients than the coarser saltation material owing to a higher percentage of clay and silt, the suspended mass fluxes are at least one order of magnitude lower than the saltation mass fluxes (Sterk *et al.*, 1996). If the contribution of saltating particles to the nutrient budget at village scale is approximately zero (provided a balance between the fallow and cultivation), the wind erosion part of the nutrient budget at village scale is controlled by the dynamics of small particles suspended in the atmosphere.

Rajot (2001) assumes that deposition of suspended material is homogeneous distributed at the village scale. This might be true for vertical deposition of suspended material but when vegetation is present, dust deposition might be non-homogenously distributed over the area. Dust deposition is often measured with passive catchers; e.g. the CAPYR (Orange and Gac, 1990) (Fig. 1A). Wind and suspended dust are blowing over the catcher and dust is deposed only under influence of gravitational forces when no obstruction of the wind field occurs. However, regarding a tree with a canopy cover (Fig. 1B) we find that the wind field is obstructed, the suspended dust is deposed at the branches and the leaves and the wind leaves the canopy at a lower speed and with a lower dust concentration. Clearly vegetation can trap large amounts of dust, which is not trapped with the passive dust catcher. The dust is washed out of the canopy during the first rainfall event and the accompanying nutrients become available for plant growth. Therefore, dust deposition during the Harmattan, measured with the conventional passive dust catchers might under-estimate total dust deposition and in areas with vegetation dust deposition may not be as homogeneously distributed as is assumed by a number of authors e.g. (Drees *et al.*, 1993; Herrmann *et al.*, 1994; Rajot, 2001).

Water erosion component

Water erosion at village scale can roughly be divided into three main processes: splash erosion, sheet erosion and rill or gully erosion. The direction of sediment transport by water is mainly determined by topography (Visser *et al.*, 2004-c). Each time a raindrop hits the surface it exerts energy to the soil particles that are consequently detached from the surface. This process is called rain splash and the impact of splash erosion is dependent on the slope gradient and surface characteristics. With a slope of 25º, 95% of the dislodged material is transported in a down slope direction. However, under windy conditions with an uphill wind direction, it is possible that a net uphill transport of sediment occurs (Erpul *et al.*, 2002). Uphill transport distances can be up till 7 m, but in case of occurrence of sheet flow, those particles will immediately be transported down hill again. Particles dislodged by splash erosion are generally transported by sheet flow.

Sheet flow is the process whereby water flows in a thin, uniform layer over the soil surface. Transport capacity of sheet flow is generally limited.

Therefore, sheet flow transports only the finest particles (clay), which generally contain most nutrients. The transport capacity of sheet flow can be increased with falling raindrops in the flow, which causes an increased turbulence. The erosional effectiveness of sheet flow is largely controlled by the characteristics of the surface including particle size, degree of particle cohesion and nature of the vegetation cover. When sheet flow concentrates, rills can form. Rills are small channels with cross-sectional dimensions of a few to a few tens of centimetres. They are usually discontinuous, may have no connection to a stream channel system and are often obliterated between one storm and the next or even during the storm when the supply from splash and sheet flow on the interrill area exceeds the transport capacity of the rill (Allen, 1994). Rills may develop into gullies and become a permanent part of the channel network. In rills and gullies also the larger particles can be transported.

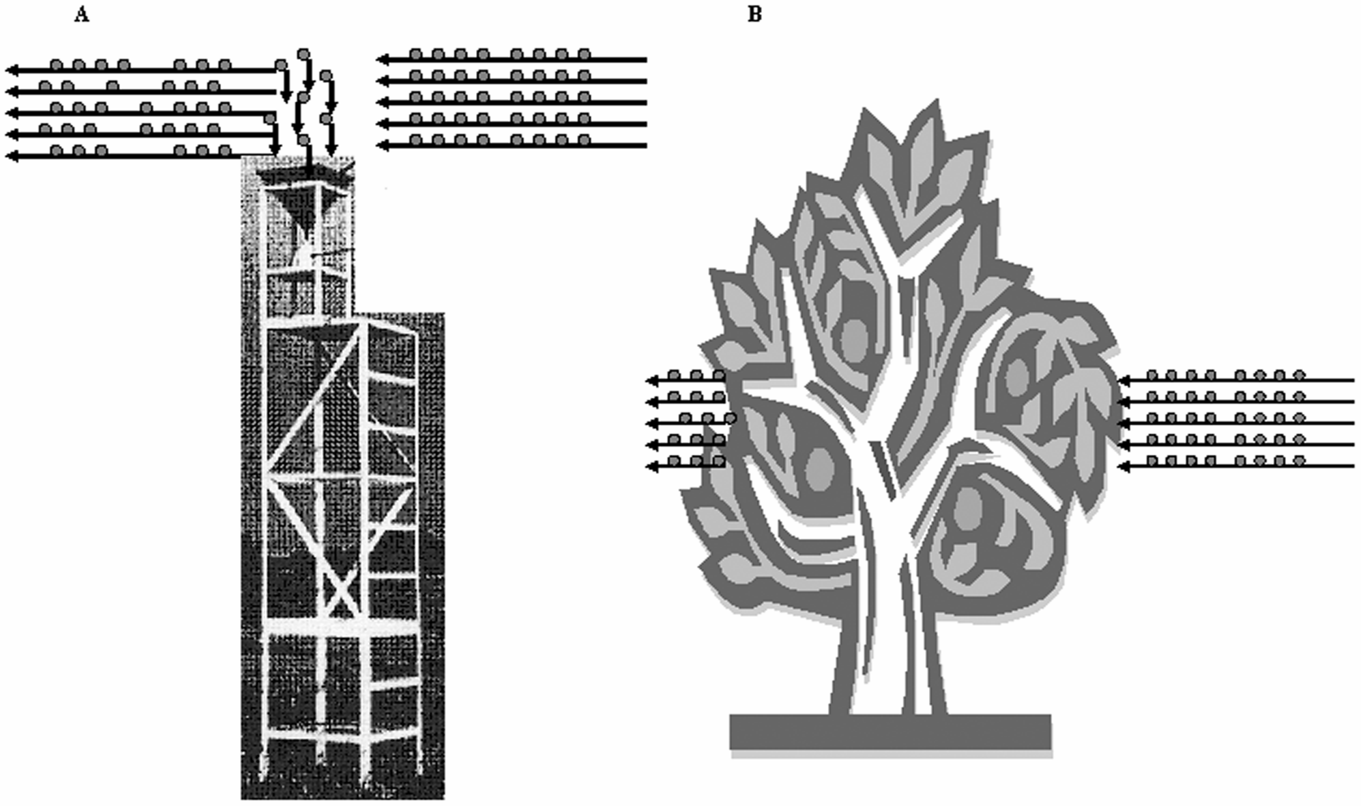

Figure 1A) Dust deposition in a passive dust catcher (the CAPYR) (Orange and Gac, 1990) under influence of gravitational forces. B) Dust deposition in tree cover.

In water the large particles are transported in rolling or sliding mode in constant contact with the soil surface. The size of these particles varies with the stream power, with a higher stream power, larger particles can be transported. Transport distances vary with the stream power as well, but also depend on the roughness of the streambed; with a rough streambed the particles are likely to get stuck behind obstacles. Nutrient contents of particles in rolling or sliding mode are generally very low to zero. Nutrient contents of saltating particles in water are smaller than nutrient contents of saltating particles in wind since in water most aggregates, which contain most nutrients, will fall apart and the sediment will be further transported in suspension mode. Suspension carries the finest particles, and so most nutrients over large distances (up to several thousands of kilometres). The velocity and its related turbulence determine the sediment transport capacity of the surface runoff and the stream flow. Once the velocity decreases due to e.g. a change in slope, the coarser particles start to deposit and when the velocity further decreases the finer particles will also deposit, until with standing water even the finest suspended particles (clay) are deposited.

Nutrient losses by water erosion

In the semi-arid zone of West-Africa soil degradation due to water erosion is a serious threat to sustainable agricultural land use as it affects soil productivity (Laflen and Roose, 1998). Water erosion is not only responsible for negative nutrient and carbon balances (Stoorvogel and Smaling, 1990) but also for the reduction of rooting depth (Morgan, 1995). Pierce and Lal (1994) indicated that low levels of N, P, K, and low cation exchange capacity are among the most important chemical and nutritional constraints accentuated by water erosion. This means that in the long term water erosion affect considerably soil productivity especially in semi-arid West Africa, where major soils, due to their low soil organic matter content are highly sensitive to erosion (Roose and Barthès, 2001).

For calculating the contribution of erosion to the nutrient budget for West Africa Stoorvogel and Smaling (1990) used an enrichment ratio (ER) of 2.0 for N, P and K. Due to the large scale they were working on, they needed to incorporate this simplification. However, from the work of several researchers, who performed their research at plot scale, we learn the ER’s are variable for the different nutrients and for rainfall events with a different intensity (Cogle *et al.*, 2002, Zougmoré, 2003, Visser *et al.*, 2004-d). Zougmoré (2003) found a wide range in ER values for his runoff plots at Saria, Burkina Faso. ER for C ranged from 3 to 7, for N from 4 to 10, for P from 2 to 4.7 and for K from 1 to 3. In general a positive relation exists between annual losses of C, N, P and K and total annual soil loss. However, ER’s become smaller when more erosion occurs (Veldkamp, 1994). As pointed out by Lal (1998) sheet erosion selectively exports clay, silt, nutrients and soil organic matter from the topsoil. This selectivity is particularly high on gentle slopes, as are often found in Sahelian Africa, when runoff and erosion rates are low (Roose and Barthès, 2001).

Visser *et al.* (2004-a) measured soil losses at plot scale at three geomorphic units in the Katchari catchment in northern Burkina Faso, applied a water erosion model at field scale and showed that measured soil losses at plot scale are larger than the soil losses at field scale. For one event the losses at plot scale were approximately a factor 10 higher than the losses at field scale. Furthermore they showed that formation of pools at fields significantly reduced runoff discharge from the field and causes resettlement of the eroded sediment. At the scale of a field water erosion was limited (in comparison with wind erosion) and caused merely a redistribution of sediment over the field.

So instead of directly using results from runoff plots in a nutrient budget analysis, which might lead to large overestimations of the erosion component of the nutrient budget, the topography of the area should be critically examined and the dynamics of sediment and nutrient transport by water at village scale should be examined. Also ER of the several elements in the water-eroded sediment should be determined in more detail, since they vary per element (Geelhoed, 1995, Zougmoré, 2003, Visser *et al.*, 2004-d).

Dynamics of water erosion

As soon as the rainfall intensity exceeds the infiltration capacity, runoff occurs. Generally, first sheet flow will develop. In hilly areas sheet flow will soon concentrate and form rills. At the scale of a Sahelian village the topography is characterised by long slopes with an angle of 2-3°. Therefore the fine sediments transported in sheet flow can travel large distances (up till several hundreds of meters) until the sheet flow either reaches a pool area or a riverbed. When sheet flow reaches the riverbed, the sediments are transported out of the area. When pool formation occurs, runoff distance is limited and sediments are resettled. These pools generally have a depth of several centimetres, but might extend over several tens of meters.

Due to the general low slopes rill development occurs only locally. These rills develop in the local areas where the slope is slightly steeper (e.g. due to cultivation practises or to sediment deposition by wind) and are discontinuous because as soon as the slope becomes smaller again the transport capacity is exceeded, deposition occurs and the runoff continues as sheet flow. Rills seldom develop into gullies.

In areas where the sheet flow reaches the riverbed a new side channel may develop due to the forces of the water flowing over the edge of the riverbed. This process generally occurs in the floodplain of the river, an area which is useless for cultivation since it is temporally flooded after large rainfall events. In the case that such a side channel extends until a cultivated field a large part of the field may be eroded.

Due to the general small slopes, sheet erosion is the most occurring process. Sheet erosion selectively exports clay, silt, nutrients and soil organic matter from the topsoil and this selectivity is highest on gentle slopes. Therefore, sheet erosion, though limited in total amounts of erosion, should not be underestimated, especially at the longer timescale it might contribute considerably to the total nutrient losses at village scale.

Nutrient erosion at village scale

The village Dangadé is situated 17 km southwest from Dori (14º00" N, 0º10"W), the capital of the Seno Province in Burkina Faso. The village is situated at a pediplane between an extensive sand dune system, which is more than 40.000 years old (Delfour and Jeambrum, 1970), and the a river flood plane. Around the village is a floodplain, a pasture zone with low vegetation cover (<10%), a pasture zone with moderate vegetation cover (10-30%), cultivated fields, fallow fields and a degraded area (Fig. 2 and 3).

Dangadé has approximately 175 inhabitants and the courts and cattle grails occupy an area of 3.5 ha. The traditional houses are made of mud with straw roofs. Fences made of mud, wood, branches or straw delimit each grail and court. Due to these fences it is assumed that in the village saltation transport by wind is limited. Slopes in the village are low and no formation of rills and gullies occurred. Furthermore, no standing water is witnessed in the village.

The area of the floodplain (16.8 ha) is characterised by the deeply incised river, which only contains water during the rainy season. A band of dense vegetation (> 80%) borders the river. During the dry season the soil under the tree and shrub cover is bare, but after the first flooding herbs fully cover the soil surface. Bed and bank erosion are the most important erosion processes in this are. Furthermore, backwards retreat of the side channels can cause significant soil losses. The area is normally flooded 6–8 hours after the onset of a large rainfall event, indicating that the water comes from upstream areas.

After flooding a thin mud layer is deposited in the flooding area. According to the local farmers this layer can grow as much as 0.5-1.5 cm during wet years. Due to the dense vegetation cover wind-blown sediment transport is not possible and all sediment in transport is deposited in the first few meters of the vegetation band.

The soils in the pasture zone (18.4 ha low cover, 6.5 ha high cover) are characterised by soil crusts. Annual grasses do grow in this area, but do not form a continuous cover. In the area with the moderate tree cover the loose sand layer on top of the crust is relatively thick (>5 cm) and percentage of grass cover is higher than in the area with low tree and shrub cover. The shrubs trap the wind-blown sediments. In the low cover area vegetation cover is too low to trap all sediments and this area is in general a source of wind-blown sediment. Slopes in the low cover area are generally low and runoff occurs in the form of sheet flow. Large pools with standing water often form in this area. When the water is evaporated a deposition crust can be found in the pool area. In the pasture zone with moderate cover the vegetation traps most wind blown sediment. Due to the sandy topsoil and the larger grass cover runoff seldom occurs.

The fields (12.8 ha) are cultivated with millet during the wet season. Herbs are removed twice by hoeing during the rainy season. The soils have a sandy to sandy-loam texture and are characterized by the occurrence of soil crusts. Crop residue sometimes remains at the fields, but the fields are grazed by cattle during the dry season and so the soils are bare and vulnerable for erosion at the onset of the rainy season. Natural vegetation remains at the field. After sowing the farmers border their fields with branches to prevent the free roaming cattle to enter the field. These “fences” are 0.7 m high and trap only parts of the incoming and outgoing wind-blown sediment.

The fallow fields are left fallow for the first time in the year the picture was taken (2001). Due to a large epidemic of meningitis not enough farmers were available to cultivate all available fields.

First the more fertile fields at the nearby dune system were cultivated. The fallow fields are bare and highly vulnerable for erosion during the entire rainy season. As soon as a crust is developed at the fields and the fallow, infiltration is hindered and runoff occurs. Also at the fields and fallow, slopes are low and runoff occurs in the form of sheet flow.

The degraded area is characterised by its lack of vegetation. The soil is entirely covered by a fully developed crust, which is partly covered by gravel. The crust is almost impermeable for water and runoff rates as high as 95% are measured in this area. The runoff develops from gentle into concentrated sheet flow; streams of 5-10 m wide and 1-3 cm deep. Due to bank erosion these streams become wider, but no deeper incision occurs, most probably because the drag force of the flowing water is not sufficient to overcome the strong cohesion of the erosion crusts. Also in this area large pools with standing water develop. Due to the openness of the landscape wind-

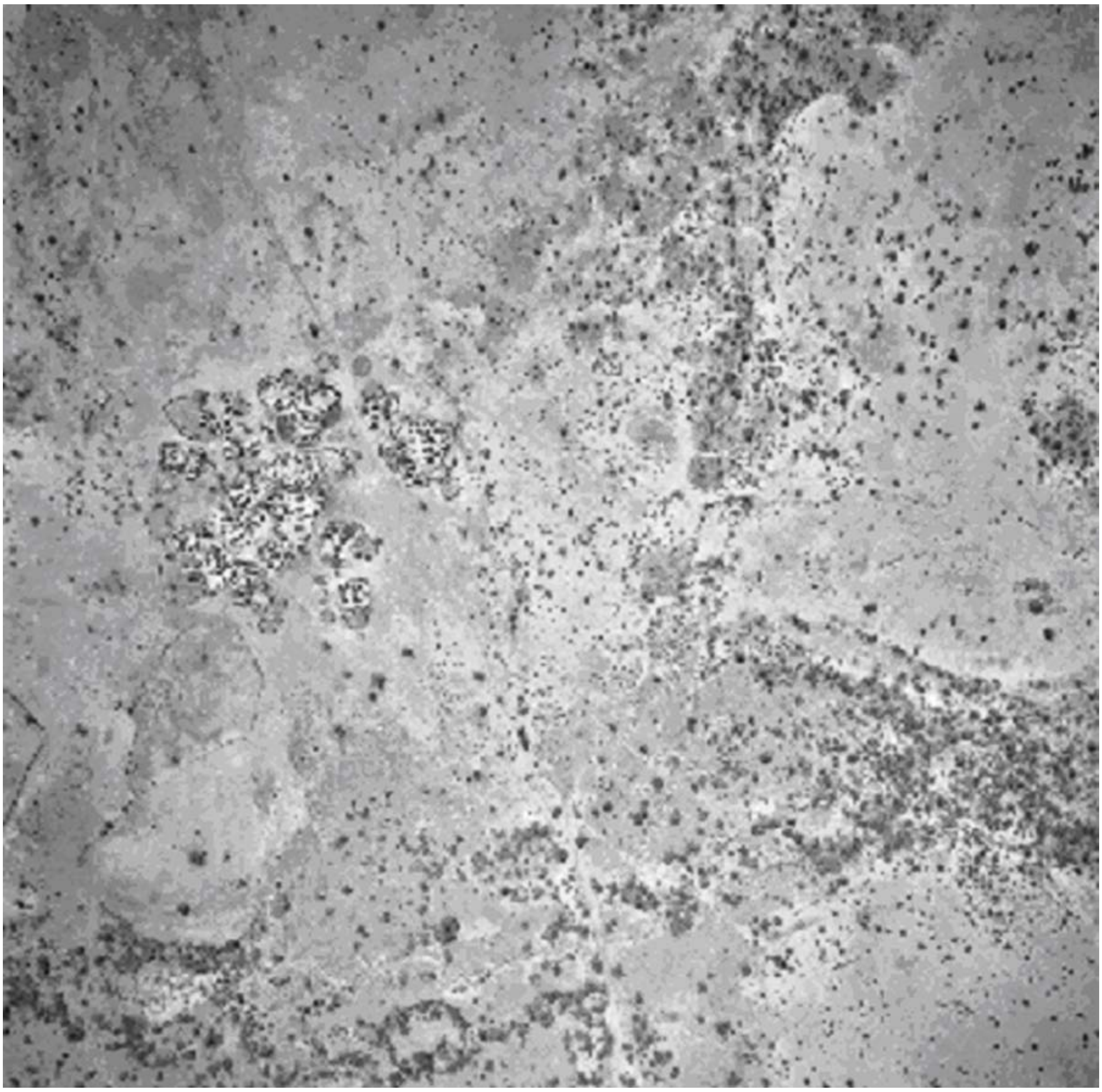

Figure 2) Aerial picture of the area around the village Dangadé (74 ha), part of the Katchari catchment, northern Burkina Faso.

blown sediment transport can freely cross the area. During intense events the saltating particles develop enough force to liberate small particles from the crust. Furthermore, all sediment detached during the previous rain leaves the area as wind-blown sediment. Visser *et al.* (2004-d) simulated soil and nutrient losses for three research sites in the Katchari catchment in northern Burkina Faso for a combined wind/water erosion event at 20 August 2000. Wind-blown sediment transport occurred during 10 minutes, the maximum wind speed was 9.7 m s^{-1} and the wind blew from the East-South-East. Directly following the wind erosion event it started to rain, a total of 19.6 mm rain fell in 50 minutes. At the degraded site soil losses of 23.94 ton ha^{-1} were calculated of which 1% was attributed to water erosion and 99% to wind erosion. At the field near the floodplain a total soil loss of only 0.036 ton ha^{-1} was calculated, of which 0.006 ton ha^{-1} was attributed to water erosion. Erosion by wind at this field was limited because wind-blown sediment transport was limited by the crop. However, an event with similar wind speeds caused soil losses of 38.5 ton ha^{-1} at the dune site and a deposition of 195 ton ha^{-1} at the valley site.

An impression of the nutrient dynamics for the event of 20 August 2000, has to remain qualitative. First several assumptions need to be made, some of which are based on the previous described literature study:

- Here we regard only possible erosion and deposition in the given area, incoming sediment from neighbouring areas is not considered since no information on this area is available.
- The soil losses calculated by Visser *et al.* (2004) are used as an indication for total qualitative soil loss by saltation and water erosion at the different geomorphic units. For dust the values measured by Rajot *et al.* (1994) and Rajot (2001) are used as an indication.
- Wind-blown sediment transport is not possible in the floodplain due to the high vegetation cover. All incoming sediment is trapped.
- All wind-blown sediment entering the pasture with moderate cover and the village area will be deposited in these areas (Bielders at al., 2002).
- Due to the availability of sediment and the lack of vegetation cover most wind erosion occurs in the fallow areas.
- All sediment eroded by water is transported to the floodplain and finally leaves the catchment. In areas where pool formation can occur part of the eroded sediment is re-deposited (Visser *et al.*, 2004-d).
- Dust emission occurs only from areas where wind-blown sediment transport is possible (Rajot, 2001).
- Dust deposition is assumed to be non-homogeneous. Areas with more vegetation cover will experience more dust deposition than areas without vegetation cover.

Figure 3 shows the qualitative analysis of the nutrient dynamics for the area around the village Dangadé for the wind/water erosion event of 20 August 2000. It is assumed that all wind-blown saltation sediment from the low cover pasture zone (I) is trapped in the floodplain (II), from the low cover pasture zone (III) and the degraded area (IV) in the village (VIII) and from the field (XI) and the low cover pasture zone (XII) in the high cover pasture zone (XIII). With these assumptions a small over-estimate of deposition in the village and an under-estimate of deposition in the high cover pasture zone are made.

From figure 3 it is clear that saltation transport by wind causes the largest soil losses. However, a part of these sediments are trapped again by other units. A south-eastern wind direction is relatively positive for this specific area, the saltating sediment is trapped in areas, which can be taken under cultivation in the future. However, the prevailing wind direction for wind erosion events in the Sahel is northeast. With a north-eastern wind most saltating material and its attached nutrients are trapped in the floodplain area. Though the nutrients do not actually leave the area, they can be considered as lost for the cultivated area since the flood plain can’t be cultivated due to the temporary flooding.

Comparing the arrows for deposition with those for erosion of saltation transport in figure 3A it is clear that in this 74 ha area no balance between fallow and fields is present. The negative balance is mainly caused by the presence of the large degraded area and the first year fallow area. These areas may cause large soil losses. To restore the balance trees and bushes need to be planted in the degraded area and the fallow fields need a mulch cover.

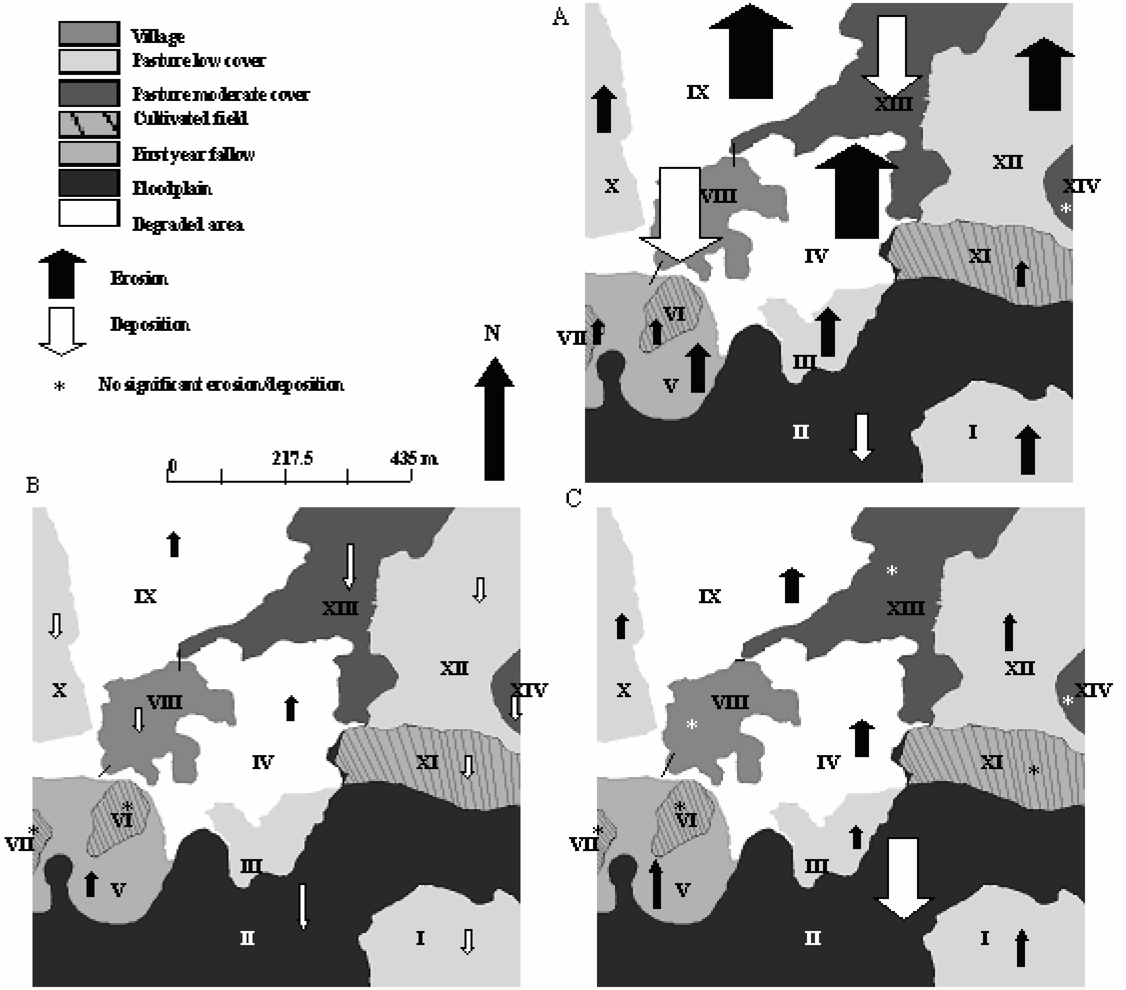

Figure 3) Land use around the village of Dangadé. Pasturage low cover means a cover till 1 %, moderate cover means tree and shrub cover from 10 till 40%. A) Qualitative indication of the distribution of net erosion and deposition due to wind-blown saltation transport. B) Qualitative indication of the distribution of net erosion and deposition due to dust transport. C) Qualitative indication of net water erosion and deposition. Larger arrows indicate higher values

In comparison with the soil and nutrient losses by wind erosion, the losses by water erosion are small (Fig. 3C). However it should be noted that with each rainfall nutrients are lost from the area by water erosion, whereas with wind erosion the direction of sediment transport is important in determining whether the nutrients are forever or only temporary lost from the area. So on the longer time scale nutrient losses by water erosion might be more important than nutrient losses by wind erosion. The role of dust deposition in this nutrient balance is very small (Fig. 3B), but may be underestimated for the area with a higher vegetation cover (Fig 1).

From this study for only one event it becomes clear that the effect of saltation transport should not be overlooked at the scale of a village. Due to the fact that most nutrient balances ignore the effect of saltation transport, these balances can’t be applied at village scale in the Sahelian environment. However at the larger district scale, the effect of saltation transport can become negligible due to the limited distances of saltation transport.

Conclusions

The fact that the erosion component for nutrient budgets on district scale in Sahelian West Africa is generally based on measurements from runoff plots and that the effect of wind-blown sediment transport is often overlooked gave a reason for a critical review of the erosion components of the nutrient budget in the Sahel. The two modes of transport of wind-eroded sediment, saltation and suspension, have different consequences for soil productivity in the Sahel. On local scale saltation moves the bulk of sediments and nutrients over short distances, from bare unprotected soils towards areas with sufficient vegetation or mulch cover. In the source areas, soil productivity declines, whereas in the sink areas soil productivity increases. Provided a good balance between fields and fallow areas the net, long-term effect of saltation transport on village scale can be assumed zero. But when the balance between field and fallow is lost, saltation transport during one event can result in tremendous soil and nutrient losses.

The suspended material can be divided in two origins; the Harmattan dust and the convectional storm dust. The Harmattan dust origins from the Sahara and some authors describe the present fertility of the Sahelian soils completely to the input of nutrients by this dust. During convectional storms, fine nutrient rich particles are taken in suspension. Parts of this suspended material is deposed again and parts may transported over thousands of kilometres, exporting the nutrients to other parts of the world.

Due to the general low slopes, sheet erosion is the most important water erosion process. Sheet erosion selectively exports clay, silt, nutrients and soil organic matter from the topsoil and this selectivity is highest on gentle slopes. Therefore, sheet erosion, though limited in total amounts of erosion, should not be underestimated especially at the longer timescale it might contribute considerably to the total nutrient losses at village scale. Various authors indicate that nutrient losses by water erosion, measured on runoff plots can cause serious losses of the basic plant nutrients. Though at village scale the losses are considerably smaller due to re-deposition, yearly nutrient losses can be considerable. Furthermore, nutrients transported by water are always directed in a down-slope direction and can’t be transported again upslope as is possible with wind erosion. Therefore nutrients lost by water erosion are forever lost for the upslope area.

Based on the conclusions from the literature review, a qualitative indication of the nutrient dynamics during a combined wind/water erosion event for the area around the village Dangadé in northern Burkina Faso is given. This analysis gives a good impression of the impact of the different process on the erosion component of the nutrient balance. The area around the village Dangadé is especially vulnerable for saltation transport and the role of water erosion and dust deposition is negligible. This indicates that the effect of saltation transport can't be ignored when calculating the erosion component of the nutrient balance at village scale in a Sahelian environment.

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Chapter 9

Summary and conclusions

S.M. Visser

Summary and conclusions

In the Sahelian zone of West-Africa ongoing soil degradation by wind and water forms a major threat to the sustainable use of soil and water resources. The Sahelian climate is characterized by a long dry season (from October till April) and a short rainy season (from May till September). In the early rainy season intense rainfall is often preceded by strong winds, which may cause severe erosion. The intense rainfall following the wind erosion event, causes partial deposition of raised dust and limits further wind erosion, but may result in severe water erosion. So wind and water erosion occur almost simultaneously at the same location. Furthermore, sediment transported by wind in one direction may partly be returned by the runoff. In the Sahel and especially in the early rainy season the processes of wind and water erosion should be investigated simultaneously at the same site.

To obtain an impression of the farmers' knowledge of the wind and water erosion and deposition process, the damage to crops and the traditional and new techniques for wind and water erosion control, in total 60 farmers from three villages in northern Burkina Faso were interviewed. In general the farmers have a good knowledge of wind erosion and its effect on crops and soils. They do not report the negative effects of water erosion and tend to mainly see the positive effects of rainfall. The farmers think soil fertility is negatively affected by erosion (both wind and water) and that deposition of sediments results in a better soil fertility. Most of the farmers report to notice infiltration changes (both increase and decrease) due to wind-blown particle transport and the processes following high intense rainfall, but can't indicate a clear reason for these changes in infiltration.

All farmers apply traditional soil conservation techniques as application of manure and mulch. The application of the tradition techniques is generally limited by labour, mulch and manure. New soil conservation techniques as stone rows, sand bunches and zaï are known and applied by some of the farmers. In general lack of knowledge and labour availability are the main constraints in application of these new techniques.

Although the processes of wind and water erosion are similar in many ways, they behave differently with respect to topography. For water erosion topography entirely determines the direction of sediment movement. For wind erosion the direction of sediment movement is determined by the wind direction, which may change for several successive events or even during one event. This different dependency on the topography of the two processes brings along different approaches for determining a mass balance for a certain area. For water erosion, a mass budget is determined for an area such that there is only an output of sediments, whereas for wind erosion, input and output of sediment is usually quantified by measurements of wind-blown particle fluxes.

To get a good insight in the interaction of both processes, it is advisable to start the research at the field scale. To obtain a complete insight into the processes at a research site, the research should include measurement techniques which quantify the impact of wind and water erosion separately and techniques which quantify the combined effect of wind and water erosion.

Mass fluxes of wind-blown sediment transport were measured with Modified Wilson and Cook sediment catchers at three geomorphic units in the Katchari catchment in northern Burkina Faso. Highest sediment fluxes were measured at the plot on the dune site then at the valley site and least mass transport was measured at the degraded site. Differences in intensity of mass transport between the three geomorphologic units were, apart from a different vegetation cover, most probably related to the sediment availability at and in the surroundings of the research plots.

To obtain an indication of the spatial variability in mass transport at a single geomorphologic unit, maps of wind-blown mass transport were produced for each plot from 17 observations per event with conditional simulation. The variogram model of the valley showed only noise, and the high nugget/sill ratio for the dune plot and the degraded plot indicates that variation due to spatially non-correlated sources is rather large at our plots. So even though we were able to produce some maps with the spatial variation of mass transport, the weak variograms of the dune and the valley and the low correlation values of the valley indicated that 17 observations is not always enough for a full characterisation of a wind-blown mass transport in the Sahel. So for relatively complex fields more samplers and a stratified sampling scheme should be used. The simulated maps clearly showed the spatial distribution of wind-blown mass transport from which sink and source areas for erosion material could be distinguished. An important consequence of this conclusion is that a wind erosion model that is applied at a Sahelian field should at least have a spatial component.

Two wind erosion models with a spatial component; the Revised Wind Erosion Equation (RWEQ and the Wind Erosion Prediction System, were tested on their applicability in the Sahel. RWEQ gave a good estimate of the critical field length but failed to predict maximum mass transport, Therefore RWEQ could not give a correct estimation of the spatial variation in mass transport and it was concluded that RWEQ in its current state is not suitable for application to the Sahelian situation.

The current version of the physically based WEPS could not predict spatial variation in mass transport, though it was originally developed for this purpose as well. Therefore the formulas of WEPS were translated to the dynamic modelling language of PCRaster. Provided with a good estimate for the roughness length WEPS in PCRaster gave a good estimation of the friction velocity and correctly predicted moments of initiation and cessation of mass transport. Furthermore, the spatial variation in mass transport at the tree geomorphic units was acceptable and it was concluded that WEPS in PCRaster is suitable for application in the Sahel.

Crust development is an important process in wind erosion since it controls the sediment availability. When crust development during the wind erosion event could be simulated, model performance could be enhanced.

The physically based water erosion model EUROSEM was also translated to the PCRaster language and adapted for application to the Sahelian environment. Finally EUROSEM in PCRaster could simulate wind-driven rain, infiltration into crusted soils, overland flow routing, formation of pools, sediment transport and erosion and deposition by interrill processes over the land surface for individual rainfall events at the scale of both a runoff plot and a field. The model was calibrated by varying the effective hydrological conductivity and testing it on the 1 m^2 plots.

In general the model predicted runoff and sediment discharge well for the 20 m^2 runoff plots and for all sites transport was transport capacity limited. At the field scale pool formation resulted in limited runoff discharge and resettlement of the eroded sediment. Therefore soil losses from the fields in ton ha^{-1} were smaller than soil losses from the runoff plots in ton ha^{-1}.

Crust development has large influence on soil erosion by water in the Sahel, both on infiltration and detachment. So far we are only working with crust-related input parameters, which are fixed during the event. Since during the event the largest part of crust development occurs, incorporating crust development would probably largely enhance model performance.

To study the nutrient dynamics due to the processes of wind and water erosion the PCRaster versions of EUROSEM and WEPS are extended with nutrient modules and tested for both separate wind and water erosion events and for a combined wind/water erosion event.

The physically based model of WEPS in PCRaster can predict patterns of erosion and deposition due to wind-blown sediment transport. Depending on wind direction, crusting pattern and vegetation cover, net erosion or deposition can occur. When erosion occurs, considerable amounts of nutrients are lost (with one wind erosion event 77.5% of the N and 100% of the P needs for crop growth may be eroded), but when deposition occurs, parts of these lost nutrients can be regained.

Soil loss by water erosion is closely related to the crust type present, which regulates infiltration and thus runoff. N loss due to dissolved transport of nitrate is negligible compared with the N loss due to sediment transport. With three rainfall events only 0.7% of N and 0.006% of P needs for crop growth is eroded.

Despite a net erosion or deposition by both wind and water erosion at the scale of a field, within the field areas with erosion and deposition can be identified. At field scale soil and nutrient losses by water erosion are negligible in comparison with wind erosion. However, the role of water erosion can be significant when spatial variation within a field is considered.

The fact that the erosion component for nutrient budgets on district scale in Sahelian West Africa is generally based on measurements from runoff plots and that the effect of wind-blown sediment transport is often overlooked gave a reason for a critical review of the erosion components of the nutrient budget in the Sahel. The two modes of transport of wind-eroded sediment, saltation and suspension, have different consequences for soil productivity in the Sahel. On local scale saltation moves the bulk of sediments and nutrients over short distances. Provided a good balance between fields and fallow areas the net, long-term effect of saltation transport on village scale can be assumed zero. But when the balance between field and fallow is lost, saltation transport during one event can result in tremendous soil and nutrient losses.

The suspended material can be divided in two types; the Harmattan dust and the convectional storm dust. The Harmattan dust origins from the Sahara and is a real input of nutrients whereas the convective storm dust has local origins and thus can’t be considered as an input of nutrients.

Due to the generally low slopes, sheet erosion is the most important water erosion process. Sheet erosion selectively exports clay, silt, nutrients and soil organic matter from the topsoil and this selectivity is highest on gentle slopes. Therefore, sheet erosion, though limited in total amounts of erosion, should not be underestimated, especially at the longer timescale it might contribute considerably to the total nutrient losses at village scale. Nutrients transported by water are always directed in a down-slope direction and can’t be transported in an opposite direction as is possible with wind erosion. Therefore nutrients lost by water erosion are forever lost for the upslope area.

Samenvatting en conclusies

Continue bodemdegradatie onder invloed van wind en water vormt een grote bedreiging voor bodem productiviteit in the Sahel zone van West-Afrika. Het klimaat in de Sahel wordt gekarakteriseerd door een lang droog seizoen (van oktober tot april) en een kort regenseizoen (van mei tot september). In het vroege regenseizoen wordt intensieve regenval vaak voorafgegaan door hevige winden. Deze winden kunnen intense erosie veroorzaken. De intensieve regenbuien die de heftige winden opvolgen, veroorzaken depositie van het stof dat zich op dat moment in de lucht bevindt en beperken verdere winderosie, maar er kan wel watererosie optreden. Dientengevolge treden wind- en watererosie bijna tegelijkertijd op dezelfde locatie op. Bovendien kan een deel van het sediment dat door de wind in de ene richting werd getransporteerd, weer worden terug gebracht door het over land stromend water. Het is dus duidelijk dat in de Sahel, en speciaal in het vroege regenseizoen de processen van wind en water tegelijkertijd op de zelfde locatie moeten worden onderzocht.

Om een indruk te krijgen van de kennis van boeren op het gebied van 1) de wind- en watererosie en depositie processen, 2) de schade aan gewassen en 3) de nieuwe en traditionele technieken voor erosie controle, zijn er in totaal 60 boeren uit drie dorpen in noord Burkina Faso geïnterviewd. Over het algemeen hebben de boeren een goede kennis van winderosie en het effect ervan op de bodem en de gewassen. Zij gaven geen melding van eventuele negatieve effecten van watererosie, maar benadrukten de positieve gevolgen van neerslag. De boeren denken dat bodemvruchtbaarheid negatief wordt beïnvloed door erosie (door zowel wind als water) en dat depositie van sediment resulteert in een betere bodemvruchtbaarheid. De meeste boeren bemerken verschillen in infiltratie (zowel toe- als afname) ten gevolge van sediment transport door de wind en de processen die volgen op intensieve regenval, maar ze kunnen geen duidelijke reden geven voor deze verschillen in infiltratie.

Alle boeren passen traditionele bodemconserveringstechnieken toe (bijv. gebruikmaking van gewasrestanten en mest). De toepassing van traditionele technieken is beperkt vanwege een tekort aan gewasrestanten, mest en arbeidskracht. Enkele boeren zijn bekend met de nieuwe technieken als stenenrijen, zandheuvels en zaï en passen deze ook toe. Over het algemeen zijn een gebrek aan kennis en arbeidskracht de meest limiterende factoren in de toepassing van de nieuwe technieken.

Hoewel de processen van wind- en watererosie in veel opzichten hetzelfde zijn, is de rol van de topografie verschillend. In watererosie wordt de stroomrichting van het water en het sediment geheel bepaald door de topografie, terwijl in winderosie niet de topografie maar de windrichting de richting van sedimenttransport bepaalt. Daarbij is voor watererosie de richting van sediment transport grofweg altijd hetzelfde, terwijl in winderosie de richting per storm of zelfs gedurende de storm kan veranderen. Vanwege deze verschillen in de afhankelijkheid van de topografie worden wind- en watererosie met een andere aanpak gemeten. In het geval van watererosie kan er een massabalans worden opgemaakt voor een gebied zodat er alleen uitstroom van sediment is, terwijl voor winderosie de in- en uitkomende massa fluxen worden gemeten om te bepalen of er netto in- of uitvoer van sediment heeft plaats gevonden. Om een goed inzicht in de interactie van beide processen te verkrijgen, is het raadzaam om onderzoek naar wind- en watererosie te beginnen op veldschaal. Voor een complete indruk van de processen die zich op het onderzoeksterrein afspelen, moet het onderzoek meettechnieken omvatten die de invloed van wind- en watererosie afzonderlijk en het combineerde effect van beide processen meten.

Massafluxen van door de wind getransporteerd sediment werden gemeten op drie geomorfologische eenheden (duin, vallei, gedegradeerde zone) in het Katchari stroomgebied in noord Burkina Faso met *Modified Wilson and Cook* sediment vangers. De grootste massa-fluxen werden gemeten op het onderzoeksterrein op de duin, gevolgd door respectievelijk de vallei het gedegradeerde gebied. De verschillen in intensiteit van massatransport op de drie geomorfologische eenheden kunnen behalve door een verschil in vegetatiebedekking ook worden verklaard door een verschil in sedimentbeschikbaarheid op het onderzoeksterrein en in de omgeving daarvan.

Om een indicatie te verkrijgen van de ruimtelijke variabiliteit in massatransport door de wind op een enkele geomorfologische eenheid, zijn er, op basis van 17 metingen (op een 80 x 80m veld) en conditionele simulatie, kaarten van massatransport geproduceerd. Het variogram model van de vallei toonde enkel ruis. De nugget/sill ratio van het variogram voor de duin en de gedegradeerde zone geven aan dat de variatie ten gevolge van ruimtelijke niet gecorreleerde bronnen groot is. Ondanks het feit dat het mogelijk is om enkele kaarten met het ruimtelijke patroon van het massatransport te produceren, geven de zwakke variogrammen van de duin en het gedegradeerde gebied met daarbij de lage correlatie waarden van de vallei aan dat 17 observaties van massatransport niet altijd voldoende is voor een totale karakterisering van sediment transport door de wind in de Sahel. Voor relatief complexe eenheden (m.a.w. een grote variatie in bijv de vegetatiebedekking) zijn meer sediment vangers en gestratificeerde monstername nodig. De gesimuleerde kaarten toonden duidelijk een ruimtelijke variatie in massa transport, waaruit de bron en depositie zones kunnen worden onderscheiden. Een belangrijk gevolg van deze ruimtelijke variatie in massatransport is dat een winderosie-model dat toegepast kan worden op een veld in de Sahel tenminste een ruimtelijke component moet hebben.

Twee winderosie-modellen met een ruimtelijke component; *de Revised Wind Erosion Equation (RWEQ)* en het *Wind Erosion Prediction System (WEPS),* zijn getest op hun toepasbaarheid in de Sahel. RWEQ gaf een goede schatting van de kritieke veldlengte maar kon geen goede voorspelling geven van de maximale transportcapaciteit. Daarom kon RWEQ ook geen goede voorspelling geven van de ruimtelijke variatie in massatransport en is er uiteindelijk geconcludeerd dat RWEQ in zijn huidige staat niet geschikt is voor toepassing in de Sahel.

De huidige versie van het op fysische vergelijkingen gebaseerde WEPS kan nog geen ruimtelijke variabiliteit in massa transport voorspellen, hoewel het model daar oorspronkelijk wel voor was ontwikkeld. Om ruimtelijke variatie in in- en output parameters mogelijk te maken zijn de formules van WEPS vertaald naar de dynamische modelleertaal PCRaster. Op voorwaarde dat er een goede schatting is van de ruwheidslengte, geeft WEPS in PCRaster een goede indicatie van de schuifspanning en tevens van de momenten van aanvang en beëindiging van massatransport. Bovendien word de ruimtelijke variatie in massatransport goed voorspeld. WEPS in PCRaster blijkt dus geschikt voor toepassing op een akker in de Sahel.

De ontwikkeling van bodemkorsten is een belangrijk proces in winderosie omdat het de beschikbaarheid van sediment reguleerd. Als het proces van korstontwikkeling gedurende de zandstorm gemodelleerd kan worden, kan dit de prestatie van het winderosie model aanzienlijk verbeteren.

Het op fysische vergelijkingen gebaseerde watererosie model EUROSEM is ook vertaald naar de taal van PCRaster en aangepast voor toepassing in de Sahel. Uiteindelijk kan het model schuine regen, infiltratie in verkorste bodems, richting van oppervlakkig afstromend water, vorming van plassen, sedimenttransport en de ruimtelijke variatie in erosie en depositie voorspellen op de schaal van een akker voor individuele regenbuien. Het model is gecalibreerd door de effectieve doorlatendheid te variëren en het model te testen op de 1m^2 erosieplots.

Over het algemeen deed het model correcte voorspellingen van de afvoer van water en sediment voor de 20 m^2 erosieplots. Het gaf voor alle geomorfologische eenheden aan dat sediment transport gelimiteerd werd door de transportcapaciteit van het afstromende water. Op de schaal van een akker resulteerde de ontwikkeling van plassen in depositie van sediment en een gelimiteerde afvoer. Daarom waren de bodem verliezen in ton ha^{-1} van de akkers kleiner dan de bodemverliezen van de erosie plots in ton ha^{-1}.

Ook op watererosie heeft korstontwikkeling een grote invloed, zowel op de infiltratie als op het losmaken van de bodemdeeltjes. Tot nog toe wordt er alleen gemodelleerd met korstgerelateerde input parameters, die niet veranderen gedurende de simulatie van de regenbui. Aangezien gedurende een regenbui de korstontwikkeling voor het grootste deel plaatsvindt, zal ook in een watererosie model een modellering van de korstontwikkeling de prestaties van het model aanzienlijk kunnen verbeteren.

Om de nutriëntendynamiek te bestuderen zijn de PCRaster versies van EUROSEM en WEPS uitgebreid met een nutriëntenmodule en getest voor zowel de afzonderlijke wind- en watererosie gebeurtenissen als voor een gecombineerde wind/water erosie gebeurtenis.

WEPS in PCRaster kan patronen van erosie en depositie goed voorspellen. Afhankelijk van de windrichting, verkorstingspatroon en vegetatiebedekking kan er netto erosie of netto depositie optreden. In het geval van erosie kunnen er aanzienlijke hoeveelheden nutriënten verloren gaan (gedurende een gebeurtenis kan er 77.5% van de N en 100% van de P behoeften voor gewasgroei verloren gaan). In het geval van depositie kan een deel van deze nutriëntenverliezen weer teruggewonnen worden.

Bodemverlies door watererosie is nauw gerelateerd aan het aanwezige korsttype, die de infiltratie en dus ook de hoeveelheid afstromend water regelt. N verliezen door opgelost transport zijn verwaarloosbaar in vergelijking met de N verliezen door sediment transport. Gedurende de processen die volgden op drie regenbuien ging er in totaal slechts 0.7% van de N en 0.006% van de P behoeftes voor gewasgroei verloren.

Ondanks een netto erosie of depositie op de schaal van een akker kunnen er binnen een akker altijd gebieden met erosie of depositie worden aangeduid. Op de schaal van een akker zijn bodem- en nutriëntenverliezen ten gevolge van watererosie verwaarloosbaar in vergelijking met de verliezen door winderosie. Maar de rol van watererosie kan van belang zijn als de ruimtelijke variatie binnen de akker wordt beschouwd.

Het feit dat de erosie component in nutriënten budgetten op districtschaal in de West-Afrikaanse Sahel over het algemeen wordt gebaseerd op metingen op erosieplots en het feit dat het effect van winderosie vaak wordt vergeten gaf aanleiding tot een kritische beschouwing van de erosie componenten van de nutriëntenbudgetten in de Sahel. Saltatie en suspensie, twee wijzen waarin sediment onder invloed van de wind getransporteerd kan worden, hebben verschillende consequenties voor de bodemproductiviteit in de Sahel. Op lokale schaal wordt de bulk van het sediment in saltatie getransporteerd over korte afstanden. Indien er een goede balans bestaat tussen de bewerkte akkers en de braakliggende akkers kan het netto langdurige effect van saltatietransport door de wind als nihil worden beschouwd. Maar indien deze balans niet langer bestaat, kan saltatie transport ten gevolge van slechts één winderosie gebeurtenis resulteren in enorme bodem- en nutriëntenverliezen.

Het sediment in suspensie (stof) kan worden onderverdeeld in twee types; Harmattan stof en stof van convectieve stormen. Het Harmattan stof vindt zijn oorsprong in de Sahara en kan worden beschouwd als een input van nutriënten. Het stof van de convectieve stormen wordt lokaal opgenomen en kan dus niet als een input van nutriënten beschouwd worden.

Vanwege de over het algemeen flauwe hellingen, is sheeterosie het belangrijkste watererosie proces. Sheet erosie transporteert selectief de fijne deeltjes als klei, leem, organisch materiaal en nutriënten van de bovenste bodemlaag en deze selectiviteit is het grootst op de flauwe hellingen. Daarom mag sheeterosie, hoewel gelimiteerd in de totale hoeveelheden erosie, niet worden onderschat. Vooral op de langere tijdschaal kan sheet erosie aanzienlijk bijdragen aan de totale nutriënten verliezen op dorpsniveau. Nutriënten die door water worden getransporteerd, worden altijd hellingafwaarts getransporteerd en kunnen niet weer in een tegengestelde richting worden getransporteerd zoals wel mogelijk is met winderosie. Daarom zijn nutriënten getransporteerd door watererosie voor altijd verloren voor het hoger gelegen gebied.

Résumé et conclusions

Dans la zone sahélienne de l'Afrique de l'Ouest la dégradation du sol par la vente et le ruissellement constituent une menace pour l'utilisation durable des sols et les ressources d'eau. Le climat sahélienne est caractérisé par une saison sèche longue (d'octobre jusqu'au mai) et une saison pluvieuse courte (d'avril jusqu'au septembre). Au début de la saison pluvieuse la chute de pluie intensive est souvent avancée par des ventes violentes qui peuvent provoquer l'érosion rigoureuse. La pluie intensive succédant à la tempête provoque la déposition partielle de la poussière soulevée et limite la continuation de l'érosion éolienne, mais risque d'entraîner l'érosion hydrique sévère. En outre le sédiment transporté par le vent dans une direction peut être remmené par le ruissellement. Evidemment l'érosion éolienne et hydrique sont imbriquées et par conséquence les processus doivent être étudiés simultanement.

Pour obtenir une impression de la connaissance des paysans, soixante producteurs de trois villages au nord du Burkina Faso sont enquêtés. Les questions s'agissaient de la connaissance du processus d'érosion et de la déposition par la vente et le ruissellement, les dégâts aux cultures et des techniques traditionnelles et nouvelles de conservation des sols. Généralement les paysans ont une connaissance assez développée d'érosion éolienne et son effet aux cultures et au sol. Au contraire ils ne font pas mention des effets négatifs d'érosion hydrique et ils ont tendance à accentuer uniquement les effets positifs de la pluie. Les paysans pensent que la fertilité du sol est affectée de la façon négative par l'érosion (éolienne et hydrique) et puis ils croient que la déposition des sédiments augmente la fertilité. La plupart des paysans rapportent d'apercevoir une changement d'infiltration d'eau (augmentation et diminution) á cause de transport du sable par le vent et les processus qui suivent une pluie intensive. Pourtant ils ne peuvent pas indiquer une raison claire pour cette observation. Tous les paysans appliquent des techniques de conservation des sols traditionnelles comme l'utilisation du fumier et la distribution des résidus de récolte. L'application des techniques traditionnelles est limitée par la disponibilité de main d'oeuvre, fumier et résidus de récolte. Les techniques modernes comme les lignes en cailloux et les demi lunes en sables et le zaï sont connues et appliquées par quelques paysans. Généralement une manque de connaissance et une manque de main d'oeuvre sont les restrictions principales de ces techniques modernes.

Malgré le fait que les processus d'érosion éolienne et hydrique se ressemblent dans plusieurs façons ils se comportent différent par rapport à la topographie. En cas d'érosion hydrique, la direction de transport des sédiments est déterminée par la topographie mais en cas d'érosion éolienne la direction de transport est déterminée par la direction du vent, qui peut changé avec les tempêtes successives ou même pendant une tempête. Conséquemment à cette dépendance distincte des processus, des méthodes d'approches différentes sont nécessaires pour déterminer la balance de masse d'un terrain spécifique. L'érosion hydrique est mesurée d'une façon qui ne permet que le mesurage d'export des sédiments. L'érosion éolienne est quantifiée par le mesururage d'entrée et de sortie des flux de matières en transports.

Pour préciser l'interaction entre les deux processus il est recommandé de commencer la recherche á l'échelle d'un champ. Pour obtenir une vue complète des processus au site de recherche, il faut inclure des techniques qui quantifient l'impact de l'érosion éolienne et de l'érosion hydrique individuellement et des techniques qui quantifient l'impact des deux processus conjoints.

Les flux des sédiments transportés par le vent sont mesurés avec les capteurs des sédiments du type Modified Wilson and Cook á trois unités géomorphiques dand un basin versant au nord du Burkina Faso.

Le transport des sédiments les plus élevés a été mesuré au site sur la dune et en suite au site dans la vallée. Le transport des sédiments le plus limité a été mesuré dans le site dégradé. Les différences en l’intensité de transport du sédiment entre les trois unités géomorphiques sont probablement relatées à la disponibilité de sable au site et à l’encerclement des sites de recherche. Pour obtenir une indication de la variabilité spatiale de transport des sédiments sur une unité géomorphique particulière, des cartes représentant le transport de masse par le vent ont été estimées pour chaque champ avec simulation conditionnelle. L’estimation est basée sur 17 observations par site. Les modèles variograms ne montraient que de bruit et les ratios nugget/sill pour la dune et la zone dégradée, indiquent que la variété causée par des sources non-correlées à la spatialité est élevée sur nos sites. Alors que nous avons réussi d’estimer quelques cartes de la variabilité spatiale, les variograms faibles de la dune et de la vallée indiquent que dix-sept observations ne sont pas toujours suffisantes pour une caractérisation complète du transport des sédiments par le vent dans la zone sahélienne. Alors pour des sites relativement complexe il est nécessaire d’utiliser un sondage plus étendu et un schème de sondage stratifié. Les cartes simulées montraient de façon claire la distribution spatiale de transport des sédiments par le vent. Avec cette carte on pouvait distinguer les sites de sources et les sites de déposition de matériel d’érosion. Une conséquence importante qui suit cette conclusion est le constat qu’il faut toujours inclure une composante spatiale dans un modèle d’érosion éolienne dans la zone sahélienne.

L’applicabilité de deux modèles d’érosion éolienne avec une composante spatiale, le Revised Wind Erosion Equation (RWEQ) et le Wind Erosion Prediction System (WEPS), a été testée pour la zone sahélienne. RWEQ donnait une estimation satisfaisante de la longueur critique des champs, mais le modèle n’arrivait pas á pronostiquer le transport des sédiments maximal. C’est pour cela que le modèle faillit á donner une estimation correcte de la variabilité spatiale du transport des sédiments, ce que nous a mis á la conclusion que le modèle RWEQ actuel ne convient pas à l’application dans la situation sahélienne.

Le modèle WEPS actuel ne peut pas pronostiquer la variabilité de transport des sédiments, bienque originalement il a été développé pour ce but. C’est pourquoi on a traduit les formules en PCRaster, une langue dynamique de modélisation. Fournit avec une estimation adéquate de la longueur de la rugosité, WEPS en PCRaster donnait une estimation satisfaisante de la vélocité de friction et pronostiquait correctement les moments d’initiation et la terminaison de transport des sédiments. En plus la variabilité de transport de sable aux trois sites géomorphiques était pronostiquée d’une manière acceptable. Ce que nous a emmené à la conclusion que WEPS en PCRaster convient á l’application dans la zone sahélienne.

La formation des croûtes constitue un processus important pour l’érosion éolienne parce qu’elle détermine la disponibilité des sédiments. La simulation de la formation des croûtes pouvait améliorer la performance du modèle. Le modèle EUROSEM a aussi été traduit en PCRaster et a été adapté à la situation sahélienne. Finalement EUROSEM en PCRaster pouvait simuler la pluie provoque par le vent, l´infiltration dans les sols encroutés, le ruissellement, le cours d´eau, la formation des flaques d´eau, le transport des sédiments, l´érosion et la déposition des sédiments pour des tempêtes individuelles a l´échelle d´une parcelle de ruissellement sur 20 m^2 et a léchelle d´un champ. Le modèle était étalonné en variant la conductivité effective et en le testant sur des parcelles de 1m$^{2.}$ En générale le modèle pronostiquait de façon acceptable l´évacuation de ruissellement et des sédiments pour les parcelles de ruissellement. Puis pour chaque site le transport des sédiments était limité par la capacité du transport. A l´échelle d´un champ la formation des flaques d´eau mène à une évacuation de ruissellement limitée et une redeposition des sédiments érodés. C‘est pourquoi les pertes de sol du champ en tonne ha^{-1} sont plus minimes que les pertes de sol des parcelles de ruissellement en tonne ha^{-1}.

Le développement des croûtes a une grande influence sur l’érosion hydrique, spécialement sur l’infiltration et le détachement. Jusqu’à présent nous avons seulement fait des simulations avec des paramètres d’input fixes qui sont liés aux croûtes. Ajouter le processus de développement des croûtes peut bien améliorer la performance du model, parce que le parti le plus importante du développement des croûtes se passe pendant la tempête.

Pour étudier les dynamiques des nutriments liées aux processus d’érosion éolienne et hydrique, les versions PCRaster de EUROSEM et WEPS sont étendues avec des composants des nutriments et ont été testées sur l’effet séparé d’érosion éolienne et hydrique et sur l’effet d’une tempête avec l’érosion éolienne et l’erosion hydrique combiné.

Le WEPS en lignes peut prédire les canevas d’érosion et déposition par suite de transport des sables par le vent. Dépendant de la direction du vent, la distribution des croûtes et la couverture végétale, l’érosion nette ou le déposition net est produit. En cas d’érosion, des quantités considérables des nutriments sont perdus (pendant une tempête 77.5% des N et 100% des P nécessaire pour le développement des cultures peuvent être érodé). En cas de déposition des sédiments, la plupart de ces nutriments peuvent être récupérées. Malgré un bénéfice net d’érosion ou de déposition par le transport des sédiments par le vent ou par l’eau à l’échelle d’un champ, des zones d’érosion et de déposition dans le champ peuvent être identifiées.

A l’échelle d’un champ, les pertes de sol et des nutriments par l’érosion hydrique sont négligeables par rapport aux pertes crées par l’érosion éolienne. Toutefois le rôle d’érosion hydrique peut être important en considérant la variation spatiale à l’intérieur d’unchamp.

Le fait que le composant d’érosion dans le budget des nutriments à l’échelle d’une région dans la zone sahélienne en Afrique d’Ouest est généralement basé sur la mésurage des parcelles du ruissellement le le fait que l’effet d’érosion éolienne n’est souvent pas remarqué, causaient une raison pour passer une inspection critique des composants d’érosion dans le budget des nutriment au Sahel. Les deux manières de transport des sédiments par le vent, saltation et suspension, ont des conséquences différentes pour la productivité du sol. À l’échelle locale, le transport par saltation transport la plupart des sédiments et des nutriment dessus des distances courtes. Supposons qu’il y a une balance entre les superficies occupés par les champs et les superficies en jachère, l’effet net à long terme du saltation peut être présumé zéro. Sauf, en cas la balance n’existe plus, le transport des sédiment par saltation se termine en des pertes du sol et des nutriment énormes.

La substance en suspension peut être divisé en deux classes ; la poussière d’Harmattan et la poussière des tempêtes convectives. L’origine de la poussière d’Harmattan est le Sahara et est considéré comme une entrée des nutriments, alors que la poussière de tempêtes convectives est d’une origine locale et ne peut pas être considéré comme une entrée des nutriments.

Par suite de pentes petites, érosion en nappe est le processus le plus important dans l’érosion hydrique. L’érosion en nappe exporte sélectivement l’argile, les nutriments et la matière organique de la couche arable. Cette sélection est la plus importante sur des pentes petites. C’est pourquoi l’érosion en nappe, malgré que les quantités sont limitéscomparé avec l’érosion totale, ne peut pas être sous-estimé. Spécialement à long terme l’érosion en nappe peut assister considerabelement àu total des pertes des nutriment à l’échelle du village. Les nutriment transportés par le ruissellement sont toujours amenés dans la direction as de la pente et ne peuvent plus etre transporté dans la direction contraire, comme est possible avec l’érosion éolienne. Pour cette raison les nutriments perdus par l’érosion hydrique sont perdus pour toujours pour la surface positionné haut.

Curriculum vitae

Saskia M. Visser is a physical geographer. She was born on 25 November 1974 in Sliedrecht, the Netherlands. She spent her childhood in this dike-village and graduated from secondary school in 1994. In this year she also began her university education in physical geography at the University of Utrecht. Her first fieldwork on the Quartair geology of the Netherlands was carried out at the Maaskant in 1995. During her second year at the university she performed a fieldwork on the geomorphic and geologic genesis in the Pré-Alps du Sud in France. Her master thesis handled a sediment-budget analysis of a torrential system in the French Alps. After a field campaign of two months she and her fellow students concluded that the Rioux Bourdoux catchment was highly vulnerable for the occurrence of a large scale debris flow. During her last year at the university she travelled to the tropical rainforest of Guyana to study the nutrient cycle in the gaps in the tropical rainforest.

Two months before obtaining her MSc degree in physical geography she accepted a doctoral research (AIO) position with the Erosion and Soil & Water Conservation Group of Wageningen University to carry out research on nutrient losses by wind and water in Burkina Faso. Between 1999 and 2003 she conducted the research leading to this book involving living two periods of 7 months in Dori, Burkina Faso, supervising various MSc-students and research assistants and performing field measurements on both wind-blown sediment transport and sediment transport by runoff.

At this moment she is still working as a researcher with the Erosion and Soil & Water Conservation Group of Wageningen University. She can be contacted at: sasvis@zonnet.nl.