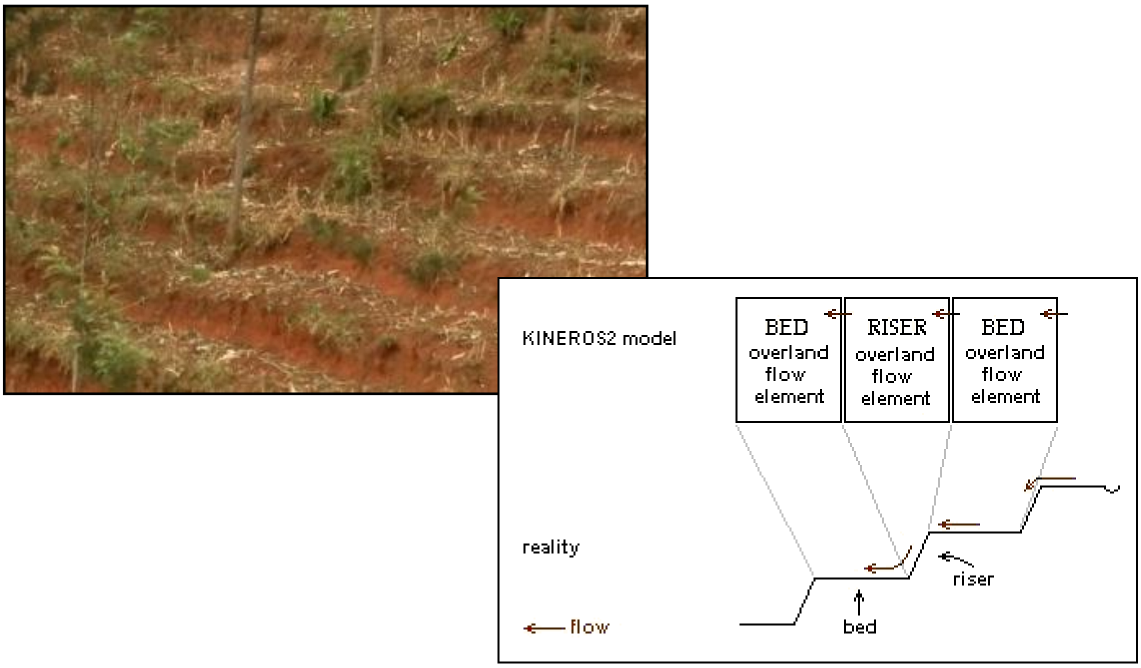
MODELLING OF SOIL EROSION AND SUSTAINABLE LAND MANAGEMENT MEASURES IN THE USAMBARA MOUNTAINS, TANZANIA

Master thesis



Margriet de Jong

April 15th, 2013

Universiteit Utrecht

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Utrecht University

Faculty of Geosciences

Department of Physical Geography

Supervisors:

Rens van Beek

Geert Sterk

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Abstract

Tanzania's population growth increases the stress on arable land, making it vulnerable to erosion especially in sloped areas like the Usambara Mountains. The construction of terraces and the growing of vegetative barriers are known to reduce erosion. Sustainable Land Management (SLM) measures are often modelled to evaluate its effects on runoff and erosion, but only few researches focus on the implementation of SLM types in erosion modelling. This research aims at incorporating SLM in KINEROS2 in order to develop a method to predict the effects of construction of SLM types on runoff and erosion beforehand. KINEROS2 is a distributed, event and physics based runoff and erosion model that represents the catchment by different connected and homogenous elements.

For the research, 6 farmer plots in the Usambara Mountains in Tanzania were selected with the SLM types supported being terraces, agroforestry and grass trips. Input parameters required for KINEROS2 were measured in the field or determined from literature. The spatial dependency of cohesion, K_s, bulk density and soil texture on distance to trees was determined by taking measurements from a transect between two *Grevillea* trees. The control plots were used for calibration of the runoff and erosion parameters K_s, G, C and S. The SLM types were then incorporated in the KINEROS2 model, by representing each riser, bed and grass strip by a single element with specific parameter values depending on slope, soil type, vegetation, etc. The incorporation of SLM was validated by comparing the model results with the actual runoff and erosion data measured using Gerlach throughs.

The Gerlach data did not show the expected effect of SLM on runoff. It did show a larger increase in erosion with increase in runoff on plots with poor or without SLM; the plot with grass strips showed the smallest increase in erosion. For the transect, no significant relationship of the measured parameters with tree distance was found. Therefore trees were not represented by single elements but its vegetation parameters were averaged over the entire plot. KINEROS2 modelled runoff as was expected from the model, but performance of the model compared to actual data resulted in moderate predictions because of the actual data not always showing the expected trend of decreasing runoff on plots with SLM. Erosion was overestimated for the plots with terraces, which was caused by the large increase in erosion on the terrace's risers. Further research on the effect of erosion on very steep slopes and the parameters influenced, and the adaption of the KINEROS2 model for rainfall on steep slopes, is needed before modelling of terraces can be accomplished in KINEROS2.

Acknowledgments

My thesis was a track of learning many different things; about erosion modelling and about performing science, but also about Tanzania and its people and about myself. My supervisors Geert and Rens gave me a free hand in choosing my working method and pace, but also helped me and corrected me when necessary, of which I am grateful. It is clear I couldn't have done this without their support and advice.

Living in Sashui was the most special part of doing my thesis. When I left, a group of children accompanied the car, running and yelling goodbye: 'Margrèti, Margrèti!'. It reflects the spontaneity of the people during the 5 weeks I lived here. I am very grateful to my host, mzee Saidi, who was always eager to give me company, let me meet with his friends and provide me any other help I needed. I will always remember him. I am also very grateful to Lutha and mammi who warmly welcomed me into their home, prepared meals, tea and bathing water and therefore let me feel like a princess. I am honoured that I got to meet them, as well as Mwanauru, now widow of Saidi, and Athma, his daughter; and many many others. Asante sana!

Last but certainly not least, I like to thank Hanno. The past years are a memorable period we had together; both working on our thesis, Hanno in Germany and I in Tanzania, getting married, moving to Eindhoven and Hanno in the mean-time getting a job. Hanno, you were a very great support for me. You knew when I needed a break and you knew when you needed to push me to keep going. Thank you for your support and for your love.

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1 Introduction

Population growth in Tanzania has increased the demand for food production, stressing the lands because the country is economically poor developed and largely depending on agriculture (Kaihura et al., 1999; Hall et al., 2009). Highland zones like the Usambara Mountains with their cooler climate provide better living (less malaria) and good agricultural conditions. In those areas population density is high and stress on the land grows rapidly (figure 1). The exploitation of the land creates a situation in which the tropical forest that acts as a natural buffer against splash detachment and runoff is removed (Meher-Homji, 1991). Together with high rainfall intensities, steep slopes and erodible soils, this can cause a dramatic increase in soil loss. The related decrease in topsoil depth also causes a loss of soil quality mainly due to the loss of organic matter and plant nutrients (Kangalawe and Lyimo, 2010).

Soil conservation measures like terraces and agroforestry are already utilized on quite a large scale in Tanzania due to governmental policies. But these are still not sufficient to meet food demands (Reij, 1991; Mbaga, 2000; Reyes et al., 2005). Sustainable land management (SLM) can be further accomplished by better implementing these measures which help prevent soil loss by hampering detachment and runoff and increasing infiltration and sedimentation (Roose and Barthès, 2001; Hammad et al., 2006; Guto, 2011). The construction of terraces and vegetative barriers decreases runoff and sediment yield on farmers' fields (Zhang et al., 2008). Vegetation like grass and trees are known to increase macro faunal activity in the soil and, correspondingly, increase infiltration (Butt et al., 2010; Giertz et al., 2004, Guto et al., 2011). It may increase porosity and decrease bulk density but also compete with crops for water and nutrients (Guto et al., 2012; Seobi et al., 2005). Grass strips are good measures for trapping sediment and its efficiency of doing so is mainly determined by its planting density while cutting and grazing of the grass may have little influence (Pan et al., 2011). Burgess et al. (1998) showed that tree roots redistribute the water in the soil, uplifting the water to the drier surface in summer time, but also transporting the water to the deeper soil after a rain event. A combination of several SLM measures and measures that replenish soil fertility can often be useful.

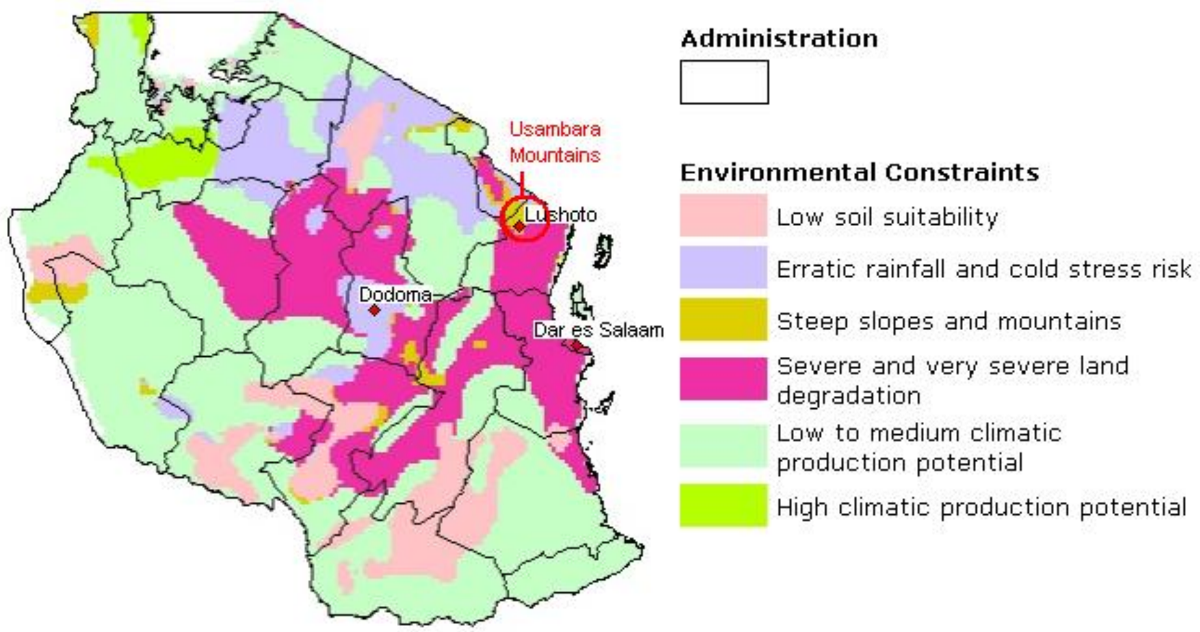

Figure 1: Environmental Constraints in Tanzania (FAO, 2011).

Soil erosion models have been developed and are often used to quantify soil losses in relation to biophysical factors, such as climate, soil characteristics and slope angle (Merrit et al., 2003). Of the existing soil erosion models, the Universal Soil Loss Equation (USLE) is largely depending on empirical values and incorporates a conservation practices factor (p-factor) that corrects soil loss for different types of land management. The event-based Kinematic Runoff and Erosion model (KINEROS), the continuous Soil Water Assessment Tool (SWAT) and the event-based Limburg Soil Erosion Model (LISEM) are physics-based so potentially the effects of soil conservation measurements can be calculated. But these models also require more input data that need to be measured (Wischmeier and Smith, 1978; Hernandez et al., 2000).

Many researches focus on modelling the effects of soil conservation measures, rather than on how those measures can be incorporated in a model and how a model can predict the effects of the implementation of soil conservation measures beforehand. Building a model that can correctly predict the changes in surface runoff and soil erosion rates with changes in land cover and management will provide a great help for determining which measures should be taken in a certain area to reduce erosion. Hessel and Tenge (2008) calculated the p-factor for different soil conservation measures and with this p-factor, they corrected and calibrated input parameters for LISEM. Although LISEM is a physics-based model, the approach of Hessel and Tenge using the p-factor is empirical; when applying this method in other areas, the p-factor needs to be estimated again using control and SLM plots. Van Dijk and Bruijnzeel (2003) used a physics-based method for the modelling of erosion on backsloping bench terraces: they subdivided the bed, riser and drain components and modelled the sediment erosion and transport in those components with good results using the Terrace Erosion and Sediment Transport mode (TEST). Pansak et al. (2010) used the Water, Nutrient and Light Capture in Agroforestry Systems (WaNuLCAS), a model that predominantly aims at the interaction between trees, crops and soil but also includes an option for predicting erosion, to model hedgerows by defining different lateral zones for different vegetation types.

In order to translate various land use characteristics like slope, vegetation and soil type to a model, it is necessary to be able to define relatively small spatially different elements. The model then needs to correctly predict the interactions between these elements. This can be done well by distributed models like KINEROS and SWAT, where the research area can be subdivided into elements (KINEROS and SWAT) or represents a grid (SWAT). Hernandez et al. (2000) evaluated the response of model performance on changes in land cover for both models and concluded that KINEROS performed better although both models did well. Moreover, KINEROS is an event-based model with time steps of minutes and therefore more suitable for modelling detailed overland flow and infiltration on small areas like farmer plots in the Usambara Mountains.

The aim of this study was to implement selected SLM measures in the Usambara Mountains in KINEROS2, model the impacts of the SLM measures on surface runoff and soil erosion and evaluate the suitability of implementing these measures in KINEROS2. The following objectives were addressed:

1. To collect plots scale data of surface runoff, soil erosion and relevant variables for soil erosion modelling.
2. To incorporate the selected SLM measures in the KINEROS2 model.
3. To apply the KINEROS2 model at plot scale and evaluate the quality of its parameters using plots without SLM measures.
4. To apply the KINEROS2 model for a number of plots with different SLM measures and compare the results with actual data collected in the plots.

2 Materials and methods

The next chapters will provide information about the research area and the research plots, the physical background of KINEROS2 and the methods used for collecting the input data, the incorporation of the different SLM types in KINEROS2 and the calibration and the validation of the research plots.

2.1 Study Area

Located just near the equator, Tanzania has a climate that ranges from tropical along the coast to temperate in the highlands. The Northern part of the country experiences bimodal rainfall, with the long rains falling in March-May and the short rains in October-December. The Northern Highlands including the Usambara Mountains have an altitude of 1000 to 2000 m and a bimodal rainfall of 1000-2000 mm (De Pauw, 1984). In the South there is only one wet season from November till April (CIA World Factbook, 2011).

The Usambara Mountains form a chain with some other mountains in Kenya and Tanzania, called the Eastern Arc. The Eastern Arc covers about 2000 km^2 and is one of the 25 ecological hotspots of the world (Myers et al., 2000). Between 1955 and 2000, a loss of forest was observed of up to 55% in montane lowland. Deforestation decreased since 1975, except for the submontane zone where deforestation increased (Hall et al., 2009). Population growth and the corresponding need for arable land causes the cultivation of previously forested land. Maize is the main food crop in Tanzania and the Usambaras and is often intercropped with other food crops like beans, bananas, sugarcane and cassava or with coffee. At larger estates, crops like cocoa, tea and sisal are grown (Reyes et al., 2005; Vigiak, 2005). Agriculture in Tanzania is often applied on a small scale, with farmers having enough yields to sustain their own family. Fiener et al. (2011) demonstrated that small scale farming already result in lower erosion rates than farming on large plots. In some cases, a reduction of soil loss will not be enough to increase farmer's yields again because the soil quality has also degraded (Roose and Barthès, 2001). As for soil conservation measures, terraces are by far the most applied method in the Usambaras (figure 2), with agroforestry being also quite common and grass strips being less common.

Figure 2: Terraces on which maize and beans are grown, planted with Grevillea Robusta; in the front a plot without SLM. Near Soni, Lushoto district.

The study area of this research was Lushoto disctrict in the West Usambara Mountains. The district inhabits several small villages and some areas with high SLM adoption as well as areas with low SLM adoption. The soils in this area consist of high amounts of clay and sand and are rich of kaolinite and quartz (Lundgren, 1980). Both kaolinite and quartz have particle densities of 2.65 g/cm^3 (Blake & Hartge, 1986). Soils in the Usambaras are well-structured. According to Minderhoud (2011) bedrock in this area is rarely found deeper than 1.5 meters. Six research plots were selected, which are located a few kilometres east of Lushoto, the main town in the Usambaras. The plots are paired, so plot 1 and 2; 3 and 4; 5 and 6 lie right next to each other. Within a 10x10 km area, plots 1-4 are located near the village of Shashui and plots 5 and 6 are located near the village of Kisiwani. A weather station is situated at approximately 500m distance to the plots near Shashui. The slopes of these plots are quite steep, from 20° up to 34°.

The research plots are 30m x 40m on average and are bordered with a furrow at the upper and lower end of the plots and sometimes bordered with a line of trees at the right and left side. The research plots have equal climate and soil type; slopes are in the range of 20-33 degrees. In the growing season, beans were grown on (parts of) the plots, except for plot 3 which was bare soil. On plot 4 some small banana trees were grown and on plot 1, 2 and 4, low-density and dried remnants of maize of the last growing season were still present. The research was conducted from the end of September to the end of November 2011, so before and during the short rainfalls, which is also the short growing season.

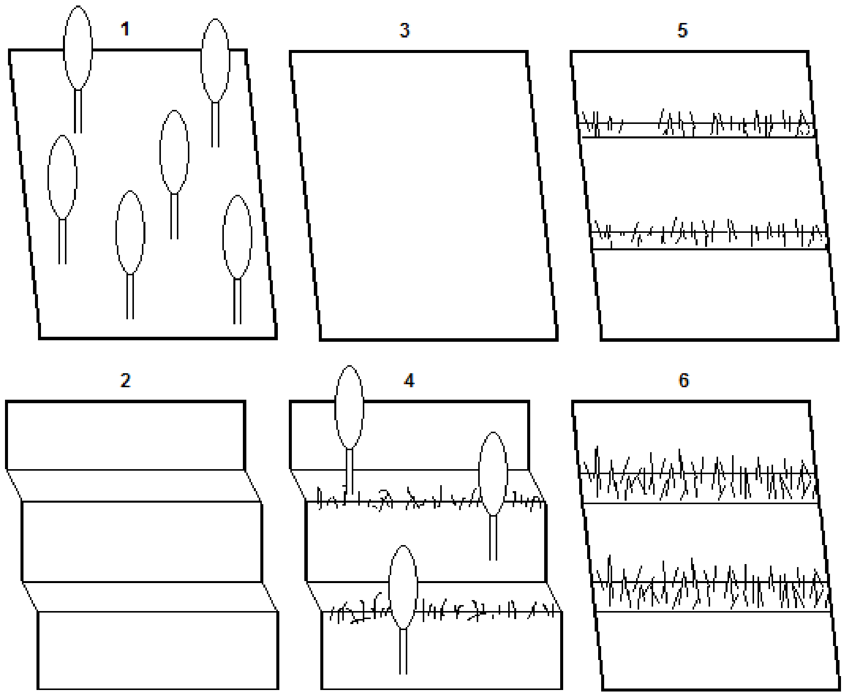

Figure 3: Schematic representation of the three control plots (upper row) and their paired plots with sustainable land management (lower row).

Three categories of SLM were distinguished in this research (figure 3): terraces, agroforestry and grass strips. These categories do not always have clear boundaries in the field: some grass strips may be partly removed and on some plots that are considered to have no agroforestry, still one or two trees grow. Terrace size steps may differ and sometimes some grass grows on its risers, without being able to call it a grass strip. These variations were taken into account as much as possible in the measurements and model implementation and otherwise were considered when evaluating the results.

Table 1: Basic characteristics of the research plots.

Field	Soil type	Slope	Width	Length	SLM type	crops
1	clay	30°	16.5 m	41 m	agroforestry	maize, beans
2	clay	29°	21 m	35 m	terraces	maize, beans
3	clay	34°	43 m	29 m	no SLM	no crops
4	clay	32°	56 m	30 m	terraces+agroforestry	maize, banana, beans
5	sandy clay	20°	29 m	31 m	poor grass strips	beans
6	clay	21°	27 m	27.5 m	grass strips	beans

Plot 1 is a control plot and a plot with agroforestry (10 trees). Agroforestry consists of single *Grevillea Robusta* trees, planted more or less randomly with a distance of several meters. The trees on the research plots are several years old, with some of the tallest trees being 8-9 meters high. The lower branches of most trees are removed, reducing the density of the canopy and reducing shade and water competition for crops. Control plot 3 is the most erosive plot, with no terraces, trees or even crops and its surface is rough, with high relief and some rills that are about 20-30 cm deep. Plot 2 and plot 4 are the plots containing terraces. The terraces are built in steps of about 1 m high vertical riser and, for plot 2 the horizontal beds are about 2-2.5 m whereas the beds of plot 4 are about 2-4 m. The beds have a slight slope of about 10-15° and the risers have a slope of about 80-85°. At plot 4, on the tip of the terraces' risers, some grass is grown. Plot 4 also has agroforestry because of the 11 *Grevillea* trees grown here. At control plot 5, two grass strips are planted with a spacing of about 10 m and a width of 25 cm; they are in a poor condition, having very low density with weeds growing between the grass and one strip only covering half the width of the plot. Plot 6 also grows grass strips with a spacing of about 10 m but with a width of 1 m and good density. The length of the grass strips follows the contour line of the hill.

2.2 KINEROS2

KINEROS2 is a distributed, physics-based and event-based model, used for small watersheds (Woolhiser et al., 1990; Hernandez et al., 2000; Marinov et al., 2005). Its flexibility in determining the shape of the erosion plots and the use of different elements makes this model suitable for implementing SLM's like terraces and grass strips. The physics behind the software is discussed in the next chapter. Concerning the units of the parameters listed in this chapter; for the input parameters, the units are the same as they are used in KINEROS2. This may cause some inequality in formulas, like one parameter presented in minutes and the other in mm/hour. It is assumed that KINEROS2 solves this internally by recalculating these parameters. For a list of all input parameters, see Appendix A.

KINEROS2 represents the catchment by a network of planes and channels (figure 1). The planes represent uniform areas with specific characteristics that are described by the input parameters. How many planes and how they are interconnected can be defined. KINEROS2 allows high temporal and spatial resolution, depending on how the user defines the input.

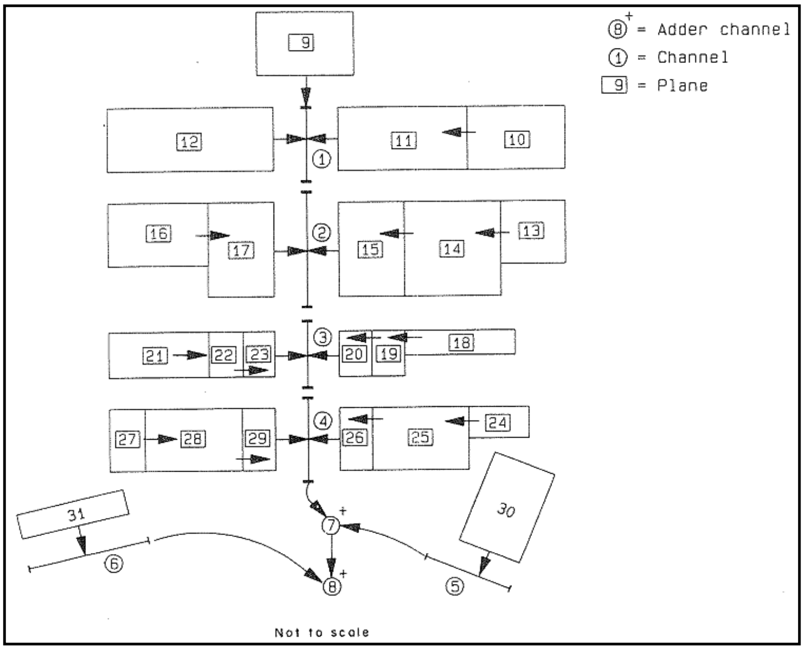

Figure 4: Graphical representation of a catchment subdivided into planes and channels in KINEROS2 (Woolhiser et al., 1990).

KINEROS2 models interception, infiltration, runoff, erosion and sediment transport, but options like pipe flow, ponding and partially paved elements for urban areas are also included. Rainfall can be equal for all elements but if there is more than one rain gauge in the catchment, rainfall can be specified for single elements and will be interpolated for the ungauged elements.

Rainfall is reduced by cover fraction until the maximum water that can be retained by the vegetation, called interception depth, is reached. After the interception depth is reached, all rainfall reaches the soil's surface.

The limiting rate at which water can enter the soil surface, the infiltrability f_c*(mm h^{-1})* is defined by the saturated hydraulic conductivity K_s*(mm h^{-1})* and the infiltrated depth *I(mm)*.

$$f_c = K_s\left[\frac{\alpha}{\exp(\alpha I / B) - 1}\right]$$ [equation 1]

In this case, *α* is a parameter representing soil type, with 0 being high permeable sand and 1 being low permeable loam. In KINDEROS2 it is a fixed value of 0.85. *B* combines the effect of capillary drive, surface water depth and storage capacity and is defined as:

$$B = (G + h_w)/(\theta_s - \theta_i)$$ [equation 2]

in which *B* is an integral capillary and water deficit parameter of the soil that combines the net capillary drive *G(mm)* with the time-dependent parameters surface water depth h_w*(mm),* saturated moisture content θ_s and initial moisture content θ_i*(volumetric).*

KINEROS2 also allows a soil profile consisting of either two soil layers, with different soil characteristics, in order to be able to calculated more complex infiltration, for example because of a layer with low impermeability beneath the top layer.

For calculating one-dimensional overland flow, the kinematic wave equation is used and solved by finite difference methods. The kinematic wave equation is a combination of the continuity equation and a storage-flow equation and is applied for calculating overland flow and subsurface flow in KINEROS2. The main limitation of the kinematic wave equation is that it cannot calculate the back water effects of downstream situations (Beven, 2001). The kinematic wave equation is defined as:

$$q(x, y) = \frac{\delta h}{\delta t} + \beta m h^{m-1} \frac{\delta h}{\delta x}$$ [equation 3]

In which $h(mm)$ is the storage of water per unit area, $t(s)$ is time, $x(mm)$ is distance in slope direction, $q(mm\ h^{-1})$ is lateral inflow rate and β and m are parameters related to roughness, slope and flow regime. There are four options for calculating roughness: using the Manning hydraulic resistance law, the Chézy's friction coefficient, or a laminar flow law until a critical Reynolds number is exceeded and after exceeding the critical Reynolds number using again Manning's $n(-)$ or Chezy $C(m^{0.5}s^{-1})$ For this research, the soil surface of the plots had some roughness so real laminar flow was considered not realistic and Manning's n was used, without using a critical value for the Reynold's number.

For channel flow, similar formulas that include the kinematic wave equation and the hydraulic radius are used in KINEROS2. Channel flow was not modeled in this research.

Beside the overland flow planes and channel elements, KINEROS2 can also define detention storage elements, where runoff from upstream elements is collected and is only passing through when the water surface elevation reaches a certain level. Infiltration losses in these elements are included.

During recession of rainfall, the ponded water depth and the fraction of land still covered by water, determines the amount of infiltration. Microtopographic relief then plays an important role: KINEROS2 requires spacing (m) and relief (mm) as input parameters to represent average spatial distance and height of the roughness of the surface.

Erosion rates are calculated using splash detachment $e_s(m^2\ s^{-1})$ and flow detachment $e_h(m^2\ s^{-1})$:

$$e_s = c_f k(h) r^2 \qquad \text{[equation 4]}$$

$$e_h = c_g (C_m - C_s) A \qquad \text{[equation 5]}$$

In which $c_f\ (s\ m^{-1})$ is the splash detachment coefficient; a constant related to soil and surface properties, $k(h)(-)$ is a reduction factor depending on water depth, $r(mm\ h^{-1})$ is the rainfall rate, $c_g(s^{-1})$ is a transfer rate coefficient inversely related to cohesion of the soil (Marques da Silva et al., 2007), C_m and $C_s\ (-)$ are sediment transport parameters at equilibrium and current transport rate and $A(m^2)$ is the cross-sectional area.

For sediment transport, an equation for shallow flow over soils is used:

$$C_{mx} = \frac{0.05}{d(\gamma_x - 1)^2} \sqrt{\frac{Sh}{g}(\Omega - \Omega_c)}$$ [equation 6]

In which *S(-)* is slope, *d(mm)* is particle diameter, γ_x *(-)* is the suspended specific gravity of the particles, *h(mm)* is water depth, *g(m* s^{-2}*)* is the gravity constant, Ω *(m* s^{-1}*)* is the unit stream power and Ω_c is a threshold of 0.004 m s^{-1} that applies to shallow flow transport capacity.

In KINEROS2, up to five soil particle size classes can be defined which means that selective erosion can be simulated. The models physics assume that 1) when the largest particle size is below its erosion threshold, the erosion of other particles is limited 2) erosion rates are proportional to the percentage of particle sizes in the soil 3) settling velocities do not depend on the concentration of other particles sizes. The option of defining different particle sizes is especially valuable for cases where the elements of the catchment vary much in texture or where selective settling occurs, for example in impoundments where flow velocity rapidly decreases.

2.3 Input data collection

The input data required for KINEROS2 was obtained from plot measurements and from literature to estimate parameter values that could not be determined on the plots. Some soil characteristics were measured using soil samples analysed in the laboratory at Mlingano Agricultural Research Institute. Actual rainfall and runoff data came from a local weather station and Gerlach troughs. Measurements were made on all six plots and on a transect between two trees on plot 4 in order to determine spatial dependency of the soil's characteristics with distance to the trees (further discussed in paragraph 2.4).

Rainfall data

The required rainfall data came from a weather station situated in Sashui, about 500 meter from plots 1-4 and 5 km from the other two research plots. Actual rainfall data for the Sashui area was available and covered a period from 10 January 2010 until 12 February 2011, including 29 suitable rainfall events in the short rain season from November until January. This rainfall was measured per hour. For a more consistent use of the KINEROS2 model, data with a much smaller interval of 5 minutes was needed so the hourly data needed to be converted. Rainfall data (34 events, from November to December) of the Kwalei catchment, a close-by catchment in the Usambara Mountains, (Vigiak et al., 2006), was analysed to determine the relation between the peak rainfall intensity and the total rainfall using a single regression analysis. Rain events of the Kwalei data chosen for regression analysis had at least 15 minutes of rainfall. Periods in which precipitation ceases for more than 15 minutes, were considered to be separations between two events.

The peak intensity of the hourly data of the Sashui catchment was calculated using the coefficients of the regression analysis of the Kwalei catchment data. The duration of a rain event measured over 1 hour was fixed at 50 minutes. If some rainfall smaller than 2 mm was measured in the hour directly following the first hour, this was added to the total amount of rainfall without changing the duration. If more than 2 mm of rain fell in a second hour, this rainfall was considered a separate event. With the duration and peak intensity determined, rainfall intensity for every step of 5 minutes could easily be interpolated assuming a triangular hyetograph with the peak intensity occurring at half the duration of the event.

Actual runoff and erosion data

At every plot, there were four Gerlach troughs with a width of 50 cm located at the bottom of the plots. They were placed with equal distances of about 4-10 m (depending on the width of the plots), covering the width of the plots. The troughs were emptied and measured once in several days, depending on the amount of rain fallen and varying per plots. One Gerlach measurement therefore often included a set of several rainfall events (Appendix B). In this paper, a set of rain events that all belong to the same Gerlach measurement is called a Gerlach period. With the Gerlach data, no exact time was recorded, only the date; so when a rain event occurred on the same day as the day that the Gerlach troughs were emptied, it was not sure whether this rain event happened before or after the emptying of the troughs and thus whether it should be included in the Gerlach period or in the next. In this case, rainfall events were assigned to the current or next Gerlach period by assuming that the troughs were emptied after a larger event but not after sunset.

The troughs were connected to a jerrycan from which the collected water was directly measured. A sample of the well-mixed water and sediment was send to the lab to measure the volume of sediment in percentages. The upstream part of the plot that contributed to the surface runoff caught in the Gerlach troughs had to be considered; Vigiak et al. (2006) found that for measured runoff in the Kwalei catchment in the Usambara Mountains, a reinfiltration length of 4 meters corresponded with model simulation results. An evaluation of the amount of measured runoff (extrapolated to the entire plot using a contributing length of 4 meters) versus the amount of rainfall showed reasonable values for this research. However, it should be considered that the use of incorrect values for the reinifiltration length may cause under- or overestimation of runoff and sediment.

Soil characteristics

Soil texture and bulk density data derived from soil core samples were already available for the six plots (Wickama, 2010). Soil texture was measured according to the USDA classification: clay (<2 μm), fine silt (2-20 μm), coarse silt (20-50 μm), fine sand (50-500 μm) and coarse sand (500-2000 μm). All core samples were taken from the upper 30 cm of the soil. Porosity was also measured in the lab.

The splash detachment coefficient c_f is a semi-empirical parameter depending on the raindrop erodibility. In this research, splash detachment coefficient was set to the default value 50 s/m and was optimized with the calibration of the model.

Soil Surface Characteristics

Spacing and relief define the variation in the micro topography; low values represent a relatively smooth surface, causing more infiltration. High values increase runoff values because the water is concentrated in streams. These values were determined using visual observation on the plots. Rock fraction was also visually estimated in the field.

Mannings *n* is a measure of the roughness of the soil surface. It was determined using values from literature (Chow, 1959; Karim et al., 2010). Slope was measured in the field using a clinometer.

The interception depth was also determined from literature, using common values provided in the KINEROS Manual. For some types of vegetation, like grass (in the Usambaras the common grass type is Vetiver, which is similar to Big Bluestem), beans and weed, the roughness and interception was not exactly known and was estimated from values for similar types of vegetation. For each vegetation type, the percentage of coverage was visually estimated in the field. Interception depth and vegetation cover together determine the total amount of interception.

Cohesion

Shear strength of the soil is defined by effective stress, angle of internal friction of the soil and the intrinsic cohesion of soil particles related to chemical bonding. The shear strength is defined by the Mohr-Coulomb relation:

$$\tau = \sigma' \tan(\phi) + c \quad \text{[equation 7]}$$

With $\tau(kPa)$ being shear strength, $\sigma'(kPa)$ the effective stress (σ-u, or normal stress minus pore water pressure), $\phi(deg)$ the angle of internal friction and $c(kPa)$ cohesion. Under saturated, undrained conditions, the internal friction of the soil particles reduces and pore water pressure increases, causing the first part of the Mohr-Coulomb equation to become negligible (Morgan et. al., 1998; Okada, 2010) and the saturated shear strength more or less equal to saturated cohesion. With a Torvane tester, measurements were done 4 times per plot, using the largest adapter that measures in the range of 0 to 0.2186 kg/cm^2. Vegetation roots increase the cohesion values and Morgan et al. (1998) provides a table for increases in soil cohesion depending on vegetation type. For the grass strips, it was not possible to measure cohesion because of the density of the grass. Morgan et al. determined the cohesion increase of grass to be 1-8 kPa. A cohesion increase of 4 kPa was therefore used in this research.

Saturated Hydraulic Conductivity and its Coefficient of Variation

The saturated hydraulic conductivity K_s *(mm h^{-1})* was measured by infiltration measurements. Double ring infiltration measurements were done 3 times for every plot, on the left, middle and right side of middle of the plot. Values were then corrected for cylindrical factors using (Reynolds, 2002):

$$K_s = \frac{q_s}{[\frac{H}{C_1 d + C_2 a}] + [1/(\omega(C_1 d + C_2 a)) + 1]}$$

[equation 8]

In which q_s *(cm^3 h^{-1})* is steady infiltration rate, *H(cm)* is ponding depth, C_1 and C_2 are constants equal to 0.59 and 0.99, *d(cm)* is the cylinder insertion depth, *a(cm)* is the cylinder radius and ω is macroscopic capillary length *(cm)* fixed at 0.12.

KINEROS2 also requires an estimate of the coefficient of variation of K_s. The coefficient of variation (CoV) is the standard deviation divided by the mean. For this research a normalized standard deviation (coefficient of variance) was calculated by subtracting the K_s plot-averages from the measured values. Assuming a normal distribution, the range of minimum and maximum of these normalized values can be considered to represent 98%, which is equal to 6 standard deviations. Dividing the difference of the maximum and minimum plots-average by 6 gives the normalized standard deviation. Dividing this deviation by the total average (over the six plots) gives the coefficient of variation *(-)*.

Soil Moisture, Depletion factor and Topsoil Depth

KINEROS2 requires antecedent soil moisture conditions for the simulation of every event. These soil moisture contents were not known for the rainfall data of 2010, so an estimation of these values was needed. On all six research plots, the volumetric soil moisture contents were measured during the research period (October 2011) at every corner of the plot using a hand-held TDR with a length of 51 mm. Due to unexpected circumstances, the measurements were not carried out for longer than 9 days. The volumetric moisture content was converted to the relative degree of saturation and the depletion factor, the rate at which the soil dries, was calculated. Due to the uncertainty in measuring these data (depending on exactly where and how deep the probe was inserted in the soil) and the limited amount of measurements, the average factor for all six plots was used.

Using the amount of infiltrated rainfall and the soil depth, the increase in soil moisture can be calculated after every rainfall event. With a depletion factor (that is a measure of how quickly the soil dries during recession) and the number of days between two events the antecedent soil moisture for the next event can subsequently be calculated when the first soil moisture content is known. Due to evaporation, capillary suction and a lack of high-intensity rainfalls, the part of the soil that is really influenced by rainfall is often only the top soil layer. Morgan (2001) included an effective hydrologic depth in his revised model, previously called rooting depth. This depth is the surface soil layer which controls the infiltration and runoff during a rainfall and is estimated to be 9cm for bare soil without a crust and 12 cm for soil with row crops (MMF 2001, table 3). Wickama (2010) measured a top soil varying between 3.3 cm and 10.4 cm for the six study plots. A value of 9-11cm was considered for calibration in KINEROS2. Because the sensor measured the soil from 0-5 cm, the depletion factor was not representative for the entire layer of 10 cm, probably being higher because the deeper soil is less prone to evaporation. No data of the entire soil layer was available so the exact depletion factor was calibrated.

Pore Size Distribution Index

The pF measurements from the transect soil samples were used to determine pore size distribution index (PSDI) and capillary drive. For pF = 1.0, 2.0, 2.4 and 2.7, the degrees of saturation were measured in the lab and the effective or normalized saturation θ_E could be calculated (Brooks & Corey, 1964; Hwang & Hong, 2006):

$$\theta_E = \left(\frac{\theta - \theta_r}{\theta_s - \theta_r} \right)$$ [equation 9]

With θ being the volumetric water content, θ_r the residual volumetric water content and θ_s the saturated volumetric water content. An estimated θ_E could be obtained by using a relation for θ_E in combination with the pressure head *h(mm)* and the air-entry value h_a*(mm)* and pore size distribution index λ*(-)*:

$$\theta_E = \left(\frac{h}{h_a} \right)^{-\lambda}$$ [equation 10]

By calculating the difference between real and estimated θ_E and solving equations 8 and 9 by calculating an optimum of minimal difference with minimal Root Mean Square Error, an optimal λ and h_a were retrieved.

Capillary Drive

Once the soil gets wet during infiltration, capillary action reduces (small pores with high capillary suction are already filled), the infiltration rate becomes less and the hydraulic conductivity increases. The capillary drive *G(mm)* is the integrated relative hydraulic conductivity across the capillary head and it influences the infiltration rate of a vertical column of soil under ponded conditions (Morel-Seytoux & Khanji, 1974; Morel-Seytoux, 1996; Hendriks, 2010; Hantush & Kalin, 2005).

$$G = \int K_r(\varphi)d\varphi$$ [equation 11]

The relative hydraulic conductivity, $K_r(mm\ h^{-1})$ is dependend on soil moisture content (Hwang and Hong, 2006) and can than be determined with the equation of Brooks & Corey (1964):

$$K_r = \theta_E^{(2/\lambda+3)}$$ [equation 12]

Of which the integral is then:

$$G = \frac{1}{3+2/\lambda+1} * \theta_E^{3+\frac{2}{\lambda}+1}$$ [equation 13]

Integrating between the minimum and maximum effective saturation, 0 and 1, makes only the first part of equation 12 important. From the calculations for the PSDI, θ_E and λ are already known so G follows from equation 12.

2.4 Incorporation of SLM types

Three main types of SLM are present in the plots: terraces, grass strips and agroforestry. The way of incorporating these methods into the KINEROS2 model, is done by distinguishing different elements in the research plot, based on characteristics like slope, vegetation cover and roughness. These elements then form the outline of the KINEROS2 input parameter file.

Terraces

The modelling of terraces (figure 5a and b) was done by specifying different connected overland flow elements for the terrace's risers and beds (see Appendix E for parameter file of plot 2). The occurrence of a furrow at the upper end of the research plot meant that the plot in KINEROS2 could be considered to be independent; no upstream area contributed to runoff measured at the lower end of the plot.

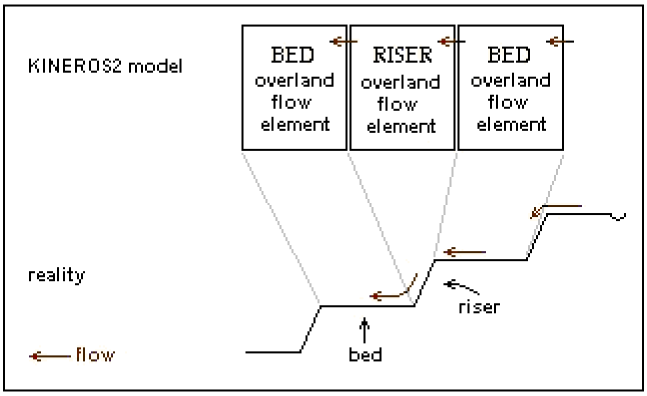

Figure 5a and 5b: terrace modelling in KINEROS2

Plot 4 consists of two sides with almost equal terraces and a furrow or stair-like path in between; the parameter file thus should contain two rows of terrace elements and a channel element in between, with the final downstream element connecting to the upstream parts. It is claimed that KINEROS2 allows more than one upstream element being assigned to another element but the version used in this research did not. Because the terrace beds are sloped, it is likely that only a very small part of the runoff flows via the path in the middle of the plot; most of the runoff will flow via the beds and risers. So the furrow was neglected and terraces were assumed to cover the entire width of the plot with only one element upstream of the other element.

Grass strips

Modelling of grass strips (figure 6) was done in the same way as for terraces by creating different overland flow planes for crop land and grass strips, on which vegetation cover, interception depth and Mannings' n differ. The density of grass strips is a major factor in hampering runoff an trapping sediment (Pan et al, 2011). Zhang et al. (2010) calculated that an optimum width lies at 12 meters; barriers smaller than 12 meters show a rapid decrease in the efficacy of removing sediment from 90% to about 30% at 1 meter. Because of the poor condition of grass strips on plot 5, a zero or minor increase in saturated hydraulic conductivity is expected and therefore neglected. Saturated hydraulic conductivity on the grass strips of plot 6 was not measured because of the density and height of the grass and the slope of the grass strips. The increase in K_s for plot 6 was therefore calibrated and discussed.

Figure 6: Research plot 6 with grass strips (plot 5 in the very front)

Agroforestry

The way of incorporating agroforestry (figure 7) into KINEROS2 depended on the spatial influence that the *Grevillea* trees have on soil parameters. Grevillea tree rows were reported to have a small influence on the water content of the soil (Livesley et al., 2004). The trees in this research area are scattered, and therefore the influence on water content was expected to be even less. To estimate the spatial dependency of the soil characteristics, measurements were made along a transect between two trees. The transect was 12 meters in length, with the maximum distance to a tree 6 meters. Bulk density from core and soil texture (from core samples) and cohesion were measured every 0.5 meter and saturated hydraulic conductivity was measured every 1 meter. For KINEROS, porosity is used as input parameter but the laboratory did not measure porosity or organic content so the only parameter that could give an indication of the variation in porosity was bulk density. The measured values close to the tree (0-2.5m) and the measured values with distance to the tree (3-6m) are compared by their averages and standard deviations. If the transect measurements showed large spatial dependency, the KINEROS2 model would be considered to have elements representing parts of the plot with trees and their corresponding soil characteristics, and elements representing parts of the plot without trees. If the transect data showed no trend, the parameter values for the entire plots would be averaged and no distinctive elements 'with trees' or 'without trees' were made.

Figure 7: Agroforestry with terraces in the background

The impact of raindrops first intercepted and later fallen from the canopy can cause splash erosion as much as direct rainfall or even worse. The kinetic energy of a raindrop is controlled by its velocity (that depends on the distance that the drop falls) and the size of the raindrop. Raindrop sizes of secondary drops falling from canopy depend on the vegetation type, with vegetation with larger leafs creating larger raindrops (Calder, 2001). *Grevillea* trees are quite large and the base of its canopy can be several meter above the ground but the trees have very small leaves so are not able to collect water and create large raindrops so extra slaking of the soil due to secondary raindrops is considered negligible (figure 8).

Figure 8: Leaves of the Grevillea tree

2.5 Model calibration and validation

An algorithm written in the open-source scripting language php was developed to run KINEROS2 for a large number of events with corresponding initial soil moisture and differentiating parameters. KINEROS2 was recompiled in order to execute these runs automatically.

Algorithm

The php script was designed in such a way that first of all, KINEROS2 was executed chronologically for every rainfall event for a specific parameter combination, starting with a fixed value for the initial saturation of the soil for the first rainfall event (Appendix C). Meanwhile running the model for every event, the script calculates the initial saturation for the next event by recharging the soil using the amount of infiltrated water in the previous event divided by the thickness of the effective hydrologic soil layer and then drying the soil again by using the amount of days between the next and previous event and the depletion factor. Then the parameter combination changes and KINEROS2 is executed again for a new set of parameters for every rainfall event as described above.

Calibration

Plot 1, 3 and 5 were the control plots without SLM and were calibrated first. From each of the calibration plots, the parameter optimum was determined and used for the validation of the corresponding SLM plot.

In order to calibrate the parameter optimum, a Matlab script (Appendix D) was developed that calculates the RMSE over modelled and measured runoff and sediment for every single value of the calibrated parameter in two different ways: the first one is the RMSE calculated over all Gerlach period values at once, the second one is the RMSE calculated over only the Gerlach periods belonging to the same rain season and thus having the same parameter combination values. The RMSE over all Gerlach periods shows the general trend of a parameter, independently of the other parameter values, whereas the RMSE per season and parameter combination is more suitable for determining the optimum parameter combination. The smaller the RMSE, the better the model prediction:

$$RMSE = \sqrt{\frac{\sum_{i}^{n}(x_{p,i} - x_{m,i})^2}{n}}$$ [equation 14]

In which x_p is the predicted value, x_m is the measured value and n can either be the amount of Gerlach periods in one season or the total amount of Gerlach periods (amount of Gerlach periods per season times all parameter combinations).

For the calibration of KINEROS2, the following six variables were used: mean capillary drive (G), hydraulic conductivity (Ks), initial soil moisture content (SA), depletion factor (Df), soil depth (T), cohesion (C) and splash detachment (S). Ranges of the parameters were determined by looking at the values measured in the plots and/or values mentioned in literature. The calibration ranges are shown in table 2. First, a lumped calibration has been done for all the parameters influencing runoff (G, Ks, SA, Df and T) and within the broad ranges of table 2. Then, the ranges for Ks and G were made smaller to gain better insight in the behaviour of SA, Df and T. The results were then evaluated and the values for SA, Df and T fixed. Second, a calibration run for only the runoff parameters G and Ks was done, followed by a more detailed run with smaller ranges or, if the optimum lies outside the range, with a broader range. The parameter with the most pronounced optimum was then fixed and a last calibration run was done to find the optimum of the last parameter. The same procedure is done for the sediment parameters C and S. The RMSE of the events modelled with the calibrated parameter optimum was compared to the RMSE of the events modelled with the measured parameter values to estimate the improvement due to the calibration.

Table 2: Range at which the most important values for calibration are expected to vary

Variables	**Min**	**Max**
Capillary drive [mm]	5	200
Saturated hydraulic conductivity [mm/h]	10	100
Initial soil moisture content [-]	0.20	0.80
Depletion factor [-]	0.90	0.95
Soil depth [mm]	90	110
Cohesion [kPa]	0.50	15
Splash detachment [s/m]	5	150

Validation

The calibrated parameter optimum of each control plot was then used for validation using the corresponding SLM plots. For plot 6, an optimal increased hydraulic conductivity for the grass strips is determined by running the model several times with different K_s. The results of the validation were plotted against measured values to show its accuracy and the RMSE calculated. The modelling results using the parameter optimum are also compared with the modelling results of the same plot using an input parameter file with minimum and maximum vegetation coverage, on which cover fraction and Mannings *n* are changed: resp. 0.0001 and 0.03 for minimum coverage and 1.0 and 0.3 for maximum coverage. This may provide a better insight in the range in which runoff and erosion are predicted to vary and in the competency of the model.

3 Results and Discussion

3.1 Input data for KINEROS2

In this chapter the values obtained from the plot measurements are presented and discussed. For the KINEROS2-variables that could not be measured, values based on literature are given. There were some problems arising with the KINEROS-manual, which is not clear about the units it uses for some parameters. The list of input parameters mentions cohesion and splash detachment coefficient as input parameter without naming its units. The online description of the physics and the manual of 1990 do not mention cohesion at all. Cohesion is typically given in kPa, so these are also the units assumed in this research. Splash detachment coefficient is given units of seconds per meter according to Heppner et al., (2005), but KINEROS states that splash erosion rate is m^2/s which would make the units in the formula [equation 4] not matching with the other parameters. KINEROS2 probably calculates erosion rates in m^3 per 1 meter length, which can be defined as m^2. In this research, an erosion rate of m^3/s and a splash detachment coefficient of s/m are therefore used. N.b.: the source code of KINEROS2 is also not very accessible, with many short-termed and unexplained variables and only few comments which is hard to unravel.

Rainfall

Rainfall was measured between 9 November 2010 and 14 January 2011. During this period a total number of 29 rain events were recorded. Except for one event (21 December 2010), the measured amounts of rainfall were below 15 mm per event (figure 9). The event of 21 December was much larger (32 mm).

The rainfall amounts were converted to peak intensities using the Kwalei data of Vigiak (2006). Analysis of the Kwalei data in order to estimate a relation between peak intensity and total rainfall resulted in a linear relation trough the origin with an R^2 of 0.75:

$$\textit{Peak Intensity} = 2.477 * \textit{Total Rainfall} \qquad \text{[equation 15]}$$

Confidence intervals (95%) for the calculated trend in the Kwalei data are shown in figure 10. These bounds show that the uncertainty in calculated peak intensities for the larger events is quite large; much of the real peak intensities fall outside the 95% confidence interval. For the rain events with magnitudes similar to the recorded data of the Sashui catchment (smaller than 15 mm), the uncertainty is smaller. But when applying equation 15 to the Sashui data, some uncertainty in the runoff and sediment modelling will still occur.

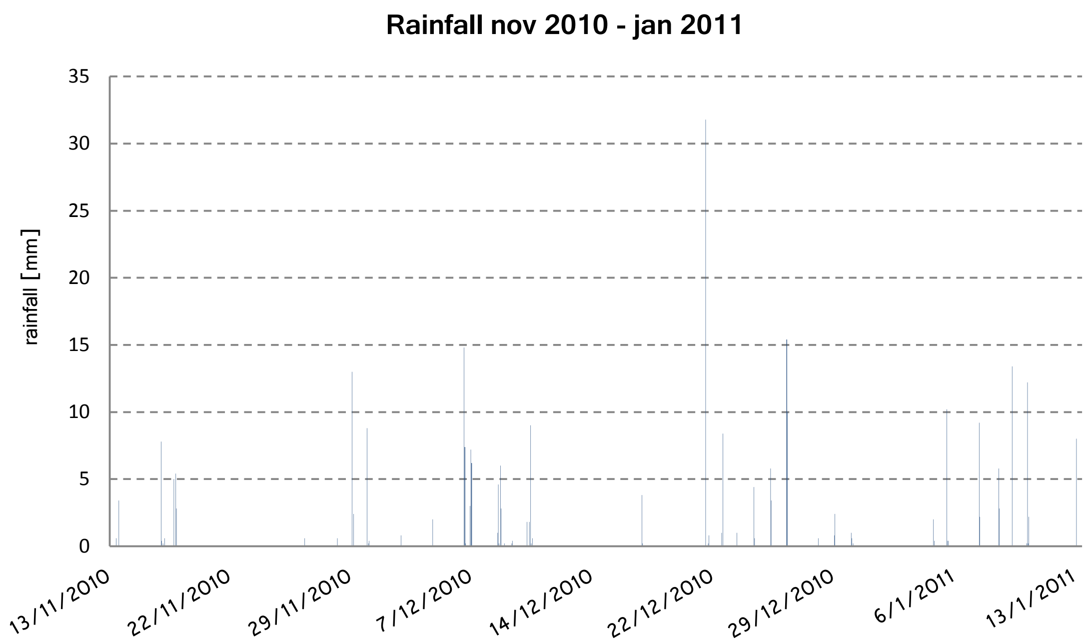

Figure 9: Rainfall recorded in the Sashui catchment

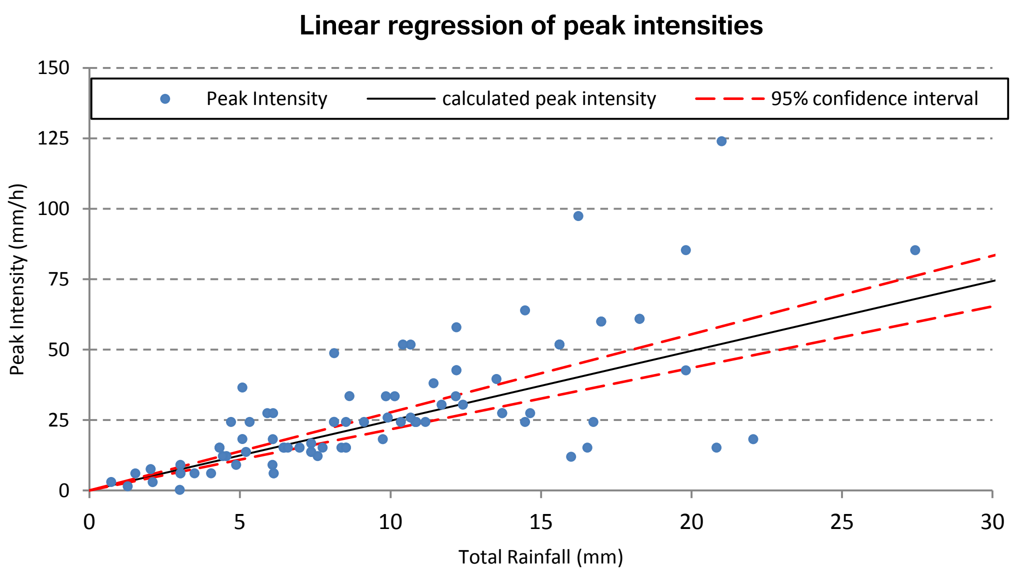

Figure 10: Calculated peak intensity using a coefficient of 2.477 (black line), with 95% confidence interval (red dashed lines) and real peak intensities (blue dots)

Actual runoff and erosion data

The Gerlach throughs were measured once in several days, depending on the amount of rain fallen. The measurements were not done at set times; the timing did vary per day and per research plot which makes the effect of specific Gerlach periods on the different plots more difficult to compare. The Gerlach data did contain two measurements for plot 6 in which the through was emptied twice on the same day with almost no rainfall occurring that day. These measurements were assumed to be true and summed into one measurement. The runoff and sediment were translated to mm and g/m2, using the reinfiltration length of 4 meters (Vigiak et al., 2006).

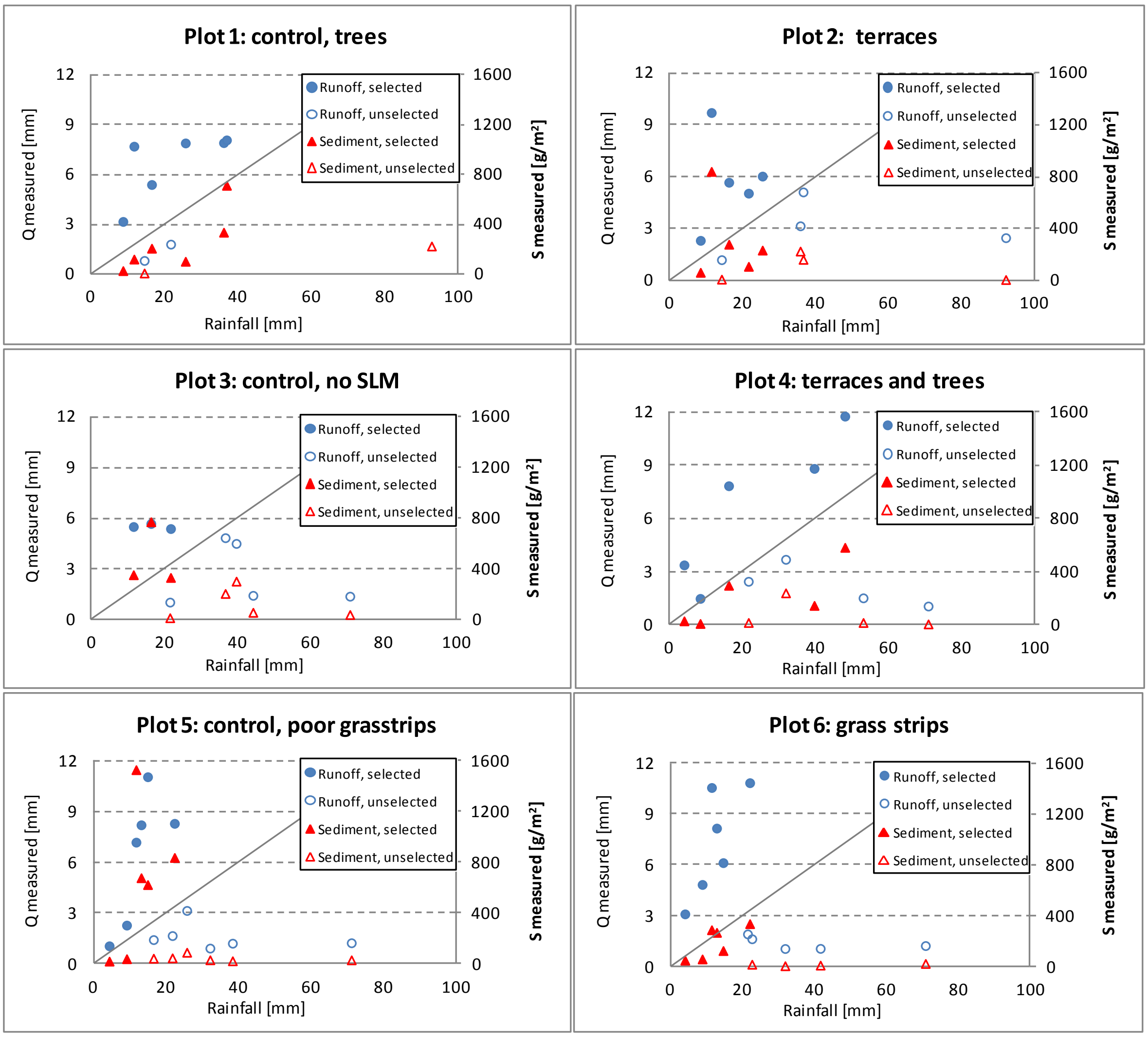

Figure 11: Runoff [mm] and erosion [kg] for the selected events with runoff coefficient above 0.15 and for the unselected events with a runoff coefficient below 0.15 (grey line).

Plotting the runoff and sediment measured in the Gerlach troughs against the amount of rainfall for each Gerlach period, a visual evaluation of the data can be made (figure 11). The amounts of runoff (mm) are for each of the plots in the same order of magnitude, with plot 3 having the lowest runoff. With an increase in rainfall, an increase in runoff is expected but this trend is not clear in the graphs. For most plots there is a dual trend; part of the Gerlach periods for plot 1 and 4 show a linear increase and part of the periods for plot 2, 5 and 6 show a much higher increase with an almost vertical line. The other periods for all plots show no increasing runoff with increasing rainfall (even with higher rainfall these events still show low runoff).

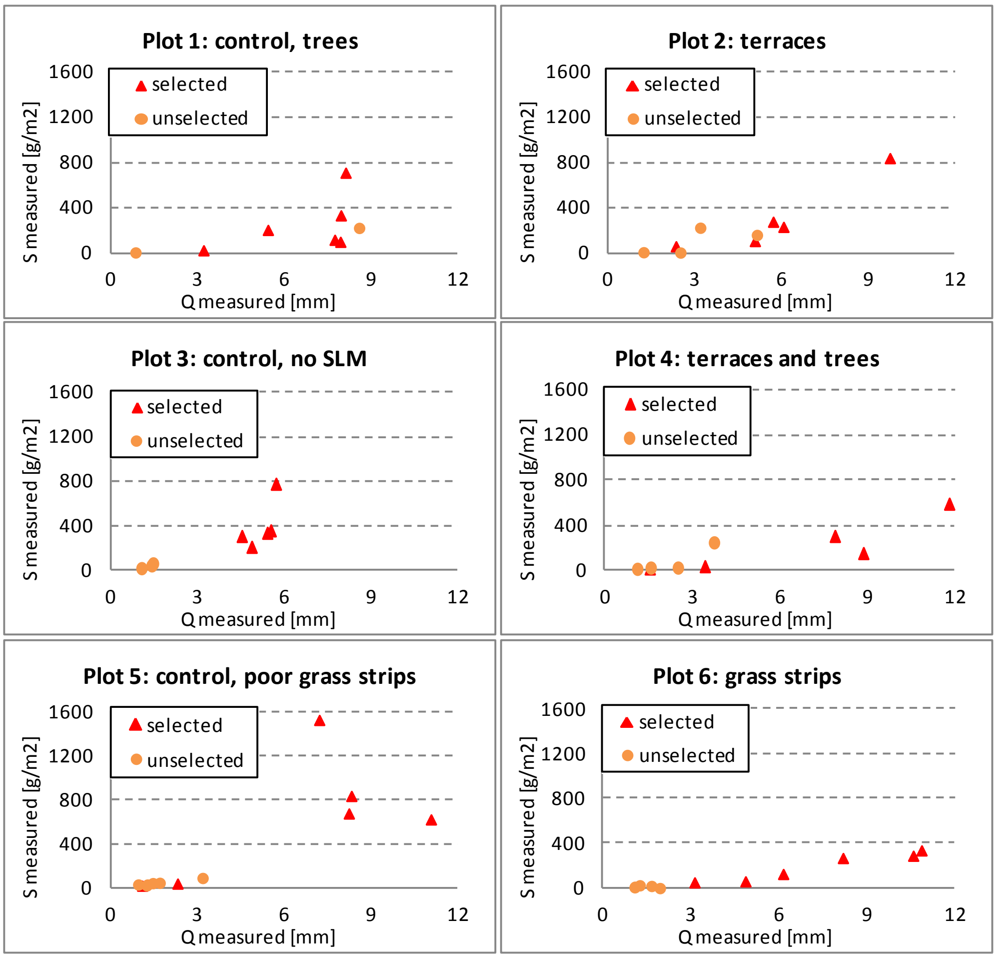

Figure 12: Measured sediment plotted against measured runoff.

In order to be able to use the data for calibration, the Gerlach periods that show the expected trend were selected by calculating a runoff coefficient (runoff divided by corresponding rainfall). With these selected periods, it was made possible to calibrate an unambiguous parameter optimum. All periods with runoff coefficient values above 15% were used for calibration, the other periods were considered not suitable for this research. The Gerlach periods that are not selected because their runoff/rainfall ratio is below 0.15 are in general the periods with low runoff and (almost) zero erosion. The data of plot 3 shows no trend at all, so plot 3 was not used for calibration; instead of plot 3, plot 1 was used as control plot for plot 4. The trends of runoff of plot 1, 2 and 4 are similar (except for one extreme

Gerlach period on plot 2 with low rainfall but measured runoff of more than 9 mm). The construction of terraces and the planting of trees apparently do not have large impacts on runoff. Even the combination of trees and terraces on plot 4 seem to result in equal runoff rates. Plot 5 and 6 show relative higher amounts of measured runoff compared to plot 1-4 and a linear increase of runoff with increasing rainfall is less clear. Plot 5 and 6 differ mainly from plot 1-4 because of their more gentle slopes, as will be described in the next paragraphs. But their different location, farther away from the weather station and on a different mountain slope, may cause the climatic conditions to differ from the conditions on plot 1-4 and the rainfall data from the weather station perhaps being less representative for plot 5 and 6.

In general, sediment increases with increase in runoff (figure 12). Plot 3 and plot 5 (both are control plots with no SLM and poor SLM) have relative higher amounts of measured sediment and plot 5 has one extreme erosion value of 1374 g/m^2, with a corresponding moderate runoff of 7.19 mm. Plot 6 has low amounts of sediment, even while the corresponding amounts of runoff are high. The sediment-runoff trend on plot 1 and 2 is a bit stronger than the trend on plot 4, suggesting the combined effect of trees and terraces does have its effect on erosion. Evaluating figure 12, it seems that well-planted grass strips have a large influence on the reduction of erosion whereas the erosion on the plots with no SLM or poor SLM increases much more with increase in runoff.

Soil characteristics

Table 3 represents the particle size distribution of the six plots, showing high contents of clay and sand. Plot 1, 2, 3, 4 and 6 were classified as clay, but with still high amounts of sand and silt. Plot 5 was classified as sandy clay. Porosities range from 0.434 to 0.560, with plot 1 clearly having the lowest value.

Table 3: Soil characteristics for the six research plots estimated in the laboratory.

	% clay (<2 μm)	**% fine silt** (2-20 μm)	**% coarse silt** (20-50 μm)	**% sand** (50-2000 μm)	**Porosity** [-]
Plot 1	47.50	12.75	3.75	36.00	0.43
Plot 2	48.00	12.25	2.25	37.50	0.51
Plot 3	48.25	13.75	2.25	35.75	0.54
Plot 4	50.00	12.75	2.75	34.50	0.52
Plot 5	37.75	7.75	3.00	51.50	0.55
Plot 6	44.00	9.75	4.00	42.25	0.56

Soil surface characteristics

Table 4 describes the soil surface characteristics and the method with which the values are estimated. The first value in a column represents the parameter value for the entire plot without SLM or for the beds when the plot has terraces or grass strips. The second value represents the value for the plot's risers and grass strips.

Plot 3 has the most extreme values for spacing and relief, vegetation cover and interception (which is the averaged value for the entire field, so it is already multiplied by cover fraction). Plots 5 and 6 have more gentle slopes. A very small rock fraction is found on plot 1 and 2 and Mannings *n* is lowest for plot 3 and the beds of plot 2, 5 and 6.

Table 4: Soil surface characteristics for the six research plots; the second value in a column represent the value for the risers

	Rock [-]	**Slope** [º]	**Relief** [mm]	**Spacing** [m]	**Man n** [-]	**Cover** [-]	**Interception** [mm]
Source	Visual	Clinometer	Visual	Visual	Literature	Visual	Literature
Plot 1	0.1	30º	80	0.25	0.20	0.65	0.86
Plot 2	0.05	29º	20/10	0.30/0.20	0.06/0.11	0.43/0.35	0.44/0.81
Plot 3	0.0	34º	140	0.60	0.06	0.17	0.28
Plot 4	0.0	32º	40/20	0.30/0.20	0.25/0.11	0.65/0.40	0.93/0.92
Plot 5	0.0	20º	30/10	0.30/0.10	0.08/0.10	0.35/0.35	0.37/0.61
Plot 6	0.0	21º	30/10	0.25/0.10	0.07/0.19	0.57/0.90	0.60/2.07

It should be noted that, while the field research was done at the end of 2011, the rainfall and Gerlach data and thus the model runs are for the short rain season of 2010. This gives some uncertainty in especially the vegetation-dependent parameters like cover fraction, interception and Mannings *n*. Trees and grass are expected to remain constant throughout the year. The main vegetation types that can drastically increase or reduce in a year are beans and weeds, but those two often replace one another and their Manning's n, cover and interception depth are similar. The impact of change in vegetation during the rain seasons on KINEROS2's input parameters is probably small; however, the change in vegetation from the dry season to the rain season will be larger, although the amount of crops planted in the short rain season is not very high. In this research, the vegetation is considered constant throughout the entire period.

Cohesion

Measured cohesion values range from 2.2 to 14.2 kPa and averages per plot range from 4.9 to 8.8 kPa, with plot 2 having the highest cohesion and plot 5 the lowest cohesion. Because of the higher variation in samples within the plots than the variation between averages of the plots, the average of all values, which is 6.73 kPa, was used for all plots.

Saturated Hydraulic Conductivity and its Coefficient of Variation

Infiltration rates during infiltration measurements were very high at the start, from 100 to even 300 mm/h but after 1½ hour reached equilibrium. Most K_s values were about 50 to 90 mm/h, with a total range of 33 to 193 mm/h and in one case infiltration decreased to 16 mm/h right from the start because of a clay lense at 15 cm depth from the soil surface at plot 1. Average values for the six plots range from 63.5 to 122.8 mm/h with a coefficient of variation of 0.3. The variation of K_s in the six plots is as large as the variation between the plots, so no specific K_s per plot was calculated. The average K_s for all measurements was 80.4 mm/h. K_s in general is known to vary widely. In the Usambara Mountains, Lundgren (1980) measured K_s values of 270 mm/h for badly eroded agricultural land in the using a double ring infiltrometer. The KINEROS manual (Woolhiser, 1990) uses much smaller values ranging from 4.3 to 2.3 mm/h for (sandy) clay loam. These values for K_s may differ due to differences in soil type, but also due to inaccurate measurements with the double ring infiltrometer by disturbance of the soil or not keeping the water level of the outer ring constantly equal to the water level of the inner ring.

Soil Moisture and Depletion Factor

Initial soil moisture contents could not be used directly for input in KINEROS2 because of not matching with the data of the rainfall and Gerlach measurements which are from the earlier year 2010. Instead, the soil moisture contents were used to calculate a depletion factor. Figure 12 shows the average relative soil moisture contents (soil moisture as fraction of pore space) of the six plots during nine days of measurements. The relative soil moisture content in general is low; between 0.1 and 0.4, while the soil in general should not be considered very dry because in the two weeks before the measurements several rain events occurred. The soil moisture content is measured in the upper 5 cm of the soil; the part which is most susceptible to drying of the sun. Probably lower soil layers have higher soil moisture content.

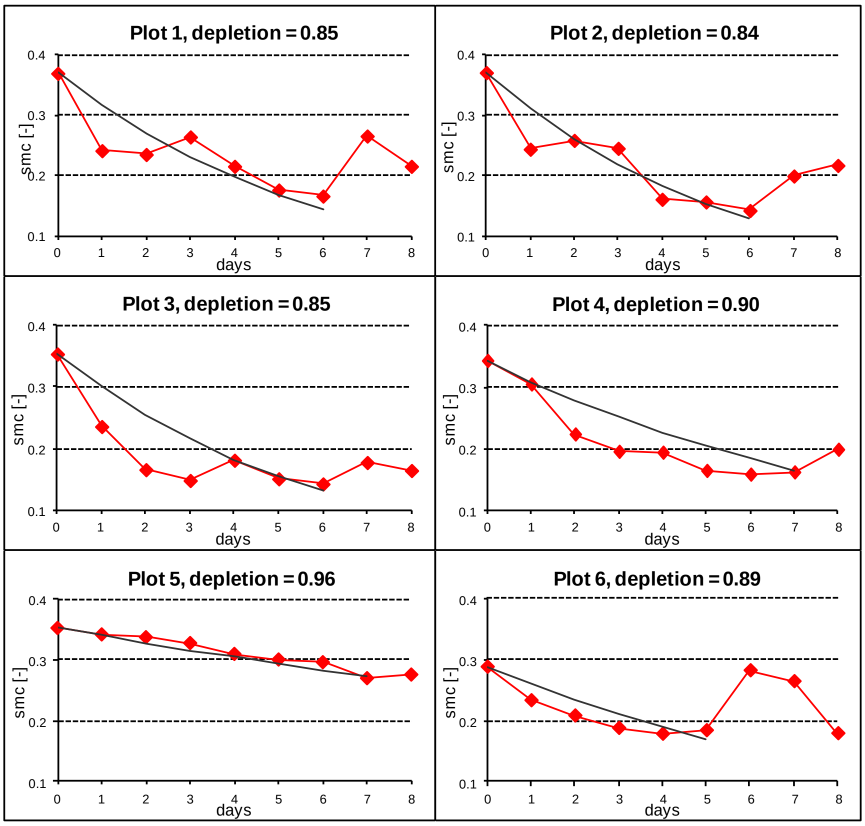

Figure 13: Actual soil moisture contents with time (dotted line) and corresponding constant depletion (solid line).

Small increases in soil moisture are considered to be variation due to measurement errors; larger increases are due to rainfall and therefore mark the end of the period suitable for calculating the depletion factor. The average depletion factor calculated from daily relative soil moisture contents is 0.88 (figure 13). Prominent is plot 5 with quite a higher soil moisture content and depletion factor than the other plots. Plot 1, 2 and 3 have the lowest depletion factors.

Pore Size Distribution Index and Capillary Drive

The optimal pore size distribution index λ and air-entry value h_a (calculated using the two formula's for effective saturation as described in paragraph 2.3) were 0.0647 and 0.001 resp., with an RMSE of 0.095. The capillary drive G was calculated to be 29 mm. Woolhiser et al. (1990) mention averages for G of about 812 mm (arithmic mean) and 375 mm (geometric mean) for silty clay textures but with large standard devations of more than 250 mm.

3.1.1 Transect

Transect measurements are plotted in figure 14-17 and averages and standard deviations of the parameters measured in the transect are shown in table 5. The figures show scattered measurements with a certain degree of variation but without a clear trend. Cohesion (figure 14) may slowly decrease with increase in distance while bulk density (figure 15) and soil texture (figure 16) represent an approximately horizontal line. The graph of K_s (figure 17) is more difficult to interpret due to 3 or 4 of the 13 sample points which have large deviations from the average and show no clear horizontal line or other trend. In order to draw valid conclusions for K_s, a larger data set is needed.

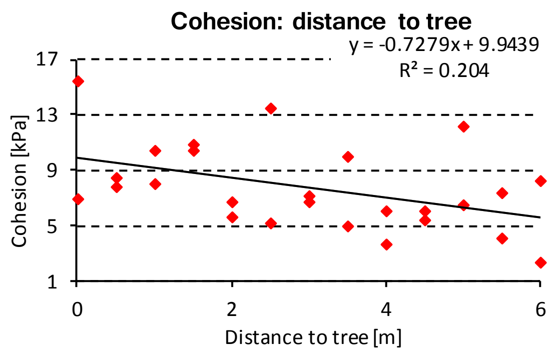

Figure 14: Variation of cohesion with distance to tree.

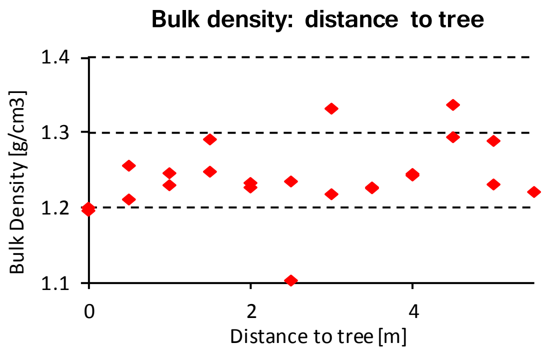

Figure 15: Variation of bulk density with distance to tree.

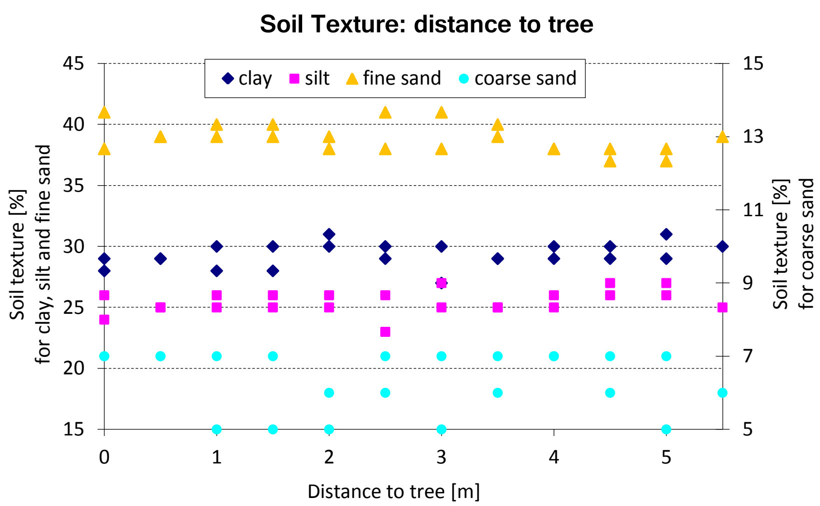

Figure 16: Variation in soil texture with distance to tree. Right y-axis: percentages of clay, salt and fine sand. Left y-axis: percentages of coarse sand.

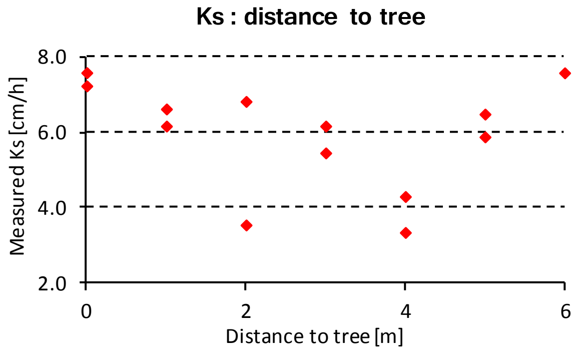

Figure 17: Variation of saturated hydraulic conductivity with distance to tree.

The results in table 5 show that the means of bulk density, texture (only the particle size classes with more variation are discussed) and K_s lie within one standard deviation of each other. The variation of the K_s in these transect measurements is equal to the variation of K_s within the different research plots. Only the means and standard deviations of cohesion are less similar, with cohesion closer to the tree being higher. It is within one standard deviation of the other mean when using the first standard deviation, but when using the standard deviation of the measurements with distance to the tree, the two means differ a little bit more than one standard deviation. Calculating the averages and means of the parameters with the division at closer or further distances than 2.5-3 m only gave less significant differences between both parts.

Table 5: Averages and standard deviations for measurements close and with distance to a tree

		Avg 0-2.5m	**StDev** 0-2.5m	**Avg** 3-6m	**StDev** 3-6m
Cohesion		9.15	3.11	6.52	2.53
Bulk density		1.22	0.046	1.26	0.045
Texture	clay	29.3	0.97	29.4	1.03
	silt	25.2	0.94	25.8	0.88
	fine sand	39.3	1.06	38.5	1.21
Ksat		6.34	1.45	5.61	1.41

Results of these transect measurements show no significant relationship between the measured parameters and distance to tree. But care must be taken to conclude there is no relationship in this particular research with *Grevillea* trees, as much research have determined some influence of trees on soil characteristics. For *Grevillea* trees, Livesley et al. (2004) found an increase in soil content of 1-2 % within 75 cm distance to the trees. Omoro and Nair (1993) did not find influence of *Grevillea Robusta* on bulk density nor infiltration. They suppose that the shape of *Grevillea* leaves fallen on the soil surface makes infiltration less easy than leaves of some other tree species do. However, their measurements and information on these two parameters were very brief. Other studies did find influence of trees in general on bulk density (Guto et al., 2011; Seobi et al., 2005). The addition of leaves to the soil increases organic content, increases porosity and decreases bulk density (Yao et al., 2009). Perhaps the trees in the research area produce relatively little litter because the trees are pruned; this would partly be an explanation for the independency of both the infiltration and bulk density on distance to a tree. The tree's roots can also increase infiltration of water, but Grevillea trees are reported to have relatively deep roots even in shallow soils (Howard et al., 1996). The independency of bulk density to trees does not exclude the dependency of porosity to trees, but it does make it very unlikely because the two parameters are closely related. The only other factor influencing porosity and likely to be dependent on tree distance is organic content, which could decrease bulk density closer to trees and at the same time increase porosity. An effect like this however is not found in this research.

3.1.2 Incorporation of SLM types

The current research results combined with other literature, did not give conclusive arguments to assume that the influence of *Grevillea Robusta* on the soil characteristics is significant and a possible degree of influence is not know (which is needed for implementation in the current research). More detailed research on this subject could give more insight and information on the processes and influence of *Grevillea* on hydraulic conductivity, bulk density and cohesion. In the current research, the trees will be implemented in the model not as an individual element, but as part of a homogeneous element with their cover fraction and interception averaged for the entire plot and cohesion, porosity, texture and K_s being the values as measured on the plot.

The transformation of the various soil conservation measures into the input files required by KINEROS2 will be a simplification of the reality. The input elements defined for terraces and grass strips have sharp and straight boundaries which allow no gradual variation in parameters. If spatial dependency of trees would be determined, it would still be difficult to implement this correct in the model without making simplifications. The homogeneity of the elements does not account for preferential flow through one or several rills and through a weakness in a terrace's riser or grass strip. Variation in hydraulic conductivity is accounted for in the model, but all other parameters do not vary within an element.

Beside erosion models which use elements as input like in KINEROS2, there are also some models which use grids and a DEM (digital elevation model) to define spatial characteristics (Rojas et al., 2008). This might result in better modeling of the spatial interaction between different structures, but these models often aim at large scale modeling, with grid sizes of several meters to hundreds of meters while a grid size of about 10 cm is desirable for the modeling of single soil conservation measures.

The possibility of including microtopography, sediment classes, a two-layered soil profile and channel and pond elements in KINEROS2 are options of value for more detailed runoff and erosion modeling. Although not used in this research, channel and pond elements can be very helpful in defining soil conservation measures like ditches and reservoirs.

3.2 Calibration

Calibration of KINEROS2 is done using the control plots 1 and 5. During the testing of the KINEROS2 model and evaluating basic input variations and its results, the model showed some singularity. With higher values of G or K_s (for about K_s = 80 and G = 40 or higher this occurs), KINEROS2 modelled some amounts of runoff while it is not expected. This runoff starts only after the rainfall has already ceased (table 5) and seems not related to infiltration or saturation excess. For the same event with K_s well below the peak intensity, runoff starts around the 3rd or 4th time step and peak runoff occurs 10-15 minutes after the peak of rainfall.

Table 6: Detailed output for runoff and sediment per time step for plot 1 with G = 50 mm, Ks = 80 mm/h, ismc = 0.5 and peak intensity 20.81 mm/h.

Time [min]	Rainfall [mm/h]	Outflow [mm/h]	Sediment [kg/s]
0	0.0000	0.0000	0.000000
5	0.5075	0.0000	0.000000
10	2.2015	0.0000	0.000000
15	5.7870	0.0000	0.000000
20	15.9700	0.0000	0.000000
25	20.8100	0.0000	0.000000
30	16.8800	0.0000	0.000000
35	12.9600	0.0000	0.000000
40	9.0300	0.0000	0.000000
45	5.1000	0.0000	0.000000
50	1.1800	0.0000	0.000000
55	0.0000	0.1253	0.000024
60	0.0000	0.1250	0.000024
65	0.0000	0.1241	0.000023
70	0.0000	0.1217	0.000023

Microtopography could delay runoff, reducing the water flow by its spacing and relief. But test runs with zero microtopography or with large microtopography gave the same delay in runoff, only changing the amount of runoff (because of water retention and change in area exposed to infiltration). G and K_s are both related to infiltration and distribution of water through the soil; perhaps their large values create difficulties calculating the redistribution of soil moisture. Whatever the reason is, this model behaviour makes the calibration complex. By keeping the duration of modelling short (a few minutes longer than the duration of the rainfall), it is tried to reduce the modelling of false runoff as much as possible.

3.2.1 Calibration of control plots

Plot 3 is the most erosive plot, with no SLM, only one tree and some weed, very steep slopes, no terraces and the most pronounced gullies. This plots showed no useful actual runoff and erosion data (as explained in paragraph 3.1) so it was not used for calibration. Plot 1 was used as the control plot for plot 2 and 4.

Depletion factor, soil moisture and soil thickness are evaluated on plot 1 and 5. RMSE values for both plots are weakly related to these parameter values and are tending towards the most extreme values that result in more runoff; apparently the model still underestimates runoff for some events even with a fixed optimal G and K_s. Too high levels of Df, SA and T will lead to totally saturated conditions which are unrealistic and KINEROS2 cannot handle. So the parameters for all plots were fixed at high but more realistic values of Df = 0.93, SA = 0.6 and T = 90 mm.

Calibration plot 1

A calibration run of plot 1 with only varying K_s and G shows RMSE values that are between 3 and 8, with a clear dip for K_s at about 18 mm/h and an RMSE of 2 mm (figure 18). The high level of RMSE for K_s values of 30-40 can be explained by the fact that the largest events still model infiltration excess and other events already have no runoff while they both have about the same measured amounts of runoff, thus showing large variation between measured and modelled runoff. Once K_s exceeds the rainfall intensities of these events with too high modelled runoff, the RMSE decreases again. Values for G vary little and do show a trend in the RMSE calculated for all Gerlach periods together, but this trend is not clearly visible in the RMSE calculated per parameter combination. Evaluating the model output for every single rainfall event, an increase in G shows a decrease in runoff for large events because the higher G enhances the distribution of water by capillary action and increases the initial infiltration rates before K_s is reached, thus levelling the more extreme events. To obtain the optimum for G in combination with the optimum K_s, again a calibration is run with K_s fixed at 18 mm/h. The results then show a more or less horizontal trend from 70 to 100 mm; G is fixed at 81 mm, the lowest value closest to the measured value.

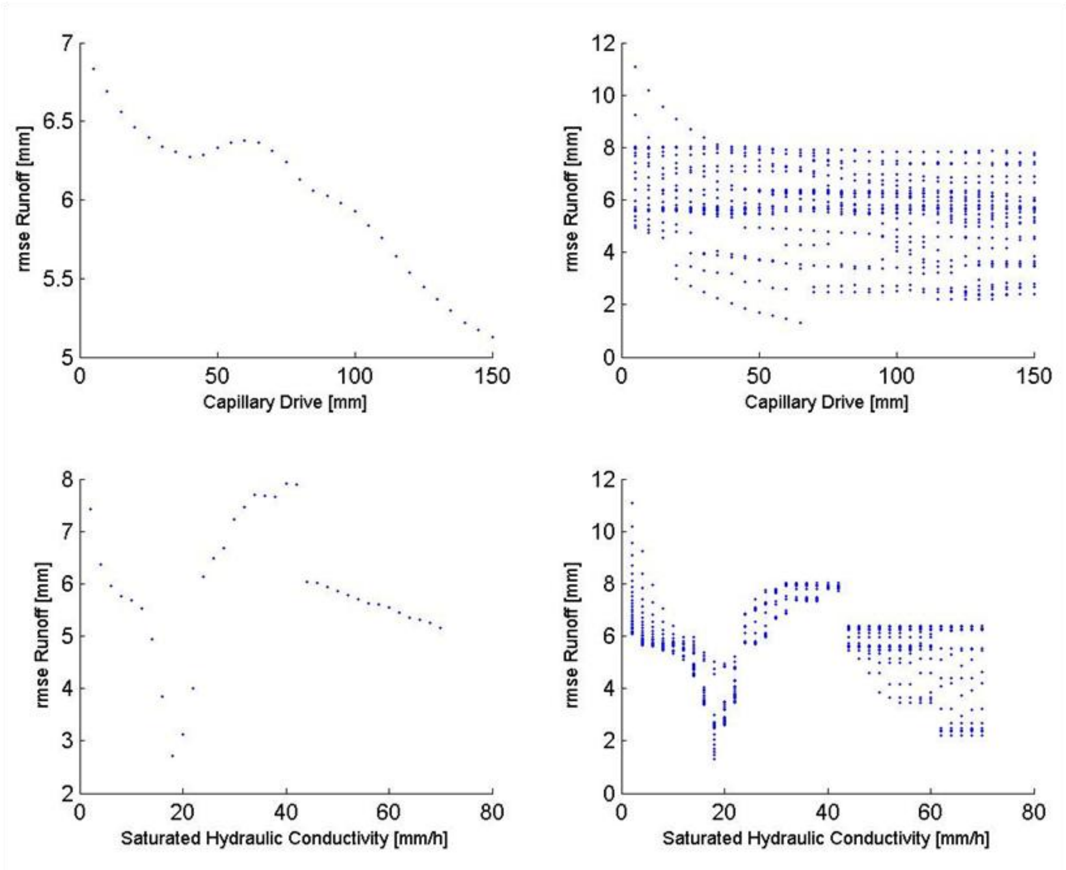

Figure 18: Runoff calibration of plot 1 with varying K_s and G; left RMSE for all Gerlach periods together and right RMSE per parameter combination

Second, a calibration run for cohesion and splash detachment coefficient had been run. Cohesion showed a neat hyperbole trend with optimum at 0.5 (figure 19a) while splash detachment varied less. After fixing cohesion, the splash detachment did vary only very little, with an optimum at 40 s/m (figure 19b). Remarkable is that with a larger increase of cohesion (exceeding the optimum value), the modelled amount of erosion also increased. When soil particles stick stronger to each other, a decrease in erosion is expected. But the particle size distribution classes in KINEROS2 make it possible to model erosion explicitly for the smaller and larger grain size particles. An increase in cohesion results in forming miniscule aggregates of the small particles which still are transported quickly when runoff flow is strong enough. Detailed output of KINEROS2 shows indeed that with an increase in cohesion, an increase in erosion of the smallest particles is modelled. Relative larger erosion rates of the smaller particles are consistent with measurements on the research plots, which show that the upper 15 cm of the soil have lower percentages of clay and higher percentages of sand, as the clay has already been eroded more.

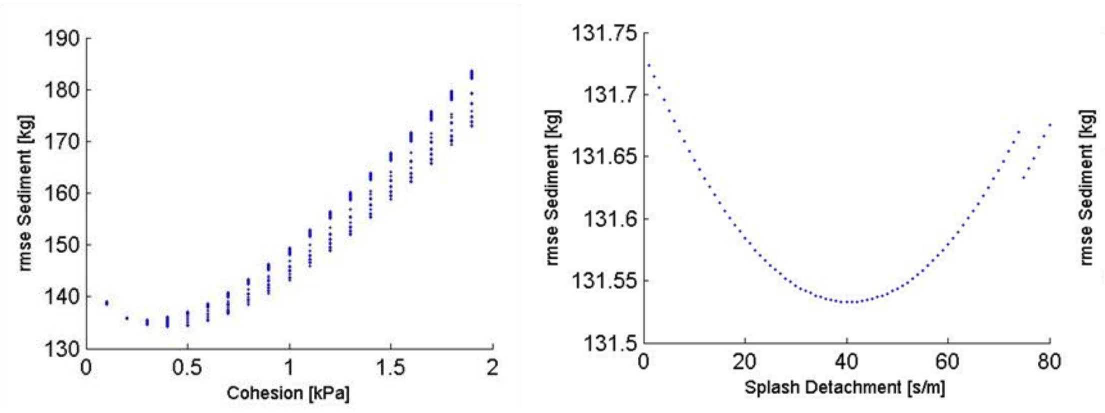

Figure 19: Calibration for erosion of plot 1 with a) cohesion, with RMSE per Gerlach period and b) splash detachment with cohesion= 0.5

Calibration plot 5

For plot 5, the K_s, G, C and S were determined in the same way as for plot 1. Optimum K_s for plot 5 is less clear than on plot 1 (figure 20a); the lowest RMSE values are around 13-14 and the optimum is fixed at 14 mm/h.

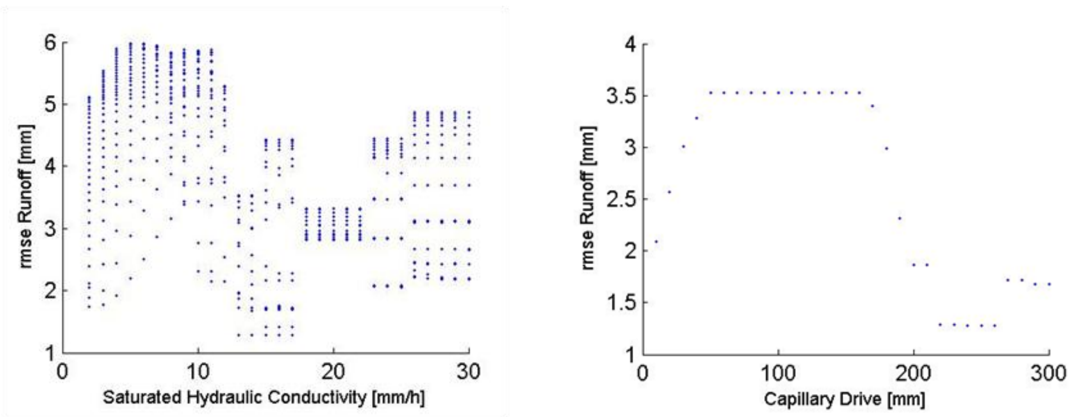

Figure 20: Calibration for plot 5, with a) K_s showing minimum RMSE's around 14 mm/h and b) G dipping at 262 mm after K_s is fixed

Around 20 mm/h, a narrow band of RMSE values is shown; for these values, the increase in K_s has no influence on the RMSE. Two underestimated events (increasing RMSE with increase in K_s) levels a slightly overestimated event (decreasing RMSE with increase in K_s) in the calculation of the RMSE. At K_s higher than 22 mm/h, the peak intensity of one of the events is exceeded by K_s resulting in no runoff, the other events changes from being overestimated to being underestimated and the balance of all events together shifts. This is similar to the high and narrow band of K_s between 30 and 40 mm/h for plot 1. For both plot 1 and 5, K_s is the strongest parameter in calibration, which suggest that infiltration excess is the dominant processes in generating runoff. The optimum G is high, at 262 mm (figure 20b).

One Gerlach period had extremely high amounts of measured sediment, which largely influenced the calibration plots. This event was excluded from calibration, which did not change the trend of the calibrations much, but it did improve the RMSE by decreasing it with about 250 kg. The calibration for erosion parameters of plot 5 (figure 21), has a low optimum splash detachment at 4 s/m, but the optimum for cohesion is very large, at 225 kPa.

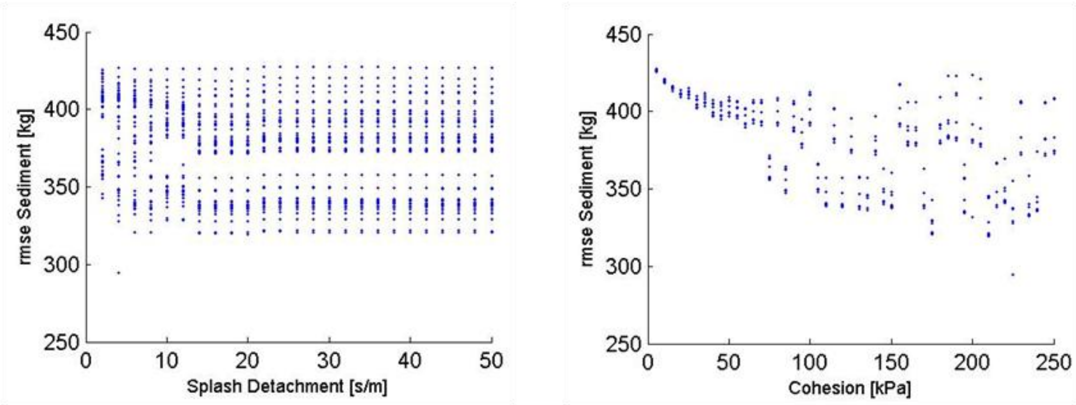

Figure 21: Calibration for plot 5 with a) splash detachment and b) cohesion

3.2.2 Evaluation of calibrated parameter values

Table 6 sums the measured values and the calibrated values of the parameters used for calibration, including its RMSE's. In order to be able to compare the different plots, the total sediment and RMSE for sediment is converted to kg/m^2. The calibrated K_s is much smaller than measured in the plots. This might be due to the method used to measure K_s. The infiltrometer is known for disturbing the soil upon installing the device, and creating cracks in the soil or space between the soil and the metal ring that enhance infiltration rates. Moreover, soil textures like the ones in this research, which are a mix of relatively coarse particles and small particles, are susceptible to slaking and sealing of the soil. When measuring infiltration with the double ring infiltrometer, the soil experiences less splash detachment and thus less break-up of aggregates and sealing of the soil. This explains the small values of modeled K_s compared to measured values. According to Woolhiser et al. (1980), values of 14-18 mm/h are higher than values associated with clayey soil types and belong to a loam or sandy loam soil. But as stated before, ranges of K_s are generally wide and the soils in the research area are well structured, improving K_s.

Table 7: Measured and calibrated parameters with corresponding RMSE's

	Ks [mm/h]	G [mm]	C [kPa]	S [s/m]	RMSE Q [mm]	Q tot [mm]	RMSE S [kg/m^2]	S tot [kg/m^2]
measured								
Plot 1	80.4	29	6.73	50	6.02	0.00	0.29	0.00
Plot 5	80.4	29	6.73	50	4.41	0.03	0.34	0.00
calibrated								
Plot 1	18	81	0.5	40	0.66	39.6	0.17	1.48
Plot 5	14	262	225	4	0.79	23.5	0.21	0.72

Calibrated capillary drives are higher than the measured values, with 81 mm for plot 1 at the minimum end of values mentioned in literature for sandy loam soils, and with the value of 262 mm for plot 5 being representative for clay loam soils (Woolhiser et al., 1990).

Measured and calibrated cohesion differ also, with the calibrated cohesion of plot 1 being more similar to the values measured by Wickama (2010); at the end of the rain season he measured cohesion in the range from 0.27 to 0.53 kPa. Values according to the EUROSEM user guide are more than a factor 10 larger; about 8-10 kPa for clayey uncompacted soils (Morgan et al., 1998). The cohesion value of plot 5 is well outside the range of literature values, which raises the question whether this value is still realistic.

Splash detachment is lower than the default value, suggesting that soil aggregates are more stable than on a moderate soil (without distinguishing between sand and clay soil). Heppner et al. (2005) estimated splash coefficients of 0.6-7.8 for silty clay loam soils using a best-fit with ground coverage (grasses). KINEROS does not use ground cover to correct for splash detachment; only water depth reduces splash erosion. The effect of vegetation on damping splash detachment is of course dependent on the type of vegetation, with vegetation allowing for much throughfall or gathering of larger raindrops having a rather enhancing effect on splash detachment. With the unrealistic high value for cohesion and the low value for splash detachment, plot 5 seems to strive to very small erosion values.

Plot 1 and 5 have similar values for calibrated K_s, but especially G and C are very different with values for plot 5 being much higher. The actual Gerlach data (figure 11 and 12) already showed that plot 5 has larger runoff with similar rainfall and a stronger increase of erosion with runoff. The higher values for G and C probably compensate for this difference. The calibration, with few and divided calibration events (missing events in the mid-range section) may also be less suitable to correct for uncertainties in the Gerlach measurements, rainfall data and differences in the Gerlach periods.

The calculated RMSE's of runoff show a large improvement before and after calibration. Modelled runoff amounts are in the order of 0-8 mm per event, so the RMSE being smaller than 1 is good. The RMSE's of sediment also decrease after calibration, but less dramatically considering that most measured total sediments range from almost zero to about 0.6 kg/m^2.

From the plots of modelled sediment against measured runoff and sediment (figure 22) can be seen that especially the larger events are underestimated for erosion. Plot 5 has a poor data set for calibration of erosion, with three very small events and 2 much larger events which does not allow to calibrate for the mid-range section of erosion. Underestimation of erosion on plot 5 may also be caused by a second parameter combination optimum of cohesion and splash detachment which is not found in the calibration. This may be due to too large calibration steps or a calibration range that was not wide enough.

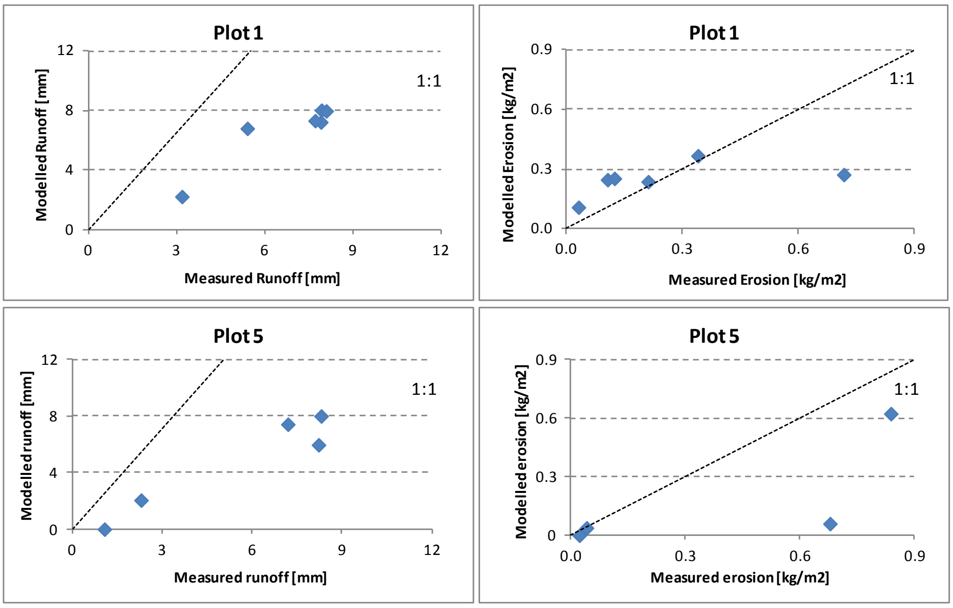

Figure 22: Modelled against measured runoff and erosion for plot 1 and 5

3.3 Validation

For the validation plots, a run was made using the calibrated parameters to evaluate the performance of SLM types in KINEROS2. For plot 2 and 4 the parameter optimums of the calibration of plot 1 was used and for plot 6 the parameter optimums of the calibration of plot 5 was used.

3.3.1 Grass strips plot 6

Plot 6 was first run with K_s identical for the beds and grass strips of the plot. After this, some runs with different K_s for the grass strips have been done to determine an optimal value of K_s for the grass strips. The run of plot 6 using single K_s shows some events with highly overestimated erosion while most events are similar to measured erosion. The modelling of plot 6 with an increase in K_s for grass strips reduces the extreme erosion events: a Ks of 18 mm/h (an increase of ~29% compared the standard K_s of 14 mm/h) gives most satisfying results, with an RMSE of 0.20 kg/m^2 for erosion while the run without correction of K_s resulted in an RMSE of 0.56 kg/m^2. Total runoff amount did slightly increase with 0.6 mm, so apparently the increase in hydraulic conductivity did decrease erosion but did not increase the amount of infiltration. Evaluation of the initial soil saturation value per event shows that runoff was generated due to infiltration excess. The increase in K_s probably leads to a decrease of the ponded water depth, which negatively affects the infiltrability of the soil. At a lower water depth, microtopography can also decrease the amount of infiltration and increase runoff because a smaller fraction of the soil surface is exposed to infiltration. And with a decrease in water depth, the flow velocity, sediment capacity and thereby erosion decreases.

3.3.2 Validation of plot 2, 4 and 6

Validation graphs with modelled against measured runoff and sediment are shown in figure 23. The RMSE's calculated for the validation plots are shown in table 8 again with total sediment and RMSE of sediment calculated in kg/m^2.

Plot 2 has reasonable predicted runoff, with values in the same order as measured but still with some deviations which results in moderate RMSE for runoff of 2.27 mm on a total runoff of 27.9 mm. The extreme measured runoff value that was shown in figure 11 with a measured runoff of 9.7 mm is being underestimated. Predicted erosion on plot 2 is higher than measured, with one extreme event being 7 times larger than measured and the other events moderately overestimated resulting in an RMSE of 0.62 kg/m^2 with total sediment 4.73 kg. Both measured runoff and erosion on plot 2 are similar to those on plot 1. Compared to plot 1, plot 2 has lower relief and vegetation values (Mannings n, vegetation cover and interception). Lower relief decreases runoff and erosion by increasing the area exposed to infiltration, lower Mannings n increases flow velocity, transport capacity and erosion and lower interception increases effective rainfall and runoff. Perhaps the increased infiltration due to lower relief equals out the increase in runoff due to flow velocity increase, while the increase in flow velocity still does increase sediment transport. Second, during the plot measurements for the input data plot 2 was measured with the highest average value for cohesion but because of the higher variation within plots than between plots, the cohesion values were averaged for all plots together. These validation results might indicate that this higher measured value for cohesion of plot 2 was a good estimate of reality and this may be the cause of the actual erosion being lower than the modelled erosion. In order to affirm this statement, additional measurements of cohesion should be taken for plot 2 as well as for the other plots, to determine more exactly the averages and the variation in cohesion. Additional measurements because of variation will be more important because a set of 4 measurements with high values for cohesion can be coincidence and not representative of the variation on the plot.

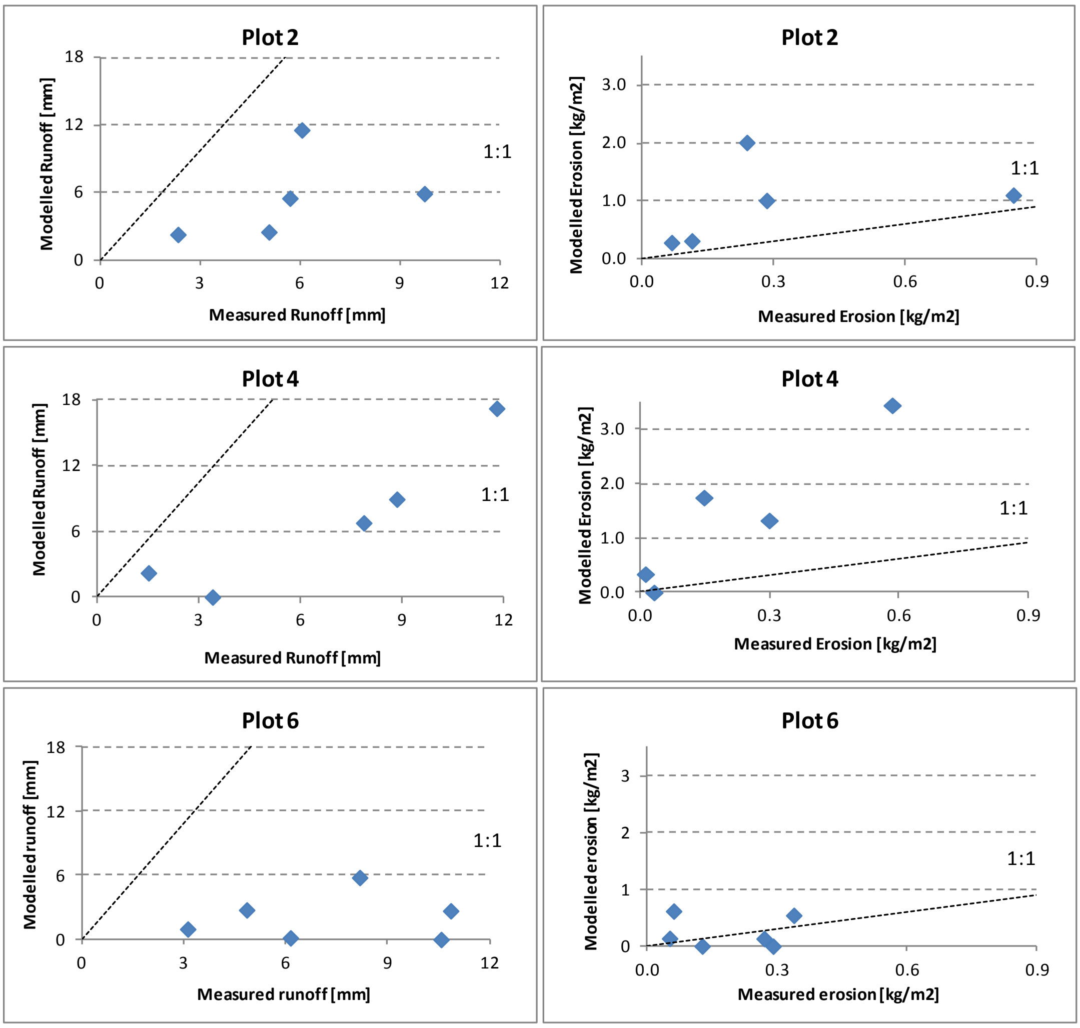

Figure 23: Measured against modelled runoff and erosion for the validation plots

Runoff for plot 4 is well predicted, with modelled events in the some order as the measured events and an RMSE of 2.07 mm with total runoff 35.2 mm. Erosion on plot 4 is largely overestimated, with the RMSE of 1.08 kg/and total sediment of 6.84 kg/m^2. Measured erosion rates on plot 4 were lower than measured erosion on plot 1, which can be part of the explanation of overestimation of erosion. But due to the presence of the high density of vegetation and terraces, much lower modelled erosion was expected. From the modelling results described per input element, it is shown that erosion is much larger on the terrace's risers than the deposition on its beds, with negative deposition values on the risers and smaller positive deposition values on the beds. Runoff amounts on the risers are similar to those on the beds. The increase in sediment transport evolves along the different connected elements downwards until the last element experiences large amounts of output sediment. Apparently the slope on the terrace risers increases flow velocity and transport capacity that much that, according to these modelling results, erosion is enhanced due to the construction of terraces. This is why plot 2 and plot 4 both model an overestimation of sediment values. It raises the question whether the slopes of the risers are steep enough for other factors to become important for influence on erosion, like falling instead of flowing of the runoff water and relief and spacing values that should be much higher because runoff is not likely to have any chance of infiltration. Ribolzi et al. (2011) studied the difference in runoff on slopes of 35 and 75%, and found that the very steep slopes experienced more infiltration and were less erodible due to the formation of micro relief and more permeable structural crusts. The specific modelling of very steep slopes of terraces and its risers in KINEROS2 would be an excellent topic for further research.

Plot 6, validated with the calibrated parameters of plot 5, shows underestimated values for runoff with RMSE 4.78 and total runoff 12.4. While the measured runoff of plot 5 and 6 are in the same order of magnitude without showing any effect of grass strips on runoff amount, the implementation of grass strips in KINEROS2 results in smaller modelled runoff – as would be expected. Plot 6 probably has smaller K_s than the calibrated 14 mm/h, or the estimated values for vegetation cover should be reduced for a correct prediction of runoff. Erosion is more or less predicted around the 1:1 line, but with large scattering of the values. From the underestimation of runoff of plot 6 can be concluded that, in case of correct prediction of runoff, the erosion rates would be overestimated and thus the calibrated erosion parameters of plot 5 are too high for plot 6. From the calibration of plot 5 it was clear that erosion on plot 5 was a bit underestimated using the optimum parameters estimated from calibration. Lower calibrated splash or cohesion that will lead to optimal erosion for plot 5, will lead to higher overestimated erosion for plot 6. Probably the damping of splash detachment by ground coverage as determined by Heppner et al. (2005) would decrease erosion rates on the grass strips of plot 6 as well. Detailed runoff results also showed that on a grass strip of 1 m with a slope of 78°, the effective rainfall is equal to the rainfall minus interception. This means that KINEROS2 does not correct rainfall for the slope of the element, while the horizontal area of a slope of 78° is only 20% of its total length and therefore will receive less rainfall. Of course, rain does not always fall straight down from the air but uncertainty due to variation in rainfall direction is inevitable while variation in the amount of rainfall catched by a sloping soil is something the model can account for.

Total amounts of runoff and sediment for the entire period for actual, minimum and maximum vegetation cover are also included in table 7, in order to evaluate the performance of the model within this range. The erosion rates summed in table 7 only account for the events used for calibration, which is about two-third of the total events during the short rain period. The actual runoff and sediment amounts for plot 2, 4 and 6 all lie between the minimum and maximum vegetated values, as was expected. Minimum and maximum total runoff for plot 4 and 6 vary greatly. Erosion rates especially for plot 6 are very high, suggesting that this plot is more susceptible to erosion. But measured erosion values state that plot 6 experiences equal amounts of erosion as the other plots. A run for plot 6 with calibrated parameters of plot 1 and increased K_s for grass strips of 20 mm/h, does show even worse predictions with an RMSE of 4.6 mm for runoff and 0.64 kg/m^2 for sediment and a duality in results with two much higher erosion events and the other events being almost zero. Measured erosion rates for the entire season are in the order of 1-2 kg/m^2 and therefore similar to the maximum rate of 1.72 kg/m^2 Vigiak et al. (2006) measured in the Kwalei catchment in the Usambara Mountains.

Table 8: RMSE's and total runoff and sediment for the validation plots with actual, minimum and maximum vegetation cover and measured values.

	RMSE Q [mm]	Qtot [mm]	Qtot [mm]	Qtot [mm]	Qtot [mm]	RMSE S [kg/m^2]	Stot [kg/m^2]	Stot [kg/m^2]	Stot [kg/m^2]	Stot [kg/m^2]
	actual	actual	min	max	meas.	actual	actual	min	max	meas.
Plot 2	2.27	27.9	33.0	14.3	28.9	0.62	4.73	13.51	2.55	1.54
Plot 4	2.07	35.2	49.9	6.4	33.4	1.08	6.84	21.5	2.42	1.08
Plot 6	4.78	12.4	43.8	6.8	43.7	0.20	1.23	32.44	0.64	1.14

4 Conclusions

This research focused on the implementation of different SLM types in the KINEROS2 model in order to adapt a physics-based model in such a way that it can predict the effects of different types of sustainable land management on changes in runoff and soil erosion. Its objectives were to collect input data for KINEROS2, incorporate the SLM types in the model, calibrate the most important parameters using control plots and apply the model with calibrated parameters on plots with different types of SLM.

KINEROS2 is especially suitable for short-term modelling and therefore requires time-detailed data concerning rainfall, actual runoff and erosion and soil moisture content. In the optimal situation, soil moisture contents would have been measured every day in November and December 2011 and rainfall and runoff data would be from the same year. Because the Gerlach data from the end of 2011 was not yet available, the data from the year before was used and the calculated soil moisture content and depletion factor was applied as an estimated value, which worked out well in the calibration. For other research with KINEROS2, with no possibility of calculating every single antecedent soil moisture, the method with depletion factor as used in this research is recommended. The lack of actual data also might have small influence on vegetation cover, interception depth and Mannings *n*.

The conversion from 1-hour to 5-minute rainfall data is rough and estimated peak intensities may differ from reality, as can be seen from the confidence interval graph of the Kwalei data. The Gerlach data also is not very time-detailed as it was not emptied every day and time was not recorded so it was sometimes difficult to assign a certain rainfall event to the correct Gerlach period. Moreover, Gerlach periods did differ between the plots, so a profound comparison of Gerlach periods in the results of the calibration was not possible. The effect a certain rainfall event might have or an error in single rainfall intensities or Gerlach periods could therefore not be revealed. Due to the selection of Gerlach periods with runoff coefficient higher than 0.15, the amount of periods (5 or 6 per plot) used for calibration was not much and a single extreme or duality in the data can have large influence on the calibration and makes it more difficult to draw conclusions. For a better quantification of the impact of SLM on runoff and erosion modelling in KINEROS2, a larger dataset with more and more detailed Gerlach events should be the primary point of interest.

From the actual data on runoff and erosion, plot 1, 2 and 4 showed a certain increase in runoff with increase in rainfall, while runoff on plot 5 and 6 seems to be more random and not specifically related to rainfall. On all plots, erosion does increase with increase in runoff. The plot with grass strips has the lowest amounts of erosion, while the plot with only poor grass strips has the highest amounts of erosion. Erosion on the other plots with SLM ranges between those two plots. The reduction of erosion is what is expected from plots with sustainable land management. Apparently the terraces and vegetation slow down runoff water enough to decrease soil detachment and transport but the fact that the amounts of runoff does not decrease as well, means that infiltration does not increase by slowing down runoff velocity. This might be due to the supposed occurring of slaking by rain drops, which seals the soil against further infiltration.

This study measured no significant influence of the trees on soil characteristics as bulk density, porosity, soil texture and saturated hydraulic conductivity. Other studies do suggest the influence of trees on these parameters. Possibly, the implementation of agroforestry as single trees in KINEROS2 will reflect reality better than by the method used in this research. But for such implementation, a quantification of the dependency needs to be estimated first in further research.

The transformation of the various soil conservation measures into the input files required by an erosion model will always be a simplification of the reality. The input elements defined in KINEROS2 have sharp and straight boundaries which allow no gradual variation in parameters and the homogeneity of the elements does not account for variation within an element, except for variation of hydraulic conductivity. Although not used in this research, channel and pond elements can be very helpful in defining soil conservation measures like ditches and reservoirs. Incorporation of SLM in KINEROS2 aims typically at plot-scale and time-detailed modelling, with spatial variations in the SLM as small as 5-10 cm.

Saturated hydraulic conductivity is the strongest parameters in runoff calibration, which suggest that infiltration excess is the dominant processes in generating runoff. Calibrated K_s is much smaller than measured in the plots but also resembles much more the K_s values for finer soils. Measuring infiltration with the double ring infiltrometer causes the soil to experience less splash detachment and thus less break up of aggregates and sealing of the soil, while the soils in the research area are probably susceptible to sealing and slaking. This was also concluded from the already shown decrease in erosion while runoff was about the same for especially plot 5 and 6. Calibrated values for capillary drive were representative for sandy loam and clay loam soils and splash detachment values were lower than the default, but with a large range, the lower value being 4 and the higher value 40 s/m. The calibration of erosion parameters for plot 5 tries to largely reduce erosion which results in a very high value for cohesion.

Predicted runoff for terraces and terraces+agroforestry using the calibration values of plot 1, are generally good. Calibration of the grass strips using the calibration values of plot 5 show an optimum increase in K_s for the grass strips of 29%. The subsequent validation of the plot shows underestimation of runoff which can be explained by the actual runoff data, where runoff amounts of the plot with grass strips are similar to the runoff amounts of control plot 5 without showing any effects of grass strips on runoff; KINEROS2 acts as expected, but the measured data does not. The predicted erosion for terraces and terraces+agroforestry is largely overestimated, which is due to KINEROS2, which models much higher erosion rates on the risers of the terraces than is deposited on the terrace's beds. The length of steep-sloped elements is used as the total length that receives rainfall in KINEROS2, but in reality a steep-sloped element will receive much less rainfall and therefore experience less erosion. This, as well as the adaptation of the microtopography and other parameters influencing flow velocity and sediment transport on steep slopes could be subject of further research.

The modelling of different Sustainable Land Management types in KINEROS2 does have potential, with this research being a first exploration in how this can be done. The option of defining different model elements representing different plot elements makes KINEROS2 very suitable for modelling terraces and grass strips, but the overestimation of erosion on steep slopes should be corrected in the model physics before incorporation of SLM's can be done seriously.

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Appendix A. Input required for KINEROS2

Global Input Block

The first block in the parameter file is the Global input block, with parameters common to all elements. The shortest permissible abbreviation of each tag is shown in blue:

Tag	Description
Units	Metric or English
Clen	The "characteristic length" — generally equal to the longest single channel element or contiguous cascade of planes

The following need only be specified when routing sediment:

Temperature	degrees C or F
Diameters	list of representative soil particle diameters (mm or in) for up to 5 particle classes
Densities	list of densities (g/cc) corresponding to the above particle classes

Following the Global input block are the element input blocks. There are two parameters which appear in every element input block:

Tag	Description
Identifier	Identification number (an integer from 1 — 999999)
Print	= 0 no printout for current element (default) = 1 summary printout for current element = 2 summary printout plus a listing of discharge and total sediment discharge at each time step = 3 summary printout plus creation of a separate, comma-delimited file with a listing of discharge, total sediment discharge and discharge by particle class
File	Name of file to create for Print = 3

Overland Flow Element (Plane)

The shortest permissible abbreviation of each tag is shown in blue.

Tag	Description
Upstream	Identifier of an upstream plane element if applicable
Length	Length in meters or feet of the element's surface
Width	Width in meters or feet — alternatively the program can compute the width based on the length and area which can be entered in primary or secondary units: Area — square meters or feet

Ha — hectares (metric units only)

Acres — acres (english units only)

Slope	Representative slope expressed as fractional rise/run
Manning	Manning roughness coefficient
Chezy	Chezy conveyance factor
X	Representative x coordinate
Y	Representative y coordinate

Coordinates do not have to be specified if there is only one rain gage

Raingage	Overrides interpolation and assigns a specific rain gage to the element. The raingage is specified using its cardinal position in the rainfall input file, i.e. 1, 2, 3 etc.
Relief	Average micro topographic relief in mm or inches
Spacing	Average micro topographic spacing in meters or feet
Interception	Interception depth in mm or inches
Canopy	Cover fraction of surface covered by intercepting cover — rainfall intensity is reduced by this fraction until the specified interception depth has accumulated

If it is a pervious surface, the following parameters describe its infiltration characteristics:

Saturation	Initial degree of soil saturation, expressed as a fraction of the pore space filled (This value overrides the interpolated value - see the rainfall file description)
CV	Coefficient of variation of Ks
Thickness	Thickness of upper soil layer in mm or inches

The following infiltration parameters can have two values, representing a two-layer soil:

Ksat	Saturated hydraulic conductivity, mm/hr or in/hr
G	Mean capillary drive, mm or inches — a zero value sets the infiltration at a constant value of Ks
Distribution	Pore size distribution index. This parameter is used for redistribution of soil moisture during unponded intervals
Porosity	Porosity
Rock	Volumetric rock fraction, if any. If Ksat is estimated based on textural class it should be multiplied by (1 - Rock) to reflect this rock volume

If sediment is being routed, the following parameters are required:

Splash	Rainsplash coefficient
Cohesion	Soil cohesion coefficient
Fractions	List of particle class fractions — must sum to one

The following parameter is optional:

Pave Fraction of surface covered by erosion pavement (0 - 1)

Note that it in this case it is not necessary to specify Rock as it is equal to zero for both layers.

Channel Element (Channel)

The shortest permissible abbreviation of each tag is shown in blue.

Tag	Description
Upstream	Identifier(s) of up to ten upstream contributing elements
Lateral	Identifier(s)of up to two plane elements contributing lateral inflow. For a compound channel, the second of two planes listed will be associated with the over bank section. Alternatively, this plane can be specified in the over bank input block
Length	Length in meters or feet
Type	Type = Simple or Compound — default is Simple
Qb	Baseflow discharge at end of channel if applicable, cu.m /s or cu.ft/s

The following geometric parameters can have two values, representing its upstream and downstream sections, or a single value denoting the average:

Width	Bottom width in meters or feet
Slope	Bottom slope expressed as fractional rise/run
Manning	Manning roughness coefficient, or
Chezy	Chezy conveyance factor
SS1, SS2	Bank side slopes — right or left is immaterial to the routing equations except for compound channels, in which case SS2 refers to the over bank side
Rwidth	If it is desired to account for rainfall on the channel area, this parameter specifies a representative width
X	Representative x coordinate
Y	Representative y coordinate

Coordinates are specified only if Rwidth is specified.

Coordinates do not have to be specified if there is only one raingage.

Raingage Overrides interpolation and assigns a specific rain gage to the element. The raingage is specified using its cardinal position in the rainfall input file, i.e.1, 2, 3 etc.

If it is a pervious channel, the following parameters describe its infiltration characteristics:

Wool Wool = Yes turns on David Woolhiser's effective wetted perimeter function. During low flows the wetted perimeter available for infiltration is reduced to account for micro channel morphology according to the equation:

P_e = min(h / W_{co}sqrt (Width), 1) P where

P_e = effective wetted perimeter

P = wetted perimeter at depth h

W_{co} = 0.15 (see below) for Width in feet but is automatically converted to an equivalent value if width is in meters

Wcoeff — Optional override of coefficient W_{co} in the Woolhiser function

Saturation — Initial degree of soil saturation, expressed as a fraction of of the pore space filled (This value overrides the interpolated value - see the rainfall file description)

CV — Coefficient of variation of Ks

Thickness — Thickness of upper soil layer in mm or inches

The following infiltration parameters can have two values, representing two layers of bed material:

Ksat — Saturated hydraulic conductivity mm/hr or in/hr

G — Mean capillarydrive mm or inches — a zero value sets the infiltration at a constant value of Ks

Distribution — Pore size distribution index. This parameter is used for redistribution of soil moisture during unponded intervals

Porosity — Porosity

Rock — Volumetric rock fraction if any. If Ksat is estimated based on textural class it should be multiplied by (1 - Rock) to reflect this rock volume

If sediment is being routed, the following parameters are required:

Splash — Rainsplash coefficient

Cohesion — Soil cohesion coefficient

Fractions — List of particle class fractions — must sum to one

The following parameter is optional:

Pave — Fraction of surface covered by erosion pavement (0 - 1)

A compound channel element has an additional input block for the Overbank section, with the same geometric, infiltration and sediment parameters as above except Length, SS1 and SS2. Additional parameters are:

Lateral — Identifier of a plane element contributing lateral inflow

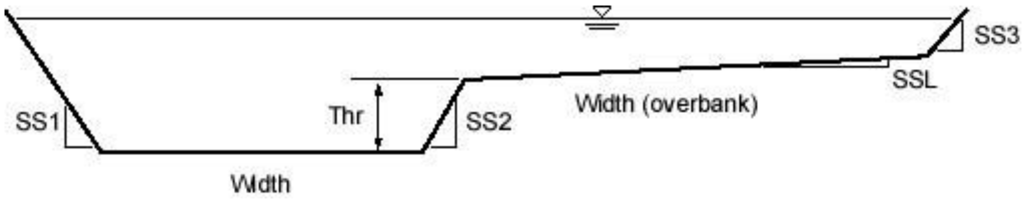
The following parameters can refer to upstream, downstream sections or the average:

SS3 — Lateral bank slope

SSL — Lateral bottom slope (towards main section)

Threshold — Threshold depth for spillover m or ft

Rwidth — If it is desired to account for rainfall on the overbank area, this parameter specifies a representative width



Pond Element (Pond)

The shortest permissible abbreviation of each tag is shown in blue.

Tag	Description
Upstream	Identifier(s) of up to ten upstream contributing elements
Lateral	Identifier(s)of up to two plane elements contributing lateral inflow
Storage	Initial storage volume in cu.m or cu.ft
N	Number of [Volume, Discharge, Surface Area] entries in the rating table
Volume	List or column of volume entries in the rating table in cu.m or cu.ft (volume must start at zero)
Discharge	Pond outflow discharge, cu.m/s or cu.ft/s, for the corresponding volume entry (there must be at least one zero value)
Surface	Surface area, sq.m or sq.ft, for the corresponding volume entry
Ksat	Constant (saturated) conductivity representing seepage, mm/hr or in/hr
X	Representative x coordinate
Y	Representative y coordinate

Coordinates do not have to be specified if there is only one raingage.

Raingage	Overrides interpolation and assigns a specific rain gage to the element. The raingage is specified using its cardinal position in the rainfall input file, i.e.1, 2, 3 etc.

Injection (Inject)

The shortest permissible abbreviation of each tag is shown in blue.

Tag	Description
File	Data to inject — a listing of time (min) and discharge (cu.m/s or cu.ft/s) pairsplus up to 5 columns of corresponding sediment concentrations by particle class
Offset	An optional positive time offset in minutes

Rainfall File

Each set of rain gage data is entered in a separate input block; the block name can be any alphanumeric string.

The shortest permissible abbreviation of each tag is shown in blue.

Tag	Description
Number	Number of data pairs
Saturation	Initial soil saturation - if there is more than one rain gage a value will be interpolated to each element

Time	Time in minutes (column or list)
Depth	Accumulated depth in mm or inches
Intensity	Intensity in mm/hr or in/hr — input can be in either depth or intensity
X	X coordinate— optional if there is only one gage
Y	Y coordinate— optional if there is only one gage

KINEROS2 Output File

The output file of the model provides a hydrograph:

Tag	Description
Time(min)	Timesteps in minutes
Q(cfs)	Discharge in cubic feet per second, for each timestep
Q(iph)	Discharge in inches per hour, for each timestep
Conc	Sediment concentration, for each timestep
Qs(t/ac/hr)	Hourly sediment rate in tonnes per acre, for each timestep
Time to peak flow rate	Time to peak in minutes
Peak flow rate	Peak flow rate in inches per hour

Further, for each element (plane or channel) the volume balance error (%) and sediment total (lbs) are given.

For all planes in total and all channels in total, infiltration (inch) and storage (inch) are also given:

Tag	Description
Storage remaining on all planes	In inches
Storage remaining in channels+conduits	In inches
Storage remaining in ponds	In inches
Total infiltration from all planes	In inches
Total infiltration from all channels	In inches
Total basin runoff	In inches
Total of storage, infiltration and runoff	In inches
Global volume error	Difference in total stor+inf+runoff and total rainfall, in percentages. Positive errors indicate loss of water and negative errors a gain of water.

Appendix B. Rainfall events per Gerlach period *

Rain Event	Gerlach event	Plot no. 1	2	3	4	5	6
	8-11-10	x					
101116.pre							
101118a.pre							
101118b.pre							
	20-11-10	x		x	x		
	21-11-10					x	x
101129a.pre							
101129b.pre							
101130.pre							
101204.pre							
101206a.pre							
101206b.pre							
101208a.pre	8-12-10		x	x	x	x	x
101208b.pre							
101208c.pre							
	9-12-10					x	x
101210a.pre							
101210b.pre							
101210c.pre	10-12-10	x	x	x	x	x	x
101217.pre	17-12-10						x
	19-12-10				x		x
101221.pre	21-12-10	x	x		x	x	x
101222.pre	22-12-10	x	x	x	x		
101224.pre							
101225a.pre							
101225b.pre	25-12-10	x	x			x	x
101226a.pre							

101226b.pre	26-12-10	x	x	x	x	x	
101229.pre							
110104.pre							
110105.pre	5-01-11	x	x	x	x	x	x
110107.pre	7-01-11					*x*	x
	8-01-11	x	x	x			
110108a.pre							
110108b.pre							
110109.pre	9-01-11					x	x
110110a.pre							
110110b.pre	10-01-11	x	x		x	x	x
	12-01-11				x	x	
110113.pre							
	17-01-11	x	x	x	x	x	x

⁎ This table shows an overview of how the events from the actual rainfall data are assigned to a specific Gerlach period. First column are the rainfall events, with their names representing the date at which they are measured: the last two numbers of the year, month and day; sometimes followed by a, b or c in case of multiple rain events on one day. Second column are the Gerlach measurements, represented by the date at which the throughs are emptied. The last part of the table represents the research plots, with *x* defining at which specific date the Gerlach throughs are measured on each plot. The rows of the outlined boxes then correspond to the rainfall events included in each Gerlach period.

Appendix C. PHP algorithm script

```php
<?php
/***
 * This script runs a modified Kineros2 for multiple configurations
 * and its results are written into a result file. The Kineros
 * modification was needed to bypass user inputs.
 *
 * PHP >= 5.3 required
 *
 */
$INITIAL_SA             = array("0.6");         //initial SA value
$DIR_PRECIP_FILES       = "./";                 //directory of precip files
$DEFAULT_PARAM_FILE     = "default_field5.par"; //should be in same dir as script
$PARAMETER_FILE         = "params.fil";
$RESULTS_FILE           = "results.txt";
$RESULTS_FILE_CUM       = "results_cum.txt";
$DESCRIPTION            = "kineros output";
$DURATION               = "60";
$TIME_STEP              = "5.000000";
$COURANT_CORRECTION     = "n";
$SEDIMENT_INCLUDED      = "y";
$MULTIPLIERS_UPDATED    = "n";
$TABLE_SUMMARY          = "y";
$API_VALUE              = "n";
$VALUES_FD              = array("0.93");
$CMD_KINEROS            = "Kineros2.exe";
$VALUES_CV              = array("0.3");
$VALUES_G               = array("262");
$VALUES_KS              = array("14.0");
$VALUES_T               = array("90.0");
//$VALUE_C              = array("0.6");
//$VALUES_S             = array("25.0");
$DEBUG                  = false;                 //=true will print Kineros output
```

```
// Fill values Splash
for( $i = 10; $i <= 100; $i += 10)
{
    $VALUES_S[] = $i;
}
// Fill values Coh
for( $i = 0.5; $i <= 50; $i += 0.5)
{
    $VALUE_C[] = $i;
}

date_default_timezone_set("UTC");

/*******************/
$precipFiles[] = "101208b.pre";
$precipFiles[] = "101208c.pre";
$precipFiles[] = "101210a.pre";
$precipFiles[] = "101210b.pre";
$precipFiles[] = "101210c.pre";
$precipFiles[] = "101217.pre";
$precipFiles[] = "101221.pre";
$precipFiles[] = "101222.pre";
$precipFiles[] = "101224.pre";
$precipFiles[] = "101225a.pre";
$precipFiles[] = "101225b.pre";
$precipFiles[] = "101226a.pre";
$precipFiles[] = "101226b.pre";
$precipFiles[] = "101229.pre";
$precipFiles[] = "110104.pre";
$precipFiles[] = "110105.pre";
$precipFiles[] = "110107.pre";
$precipFiles[] = "110108a.pre";
$precipFiles[] = "110108b.pre";
$precipFiles[] = "110109.pre";
$precipFiles[] = "110110a.pre";
$precipFiles[] = "110110b.pre";
/******************/
```

```
$resultsFileContents    = "PrecipFile\tDf\tG\tKS\tSA\tT\tS\tinfiltWater\toutWater\toutSed\train\n";
$resultsFileContentsCum = "";
//run Kineros for each combination of parameters
$totalRuns = count($INITIAL_SA) * count($VALUE_C) * count($VALUES_FD) * count($VALUES_G) * count($VALUES_KS) * count
($VALUES_T) * count($VALUES_S) * count($precipFiles);
$currentRun = 0;
    foreach($VALUE_C as $valC) {
        foreach($INITIAL_SA as $SA) {
            foreach($VALUES_FD as $F_D) {
                foreach($VALUES_G as $valG) {
                    foreach($VALUES_KS as $valKS) {
                        foreach($VALUES_T as $valT) {
                            foreach($VALUES_S as $valS) {
                                //run Kineros for each precipfile
                                unset($valSA); //unset SA value for next runs
                                $counterRainevent = 1;
                                $resInfiltWater = 0;
                                $resOutWater = 0;
                                $resOutSediment = 0;
                                $resRainfall = 0;
                                foreach($precipFiles as $precipFile) {
                                    $currentRun++;
                                    if(!isset($valSA)) {
                                        $valSA = $SA; //first run use initial value
                                    } else {
                                        //calculate number of days from last precip file
                                        //filename format should be 'yymmdd' e.g. 101224 for 24/12/2010
                                        $prevDate = date_create_from_format("ymj", substr($prevPrecipFile,0,6));
                                        $currDate = date_create_from_format("ymj", substr($precipFile,0,6));
                                        $numDays  = date_diff($prevDate, $currDate)->format("%a");
                                        //calculate new SA value to be used in next run
                                        $valSA = ($valSA * pow($F_D,$numDays)) + ($prevPrecip/$valT);
                                      //valT = effective soil depth
                                    }
                                    //write parameter file
                                    $paramFileContent = file_get_contents($DEFAULT_PARAM_FILE);
                                    $paramFileContent = str_replace("#SA#", $valSA, $paramFileContent);
                                    $paramFileContent = str_replace("#KS#", $valKS, $paramFileContent);
                                    $paramFileContent = str_replace("#G#",  $valG,  $paramFileContent);
                                    $paramFileContent = str_replace("#T#", $valT, $paramFileContent);
                                    $paramFileContent = str_replace("#S#", $valS, $paramFileContent);
                                    $paramFileContent = str_replace("#C#", $valC, $paramFileContent);
                                    file_put_contents($PARAMETER_FILE, $paramFileContent);
                                    //write kin.fil
```

```
$outputFile = "results.out";
file_put_contents("kin.fil",
    $PARAMETER_FILE."\n".
    $precipFile."\n".
    $outputFile."\n".
    $DESCRIPTION."\n".
    $DURATION."\n".
    $TIME_STEP."\n".
    $COURANT_CORRECTION."\n".
    $SEDIMENT_INCLUDED."\n".
    $MULTIPLIERS_UPDATED."\n".
    $TABLE_SUMMARY."\n".
    $API_VALUE."\n");

//run kineros
unset($output);
echo "Running Kineros ". $currentRun ." of ". $totalRuns ."\n";
exec($CMD_KINEROS, $output);
if($DEBUG) echo "========== BEGIN KINEROS OUTPUT ===========\n";
$lineCnt = 1;
foreach($output as $outputline) {
    if($DEBUG) echo "    ".$lineCnt.":\t".$outputline."\n";
    $lineCnt++;
}
//substract precipitation from KINEROS output
unset($rainfall);
foreach($output as $line) {
    $line=trim($line);
    if(strlen($line) > 8)
    if(substr_compare($line,"Rainfall",0,8) == 0) {
        $parts = explode("mm",substr($line,8));
        $rainfall = (double)trim($parts[0]);
        break;
    }
}
if(!isset($rainfall)) {
    echo "\nERROR: No Rainfall in Kineros Output\n";
    exit(1);
}
if($DEBUG) echo "=========== END KINEROS OUTPUT ===========\n";
//write data nicely to general output file
$outputFileContents = file_get_contents($outputFile);
$outputFileContents = explode("\n", $outputFileContents);
$planeElement5 = false;
```

```
for($i = 0; $i < count($outputFileContents); $i++) {
    $line=trim($outputFileContents[$i]);
    if($planeElement5) {
        if(strlen($line) >= 5)
        if(substr_compare($line,"Water",0,5) == 0) {
            //next lines are important!
            // i    >             Water balance                          Sediment balance
            // i+1  > -------------------------------------     ------------------------
            // i+2  >   Rain:   5.969555 cu m   4.787133 mm             In:  0.0000000 kg
            // i+3  > Inflow:   0.000000 cu m   0.000000 mm      Deposited:  0.0000000 kg
            // i+4  > Infilt:   5.969557 cu m   4.787135 mm      Suspended:  0.0000000 kg
            // i+5  > Stored:   0.000000 cu m   0.000000 mm            Out:  0.0000000 kg
            // i+6  >    Out:   0.000000 cu m   0.000000 mm          Error:       0.00 %
            $temp = explode("mm", $outputFileContents[$i+4]);
            $temp = explode("cu m", $temp[0]);
            $infiltWater = (double)trim($temp[1]);
            $temp = explode("mm", $outputFileContents[$i+6]);
            $temp = explode("cu m", $temp[0]);
            $outWater = (double)trim($temp[1]);
            $temp = explode("Out:", $outputFileContents[$i+5]);
            $temp = explode("kg", $temp[1]);
            $outSediment = (double)trim($temp[0]);
            break;
        }
    } else {
        if(strlen($line) >= 18)
        if(substr_compare($line,"Plane Element    5",0,18) == 0) {
            $planeElement5 = true;
        }
    }
}
$resultsFileContents .=
$precipFile."\t".$F_D."\t".$valG."\t".$valKS."\t".$valSA."\t".$valT."\t".$valS."\t".$infiltWater."\t".$outWater."\t".$outSed
iment."\t".$rainfall."\t".$SA."\t".$valC."\n";

$resInfiltWater += $infiltWater;
$resOutWater += $outWater;
$resOutSediment += $outSediment;
$resRainfall += $rainfall;

$writeout = false;
if($counterRainevent == 2 ||
   $counterRainevent == 5 ||
   $counterRainevent == 6 ||
```

```
                                        $counterRainevent == 7 ||
                                        $counterRainevent == 11 ||
                                        $counterRainevent == 13 ||
                                        $counterRainevent == 16 ||
                                        $counterRainevent == 17 ||
                                        $counterRainevent == 20 ||
                                        $counterRainevent == 22) {
                                         $writeout = true;
                                     }
                                     if($writeout) {

                                         $resultsFileContentsCum .=
$F_D."\t".$valG."\t".$valKS."\t".$valSA."\t".$valT."\t".$valS."\t".$resInfiltWater."\t".$resOutWater."\t".$resOutSediment."\
t".$resRainfall."\t".$SA."\t".$valC."\n";
                                         $resInfiltWater = 0;
                                         $resOutWater = 0;
                                         $resOutSediment = 0;
                                         $resRainfall = 0;
                                     }
                                     $counterRainevent++;

                                     $prevPrecip = $infiltWater;
                                     //calculate diff days to next precipFile
                                     $prevPrecipFile = $precipFile;
                                 }
                             }
                         }
                     }
                 }
             }
         }
    }
file_put_contents($RESULTS_FILE, $resultsFileContents);
file_put_contents($RESULTS_FILE_CUM, $resultsFileContentsCum);

?>
```

Appendix D. Matlab RMSE script

```
clear
close all
%numPreFiles=3;                       % No. of precip files used for this model result set
resultFile='results_cum.txt';         % Filename of the result set
gerlachFile='Gerlach1QSa.txt';        % Filename of the gerlach data
modelled=dlmread(resultFile, '\t');   % Read model result data from the file; data in this file is summed per Gerlach
measurement
gerlach=dlmread(gerlachFile, '\t');   % Read gerlach data from file
%AllResults='results_edited.txt';     % Filename of the all results data; data in this file is raw data for all single
events
%allresults=dlmread(AllResults, '\t');% Read gerlach data from file

    %resultFile and AllResults column header:
% 1.Df[-]  2.G[mm]  3.Ks[mm/h]  4.SA[-]  5.Thickness [mm] 6.Splash[m/s] 7.Infilt[mm] 8.Runoff[mm]  9.Sediment[kg]
10.Rainfall[mm]
% the modelresults has many rows; sorted on time (.prefile) and per parameter combination. So first, one parameter
combination is % runned for event1, event2, etc; second the next paramter combi again for each event, etc.

    %Gerlach column header:
% 1.Runoff[mm]  2.Sediment[g]
% the Gerlach data contains 8 rows (using data of winter2010-2011 for
% field3), with the 8 times the Gerlachs were being emptied and runoff and sediment was measured

% Next, the Gerlach data contains 8 events for only 1 period, whereas
% the model results contain the same 8 events but multiple times for each parameter combination.
% A for loop is used, starting at 1, with stepsize similar to the gerlach set(=8),
% and total length equal to the length of the modelled data set.
% Within the Gerlach stepsize, again a for loop(stepsize 1) is used to  calculate the ratio of the
% modelled and Gerlach Runoff and Sediment values and write them in the ratio matrix.
modelledAll = modelled;
sizeGerlach=size(gerlach);
sizeModel=size(modelledAll);
lengthModel = sizeModel(1)/8*sizeGerlach(1);

   for i = 1:sizeGerlach(1):lengthModel(1)     %sizeModelled divided by total rainevents and multiplied by total Gerlach
events
          modelled(i,:)=[]; % removes Gerlach period with Rc too low (not suited for calibration)
          modelled(i+2,:)=[]; % removes Gerlach period with Rc too low (not suited for calibration)
   end
```

```
%--------------------------------------calculate rmse for all single rain periods-----------------------------------------%
sizeModelled=size(modelled);
sqrsum=zeros(sizeModelled(1)/sizeGerlach(1),7);

   for i = 1:sizeGerlach(1):sizeModelled(1) %in which i is a specific parameter combination
       index = ceil(i/sizeGerlach(1));
       sqrsum(index,1) = modelled(i,1); % Depletion
       sqrsum(index,2) = modelled(i,2); % G[mm]
       sqrsum(index,3) = modelled(i,3); % Ks[mm/h]
       sqrsum(index,4) = modelled(i,6); % Splash[-]
       sqrsum(index,5) = modelled(i,12);% Cohesion[mm]
       for j = 1:sizeGerlach(1)         %in which j is a rain event; all events from 1 to j together represent one rain
period
          sqrsum(index,6) = sqrsum(index,6)+((modelled(i+j-1,8) - gerlach(j,1))^2); %=Runoff [mm]
          sqrsum(index,7) = sqrsum(index,7)+((modelled(i+j-1,9) - gerlach(j,2))^2); %=Sediment [g]
       end
   end


 sqrsum = sortrows(sqrsum,5); %sorteer sqrsum op Cohesion
 sizeSqrsum = size(sqrsum);
 numUniqueC = size(unique(sqrsum(:,5)));
 numRepC = sizeSqrsum(1) / numUniqueC(1);
 rmseUniqueC = zeros(numUniqueC(1),3);
 for i = 1:numRepC:sizeSqrsum(1)
     index = ceil(i/numRepC);
     for j = 1:numRepC
        rmseUniqueC(index,1) = sqrsum(i+j-1,5); %=T
        rmseUniqueC(index,2) = rmseUniqueC(index,2) + sqrsum(i+j-1,6); %=Runoff (sum)
        rmseUniqueC(index,3) = rmseUniqueC(index,3) + sqrsum(i+j-1,7); %=Sediment (sum)
     end
     rmseUniqueC(index,2) = sqrt(rmseUniqueC(index,2) / (numRepC*sizeGerlach(1))); %=RMSE Runoff
rmseUniqueC(index,3) = sqrt(rmseUniqueC(index,3) / (numRepC*sizeGerlach(1)));      %=RMSE Sediment
       %delen door sizeModelled (=totaal); gaat over alle runs die eerder al per periode opgeteld zijn maar nog niet
gedeeld.
 end

 sqrsum = sortrows(sqrsum, 2); %sorteer sqrsum op G
 sizeSqrsum = size(sqrsum);
 numUniqueG = size(unique(sqrsum(:,2)));
 numRepG = sizeSqrsum(1) / numUniqueG(1);
 rmseUniqueG = zeros(numUniqueG(1),3);
 for i = 1:numRepG:sizeSqrsum(1)
     index = ceil(i/numRepG);
```

```
    for j = 1:numRepG
       rmseUniqueG(index,1) = sqrsum(i+j-1,2); %=G
       rmseUniqueG(index,2) = rmseUniqueG(index,2) + sqrsum(i+j-1,6); %=Runoff (sum)
       rmseUniqueG(index,3) = rmseUniqueG(index,3) + sqrsum(i+j-1,7); %=Sediment (sum)
    end
    rmseUniqueG(index,2) = sqrt(rmseUniqueG(index,2) / (numRepG*sizeGerlach(1))); %=RMSE Runoff
    rmseUniqueG(index,3) = sqrt(rmseUniqueG(index,3) / (numRepG*sizeGerlach(1))); %=RMSE Sediment
end

sqrsum = sortrows(sqrsum, 4); %sorteer sqrsum op S
sizeSqrsum = size(sqrsum);
numUniqueS = size(unique(sqrsum(:,4)));
numRepS = sizeSqrsum(1) / numUniqueS(1);
rmseUniqueS = zeros(numUniqueS(1),3);
for i = 1:numRepS:sizeSqrsum(1)
    index = ceil(i/numRepS);
    for j = 1:numRepS
       rmseUniqueS(index,1) = sqrsum(i+j-1,4); %=S
       rmseUniqueS(index,2) = rmseUniqueS(index,2) + sqrsum(i+j-1,6); %=Runoff (sum)
       rmseUniqueS(index,3) = rmseUniqueS(index,3) + sqrsum(i+j-1,7); %=Sediment (sum)
    end
    rmseUniqueS(index,2) = sqrt(rmseUniqueS(index,2) / (numRepS*sizeGerlach(1))); %=RMSE Runoff
    rmseUniqueS(index,3) = sqrt(rmseUniqueS(index,3) / (numRepS*sizeGerlach(1))); %=RMSE Sediment
end


sqrsum = sortrows(sqrsum, 1); %sorteer sqrsum op Df
sizeDqrsum = size(sqrsum);
numUniqueD = size(unique(sqrsum(:,1)));
numRepD = sizeDqrsum(1) / numUniqueD(1);
rmseUniqueD = zeros(numUniqueD(1),3);
for i = 1:numRepD:sizeSqrsum(1)
    index = ceil(i/numRepD);
    for j = 1:numRepD
       rmseUniqueD(index,1) = sqrsum(i+j-1,1); %=D
       rmseUniqueD(index,2) = rmseUniqueD(index,2) + sqrsum(i+j-1,6); %=Runoff (sum)
       rmseUniqueD(index,3) = rmseUniqueD(index,3) + sqrsum(i+j-1,7); %=Sediment (sum)
    end
    rmseUniqueD(index,2) = sqrt(rmseUniqueD(index,2) / (numRepD*sizeGerlach(1))); %=RMSE Runoff
    rmseUniqueD(index,3) = sqrt(rmseUniqueD(index,3) / (numRepD*sizeGerlach(1))); %=RMSE Sediment
end

sqrsum = sortrows(sqrsum, 3); %sorteer sqrsum op Ks
sizeSqrsum = size(sqrsum);
```

```
numUniqueK = size(unique(sqrsum(:,3)));
numRepK = sizeSqrsum(1) / numUniqueK(1);
rmseUniqueK = zeros(numUniqueK(1),3);
for i = 1:numRepK:sizeSqrsum(1)
    index = ceil(i/numRepK);
    for j = 1:numRepK
       rmseUniqueK(index,1) = sqrsum(i+j-1,3); %=Ks
       rmseUniqueK(index,2) = rmseUniqueK(index,2) + sqrsum(i+j-1,6); %=Runoff (sum)
       rmseUniqueK(index,3) = rmseUniqueK(index,3) + sqrsum(i+j-1,7); %=Sediment (sum)
    end
    rmseUniqueK(index,2) = sqrt(rmseUniqueK(index,2) / (numRepK*sizeGerlach(1))); %=RMSE Runoff
    rmseUniqueK(index,3) = sqrt(rmseUniqueK(index,3) / (numRepK*sizeGerlach(1))); %=RMSE Sediment
end

%-------------------------------------------calculate rmse per 8 rainevents-----------------------------------------------%
sqrsums=zeros(sizeModelled(1)/sizeGerlach(1),8);

   for i = 1:sizeGerlach(1):sizeModelled(1)%in which i is a specific parameter combination
       index = ceil(i/sizeGerlach(1));
       sqrsums(index,1) = modelled(i,1); % Depletion
       sqrsums(index,2) = modelled(i,2); % G[mm]
       sqrsums(index,3) = modelled(i,3); % Ks[mm/h]
       sqrsums(index,4) = modelled(i,6); % Splash[-]
       sqrsums(index,5) = modelled(i,12);% Cohesion [kPa]
       for j = 1:sizeGerlach(1)          % in which j is a rain event; all events from 1 to j together represent one rain
period
          sqrsums(index,6) = sqrsums(index,6)+((modelled(i+j-1,8) - gerlach(j,1))^2); %=Runoff
          sqrsums(index,7) = sqrsums(index,7)+((modelled(i+j-1,9) - gerlach(j,2))^2); %=Sediment
       end
       sqrsums(index,8) = sqrt(sqrsums(index,6)/sizeGerlach(1));                      %=Runoff rmse
       sqrsums(index,9) = sqrt(sqrsums(index,7)/sizeGerlach(1));                      %=Sediment rmse
   end

 rmseD(:,1) = sqrsums(:,1);  %value of Df
 rmseD(:,2) = sqrsums(:,8);  %Runoff rmse
 rmseD(:,3) = sqrsums(:,9);  %Sediment rmse

 rmseG(:,1) = sqrsums(:,2);  %value of G
 rmseG(:,2) = sqrsums(:,8);  %Runoff rmse
 rmseG(:,3) = sqrsums(:,9);  %Sediment rmse

 rmseK(:,1) = sqrsums(:,3);  %value of Ks
 rmseK(:,2) = sqrsums(:,8);  %Runoff rmse
 rmseK(:,3) = sqrsums(:,9);  %Sediment rmse
```

```
    rmseC(:,1) = sqrsums(:,5);  %value of Th
    rmseC(:,2) = sqrsums(:,8);  %Runoff rmse
    rmseC(:,3) = sqrsums(:,9);  %Sediment rmse

    rmseS(:,1) = sqrsums(:,4);  %value of S
    rmseS(:,2) = sqrsums(:,8);  %Runoff rmse
    rmseS(:,3) = sqrsums(:,9);  %Sediment rmse

% ------------------------- rmse Sediment -------------------------------%
    %plot rmse (per parameter combination) Sediment vs Cohesion
    subplot(2,2,1);
    scatter(rmseUniqueC(:,1), rmseUniqueC(:,3),3, 'filled'); % plot T vs RMSE Sediment
    xlabel('Cohesion [kPa]', 'fontsize', 8), ylabel('rmse Sediment', 'fontsize', 8);
    %set(gca, 'YScale', 'log');

    %plot rmse (per parameter combination) Sediment vs Splash
    subplot(2,2,3);
    scatter(rmseUniqueS(:,1), rmseUniqueS(:,3),3, 'filled'); % plot S vs RMSE Sediment
    xlabel('Splash Detachment [-]', 'fontsize', 8), ylabel('rmse Sediment', 'fontsize', 8);
    %set(gca, 'YScale', 'log');

    %plot rmseAll Sediment vs Cohesion
    subplot(2,2,2);
    scatter(rmseC(:,1), rmseC(:,3),3, 'filled');
    xlabel('Cohesion [kPa]', 'fontsize', 8), ylabel('rmse Sediment', 'fontsize', 8);
    %set(gca, 'YScale', 'log');

    %plot rmseAll Sediment vs S
    subplot(2,2,4);
    scatter(rmseS(:,1), rmseS(:,3),3, 'filled');
    xlabel('Splash Detachment [-]', 'fontsize', 8), ylabel('rmse Sediment', 'fontsize', 8);
    %set(gca, 'YScale', 'log');

   print -djpeg RMSESediment.jpeg

% ------------------------- modeled Sediment ----------------------------%
    %plot of modelled Sediment vs Coh
    subplot(2,1,1);
    scatter(modelled(:,12), modelled(:,9),3, 'filled');
    xlabel('Cohesion [kPa]', 'fontsize', 8), ylabel('modeled Sediment', 'fontsize', 8);

    %plot of modelled Sediment vs S
    subplot(2,1,2);
```

```
   scatter(modelled(:,6), modelled(:,9),3, 'filled');
   xlabel(' Splash Detachment [-]', 'fontsize', 8), ylabel('modeled Sediment', 'fontsize', 8);

  print -djpeg ModeledSediment.jpeg

% ------------------------- modeled Runoff ---------------------------------%
   %plot of modelled Runoff vs G
   subplot(2,2,1);
   scatter(modelled(:,2), modelled(:,8),3, 'filled');
   xlabel('Capillary Drive [mm]', 'fontsize', 8), ylabel('modeled Runoff [mm]', 'fontsize', 8);

   %plot of modelled Runoff vs Ks
   subplot(2,2,2);
   scatter(modelled(:,3), modelled(:,8),3, 'filled');
   xlabel('Saturated Hydraulic Conductivity [mm/h]', 'fontsize', 8), ylabel('modeled Runoff [mm]', 'fontsize', 8);

   %plot of modelled Runoff vs Rain
   subplot(2,2,3);
   scatter(modelled(:,10), modelled(:,8),3, 'filled');
   xlabel('Rainfall [mm]', 'fontsize', 8), ylabel('modeled Runoff [mm]', 'fontsize', 8);

   %plot of modelled Runoff vs SA
   subplot(2,2,4);
   scatter(allresults(:,4), allresults(:,8),3, 'filled');
   xlabel('Initial Soil Moisture', 'fontsize', 8), ylabel('modeled Runoff', 'fontsize', 8);

   print -djpeg Runoff.jpeg

   %plot of modelled Runoff vs C
   subplot(2,2,1);
   scatter(modelled(:,12), modelled(:,8), 3, 'filled');
   xlabel('Cohesion [kPa]', 'fontsize', 8), ylabel('modeled Runoff', 'fontsize', 8);

   %plot of modelled Runoff vs Splash
   subplot(2,2,2);
   scatter(modelled(:,6), modelled(:,8), 3, 'filled');
   xlabel('Splash [-]', 'fontsize', 8), ylabel('modeled Runoff', 'fontsize', 8);

   print -djpeg ModeledRunoffCS.jpeg

% ---------------------------- rmse Runoff ------------------------------%
   %plot rmseAll of Runoff vs G
   subplot(2,2,1);
   scatter(rmseUniqueG(:,1), rmseUniqueG(:,2),3, 'filled'); % plot G vs RMSE Runoff
```

```
  xlabel('Capillary Drive [mm]', 'fontsize', 8), ylabel('rmse Runoff', 'fontsize', 8);
  %set(gca, 'YScale', 'log');

  %plot rmseAll of Runoff vs Ks
  subplot(2,2,3);
  scatter(rmseUniqueK(:,1), rmseUniqueK(:,2),3, 'filled'); % plot K vs RMSE Runoff
  xlabel('Saturated Hydraulic Conductivity [mm/h]', 'fontsize', 8), ylabel('rmse Runoff', 'fontsize', 8);
  %set(gca, 'YScale', 'log');

  %plot rmseAll of Runoff vs T
  %subplot(3,2,5);
  %scatter(rmseUniqueT(:,1), rmseUniqueT(:,2),3, 'filled'); % plot T vs RMSE Runoff
  %xlabel('Thickness Soil Depth', 'fontsize', 8), ylabel('rmse Runoff', 'fontsize', 8);
  %set(gca, 'YScale', 'log');

  %plot rmseAll of Runoff vs Df
 % subplot(3,2,5);
 % scatter(rmseUniqueD(:,1), rmseUniqueD(:,2),3, 'filled'); % plot Df vs RMSE Runoff
 % xlabel('Depletion factor', 'fontsize', 8), ylabel('rmse Runoff', 'fontsize', 8);
  %set(gca, 'YScale', 'log');

  %plot rmsePP of Runoff vs G
  subplot(2,2,2);
  scatter(rmseG(:,1), rmseG(:,2), 3, 'filled');
  xlabel('Capillary Drive [mm]', 'fontsize', 8), ylabel('rmse Runoff [mm]', 'fontsize', 8);
  %set(gca, 'YScale', 'log');

  %plot rmsePP of Runoff vs Ks
  subplot(2,2,4);
  scatter(rmseK(:,1), rmseK(:,2), 3, 'filled');
  xlabel('Saturated Hydraulic Conductivity [mm/h]', 'fontsize', 8), ylabel('rmse Runoff [mm]', 'fontsize', 8);
  %set(gca, 'YScale', 'log');

print -djpeg RMSERunoff.jpg
```

Appendix E. Input parameter file

! Info: Lushoto, Usambaras, Tanzania

! Field nr 5, owner: Nasoro

! field with poor grass strips

! at the time of research(sept-dec 2011), no crops were grown only some weed; in december, beans were planted

BEGIN GLOBAL

Clen = 31, Units = Metric

Diams = 0.0015, 0.009, 0.015, 1 ! mm

Density = 2.65, 2.65, 2.65, 2.65 ! g/cc

Temp = 29 ! deg C

END GLOBAL

BEGIN PLANE ! BED 1

ID = 1

Print = 3

File = 3test

Length = 7.5, Width = 29.0 ! m

Slope = 0.22 ! fraction

Mann = 0.085 !

Relief = 30, Spacing = 0.3

Int = 1.05, Canopy = 0.35

Sa = #SA#, CV = #CV#, Thickness = #T#

KS = #KS# !mm/h

G = #G#, Distribution = 0.0647

Fractions = 0.3775, 0.0775, 0.030, 0.515

Splash = #S#

Por = 0.546

Coh = 0.05

END PLANE

BEGIN PLANE ! GRASSSTRIP 1

ID = 2

Print = 3

File = 3test

Up = 1

```
Length = 0.25, Width = 29.0 ! m
Slope = 0.22 ! fraction
Mann = 0.08 !
Relief = 10, Spacing = 0.1
Int = 2.3, Canopy = 0.2
Sa = #SA#, CV = #CV#, Thickness = #T#
KS = #KS# !mm/h
G = #G#, Distribution = 0.0647
Fractions = 0.3775, 0.0775, 0.030, 0.515
Splash = #S#
Por = 0.546
Coh = 0.05
END PLANE

BEGIN PLANE                                                     ! BED 2
ID = 3
Print = 3
File = 3test
Up = 2

Length = 14.2, Width = 29.0 ! m
Slope = 0.22 ! fraction
Mann = 0.085 !
Relief = 30, Spacing = 0.3
Int = 1.05, Canopy = 0.35
Sa = #SA#, CV = #CV#, Thickness = #T#
KS = #KS# !mm/h
G = #G#, Distribution = 0.0647
Fractions = 0.3775, 0.0775, 0.030, 0.515
Splash = #S#
Por = 0.546
Coh = 0.05
END PLANE


BEGIN PLANE                                                     ! GRASSSTRIP 2
ID = 4
Print = 3
File = 3test
```

```
Up = 3

Length = 0.22, Width = 29.0 ! m
Slope = 0.22 ! fraction
Mann = 0.103 !
Relief = 10, Spacing = 0.1
Int = 2.3, Canopy = 0.35
Sa = #SA#, CV = #CV#, Thickness = #T#
KS = #KS# !mm/h
G = #G#, Distribution = 0.0647
Fractions = 0.3775, 0.0775, 0.030, 0.515
Splash = #S#
Por = 0.546
Coh = 0.05
END PLANE

BEGIN PLANE                                              ! BED 3
ID = 5
Print = 3
File = 3test
Up = 4

Length = 8.8, Width = 29.0 ! m
Slope = 0.22 ! fraction
Mann = 0.085 !
Relief = 30, Spacing = 0.3
Int = 1.05, Canopy = 0.35
Sa = #SA#, CV = #CV#, Thickness = #T#
KS = #KS# !mm/h
G = #G#, Distribution = 0.0647
Fractions = 0.3775, 0.0775, 0.030, 0.515
Splash = #S#
Por = 0.546
Coh = 0.05
END PLANE
```