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Modeling response of soil erosion and runoff to changes in precipitation and cover

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Abstract

Global climate has changed over the past century. Precipitation amounts and intensities are increasing. In this study we investigated the response of seven soil erosion models to a few basic precipitation and vegetation related parameters using common data from one humid and one semi-arid watershed. Perturbations were made to inputs for rainfall intensities and amounts, and to ground surface cover and canopy cover. Principal results were that: soil erosion is likely to be more affected than runoff by changes in rainfall and cover, though both are likely to be significantly impacted; percent erosion and runoff will likely change more for each percent change in rainfall intensity and amount than to each percent change in either canopy or ground cover; changes in rainfall amount associated with changes in storm rainfall intensity will likely have a greater impact on runoff and erosion than simply changes in rainfall amount alone; changes in ground cover have a much greater impact on both runoff and erosion than changes in canopy cover alone. The results do not imply that

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future changes in rainfall will dominate over changes in land use, since land use changes can often be drastic. Given the types of precipitation changes that have occurred over the last century, and the expectations regarding changes over the next century, the results of this study suggest that there is a significant potential for climate change to increase global soil erosion rates unless offsetting conservation measures are taken.

Keywords: Climate change; Conservation; Erosivity; Land cover; Land degradation; Rainfall; Rainfall intensity; Sediment; Soil conservation; Soil erosion; Soil erosion models; Watersheds

1. Introduction

The consensus of atmospheric scientists is that the earth is warming, and as global temperatures increase the hydrologic cycle is becoming more vigorous. The Intergovernmental Panel on Climate Change (IPCC) has reported with virtual certainty (probability >99%) that both land and sea surface temperatures have increased by 0.4 to 0.7 °C since the late 19th century (IPCC Working Group I, 2001). Globally, 9 of the 10 warmest years since 1860 have occurred since 1990 (WMO, 2001). The IPPC also reported that there has been a very likely increase (probability 90–99%) in precipitation during the 20th century in the mid-to-high latitudes of the Northern Hemisphere. Groisman et al. (2001), for example, reported linear trends in precipitation weighted over the continental United States 0% in winter, +10% in the spring, +7% in summer, and +15% in autumn for the period 1910 to 1996.

Much of the increase in precipitation that has been observed worldwide has been in the form of heavy precipitation events (IPCC Working Group I, 2001; Easterling et al., 2000a,b,c). For example, Karl and Knight (1998) reported that from 1910 to 1996 total precipitation over the contiguous US increased, and that 53% of the increase came from the upper 10% of precipitation events (the most intense precipitation). The percent of precipitation coming from days of precipitation in excess of 50 mm also increased significantly. Climate models are predicting a continued increase in intense precipitation events during the 21st century (IPCC Working Group II, 2001).

Soil erosion rates may be expected to change in response to changes in climate for a variety of reasons, the most direct of which is the change in the erosive power of rainfall (Favis-Mortlock and Savabi, 1996; Williams et al., 1996; Favis-Mortlock and Guerra, 1999; Nearing, 2001; Pruski and Nearing, 2002a). Soil erosion responds both to the total amount of rainfall and to differences in rainfall intensity, however, the dominant variable appears to be rainfall intensity and energy rather than rainfall amount alone. One study predicted that for every 1% increase in total rainfall, erosion rate would increase only by 0.85% if there were no correspondent increase in rainfall intensity. However if both rainfall amount and intensity were to change together in a statistically representative manner predicted erosion rate increased by 1.7% for every 1% increase in total rainfall (Pruski and Nearing, 2002a).

A second dominant pathway of influence by climate change is through changes in plant biomass. The mechanisms by which climate changes affect biomass, and by which biomass changes impact runoff and erosion are complex (Williams et al., 1996; Pruski and Nearing, 2002b; Favis-Mortlock and Guerra, 1999) For example, anthropogenic increases in atmospheric carbon dioxide concentrations cause increases in plant production rates and changes in plant transpiration rates (Rosenzweig and Hillel, 1998), which translate to an increase in soil surface canopy cover and, more importantly, biological ground cover. On the other hand, increases in soil and air temperature and moisture will likely cause faster rates of residue decomposition due to an increase in microbial activity. More precipitation may also lead to an increase in biomass production. Temperature changes also affect biomass production levels and rates in complex ways. Corn biomass production, for example, may increase with increasing temperature, particularly if the growing season is extended, but then may decrease because of temperature stresses as the temperature becomes too high (Rosenzweig and Hillel, 1998).

Another potential impact of climate change is associated with the changes from snowfall to rainfall. If decreased days of snowfall translates correspondingly to increases in days of rainfall, erosion by storm runoff is liable to increase. Higher temperatures may translate to higher evaporation rates, while more rainfall would tend to lead to higher soil moisture levels. Even changes in soil surface conditions, such as surface roughness, sealing, and crusting, may change with shifts in climate, hence impacting erosion rates.

Finally, if farmers react to climate change by implementing different crops, crop varieties or even change land use patterns, the erosion and deposition rates and patterns within catchments may change completely and therefore net soil loss may change as well. For example, in western Europe, rainwater storage buffers are often used to protect villages from mud flows. The effect that a change in rainfall will have on the locations and dimensions of these buffers is on the political agenda.

Several studies have been conducted on the effects of climate change on soil erosion using computer simulation models. Favis-Mortlock and Boardman (1995) used the EPIC model, and Favis-Mortlock and Savabi (1996) used the WEPP model, to study the response of erosion to climate change on the South Downs of the UK. These studies showed a non-linear spatial and temporal response of soil erosion to climate change, with relatively greater increases in erosion during wet years compared to dry years, and patchy increases spatially. Favis-Mortlock and Guerra (1999) used the WEPP model to study erosional response to climate change in the Mato Grosso region of Brazil using inputs from a general circulation model (GCM). They predicted an average increase in soil erosion of the order of 27% between 1995 and 2050. Pruski and Nearing (2002b) simulated erosion at eight locations in the United States using the WEPP model, with GCM input. The results indicated a complex set of interactions between the several factors that affect the erosion process. Overall, these results suggested that where precipitation increases were significant, erosion increased. Where precipitation decreases occurred, the results were more complex due largely to interactions of plant biomass, runoff, and erosion, and either increases or decreases in overall erosion could occur. The Soil and Water Conservation Society recently published a comprehensive review on the conservation implications of climate change on soil erosion and runoff from cropland (SWCS, 2003). The review details most of the recent studies related to observed and simulated changes in precipitation patterns, and their correspondent effects on soil erosion and runoff. That report also discusses the implications of these factors on conservation programs within the United States, the key concepts of which have relevance worldwide.

Every soil erosion model has limitations in terms of its representation of erosion processes (see, e.g., Jetten et al., 1999, 2003), and thus there is always a level of uncertainty in interpreting the results of studies that look at climate change impacts on soil erosion. The objective of the current study was to investigate the response of a variety of different soil erosion models to a few key variables related to climate change, i.e., to a few basic precipitation and vegetation related parameters. Seven different erosion models were calibrated by scientists familiar with those models to common data from a humid watershed in the Belgium and a semi-arid watershed in the southwest United States. Perturbations were then made to rainfall intensities and amounts and to ground surface and plant canopy covers in order to assess and compare the sensitivities of the models to runoff and erosion.

2. Methods

Data were provided to modelers for two watersheds, including information on topography, soils, land use, and weather for a specific time period. Three storms were selected from each of the data sets for analysis in the exercise. Scenarios were designated as perturbations to the climate and land cover information for those storms as described below. The modelers then gathered at a meeting of the Soil Erosion Network in Tucson, AZ, USA on November 17–19, 2003 and presented an overview and the results of the exercise for their model.

2.1. Lucky Hills watershed description and data

The Lucky Hills instrumented watershed number 103 was used (Table 1). Lucky Hills is located within the Walnut Gulch Experimental Watershed, which covers 150 km^2 in southeastern Arizona, USA (31°43′N, 110°41′W) near the town of Tombstone. The watershed is contained within the upper San Pedro River Basin which encompasses 7600 km^2 in Sonora, Mexico and Arizona. The watershed is representative of approximately 60 million hectares of brush and grass covered rangeland found throughout the semi-arid southwest and is a transition zone between the Chihuahuan and Sonoran Deserts. Elevation of the watershed ranges from 1250 m to 1585 m MSL. Cattle grazing is the primary land use with mining, limited urbanization, and recreation making up the

Table 1
Characteristics of the tested watersheds

Characteristic	Lucky Hills watershed	Ganspoel watershed
Area (ha)	3.7	109.4
Annual rainfall (mm)	300	740
Land use/plant community	Shrub dominated rangeland	Mixed agricultural crops (beets, potatoes, maize)
Plant cover (%)	25%	40–90%
Soil type	Gravelly Sandy Loam	Silt Loam

remaining uses. Walnut Gulch is dry about 99% of the time. Average slope in the watershed is 6%.

Mean annual temperature at Tombstone is 17.6 °C and mean annual precipitation is approximately 300 mm. There is both a winter and summer rainy season at Walnut Gulch, but runoff results almost exclusively from convective storms during the summer season of July through September. These storms tend to be very localized and of short duration. Winter rains are generally low-intensity events that cover a large area.

The Lucky Hills watershed 103 is approximately 3.7 ha in size. Land cover is shrub dominated, semi-arid rangeland characterized by mounds under shrub and lower inter-shrub area. Cover during the rainy season is approximately 25% bare soil, 25% canopy, and 50% erosion pavement (rocks). Dominant vegetation includes: Creosote (Larrea tridentata, shrub) and Whitethorn (Acacia constricta, shrub), with lesser populations of Desert Zinnia (Zinnia acerosa, shrub), Tarbush (Flourensia cernua, shrub), and Black Grama (Bouteloua eriopoda, grass). The dominant soil is a McNeal Gravelly Sandy Loam, with approximately 25% rock fragments in the surface layer. The matrix material of surface layer is composed of 60% sand, 25% silt, and 15% clay. The soil formed in coarse-grained material of a deep foothill alluvial fan of the Dragoon Mountains.

Sediment from the watershed is monitored with a supercritical flume with an automatic traversing slot sampler. Precipitation is monitored in Walnut Gulch with a network of 88 weighing-type recording raingages, one of which was located within the Lucky Hills area.

Data on precipitation, runoff amounts, peak runoff rates, runoff duration, and sediment amounts were provided to the modelers for all storms occurring from 1982 through 1992. The storms of 1 September, 1984, 10 September, 1982, and 12 August, 1982 were selected to be used for the modeling comparison exercise. These represent a large, medium, and small storm, respectively, from the record (Table 2). In addition, detailed soil data, surface cover information, and precipitation hyetographs for all storms were provided, along with a Digital Elevation Model of the area.

2.2. Ganspoel watershed description and data

Ganspoel is a 109.4 ha catchment west of Leuven (Belgium) (Table 1). The landscape is typical for large parts of northwest Europe that were covered with Loess deposits in the late Pleistocene. The majority of the area has slopes less than 10%, except for a central dry

Table 2
Observed runoff and sediment at Ganspoel and Lucky Hills 103 watersheds for the storms used in the model comparison

Watershed	Year	Month	Day	Rainfall depth (mm)	Runoff volume (mm)	Peak runoff rate (mm/h)	Runoff duration (min)	Event sediment (kg/ha)
Ganspoel	1998	9	14	41.0	9.44	3.35	774	604.5
109.4 ha	1997	7	11	19.5	2.20	2.84	206	393.1
	1997	5	19	10.0	0.23	0.34	210	83.4
	1997	5	21	3.0	0.16	0.18	184	24.9
Lucky Hills	1984	9	1	32.8	15.00	45.98	78	3075.1
3.7 ha	1982	9	10	18.8	3.26	8.70	133	721.3
	1982	8	12	6.6	0.33	2.87	22	81.9

valley which has slopes as high as 20–25%. The Silt Loam soils are suitable for agriculture, but also prone to crusting. The land use in Ganspoel consists of intensive arable farming (there are about 80 fields) with some roads, buildings, grassland, and forest. Main crops are sugar beet, potatoes and fodder maize (sown in April and harvested in September), and winter cereals (sown in November and harvested in August). For detailed catchment characteristics and analyses of erosion and sedimentation features and processes, the reader is referred to Steegen et al. (2001), Desmet and Govers (1996), and Van Oost et al. (2000).

The Ganspoel database did not include soil physical parameters so data were taken from the Limburg catchments of the LISEM database, which are very similar and relatively near (see, e.g., Takken et al., 1999). However, the data set did include structured observations during the course of year of soil cover (plant and residue), crust classes, and soil roughness classes (2 weekly observations). Based on these observations assumptions were made about temporal changes in saturated hydraulic conductivity (K_{sat}) (2–200 mm/h), soil surface roughness (0.5–1.5 cm), plant cover (40–90%), soil cohesion (2–7 kPa), and Manning's n (0.02–0.12) values. Because information on the basal cover was not present, percent changes of Manning's n values were used for the Ganspoel scenarios instead. This is of course not the same and is likely to influence the scenario results.

The climate of this area shows relatively dry summers and mild winters. Average annual precipitation is 740 mm occurring largely in spring and autumn. This climate combined with the cropping cycle means that the erosion risk is highest in early spring when the crop cover is low and sedimentary crusts may have formed, or in late autumn after harvest.

Six rainstorms were selected for model calibration from the 3-year database that ranged in size from 3.0 to 41.0 mm, with runoff amounts ranging from 0.16 to 9.4 mm. Out of these six events, three were chosen to model the scenarios (see Table 2). It is important to note that the main drainage way is a narrow channel that is covered with grass, which probably affects the shape of the hydrograph and may also mask the effect of scenario changes of Manning's n on the fields. The average measured response time is more than 60 min for all chosen events, which is relatively long for this type of catchment.

2.3. Modeling scenarios

The intention of the modeling exercise was to perform a sensitivity analysis as a first step at looking at climate change impacts on erosion. Sensitivity of runoff amounts, peak runoff rates, gross erosion, and net sediment yield were assessed relative to changes in rainfall intensities and amounts and differences in canopy and ground cover.

The basic methodology was to calibrate the models to measured data from two watersheds, a humid area, cropped watershed in the Belgium and a semi-arid rangeland watershed in Arizona, and to then superimpose change scenarios on those baseline simulations. The scenarios tested are listed in Table 3.

Because of model limitations, not all models were capable of application on both data sets, and hence were only run on one data set. In one case the model was not able to represent the watershed scale, and could only be applied at a hillslope scale. In these cases calibration was not performed in the same manner as was possible with the other models,

Table 3
Definitions of rainfall and cover change scenarios tested for model sensitivity

Scenario	Variable	Instructions for conducting scenarios
1A	rainfall amount and intensity	Change in rainfall depth (total rainfall amount) by −20%, −10% 0, +10%, and +20% by changing rainfall intensity by −20%, −10% 0, +10%, and +20%, holding rainfall duration (time) constant.
1B	rainfall amount and duration	Change in rainfall depth (total rainfall amount) by −20%, −10% 0, +10%, and +20% by changing rainfall duration (time) by +20%, +10% 0, −10%, and −20%, holding rainfall intensities constant.
2	rainfall intensity alone	Hold total rainfall depth (amount) per storm constant, looking at rainfall intensity effects separate from rainfall amount effects by simultaneously changing rainfall intensities and durations as: • −20% intensity with +25% duration (0.8 * 1.25 = 1); • −10% intensity with +11.1% duration (0.9 * 1.11 = 1.0); • 0% intensity with 0% duration; • +10% intensity with −9.1% duration (0.909 * 1.1 = 1.0); • +20% intensity with −16.7% duration changes (1.2 * 0.833 = 1.0).
3A	ground cover	Ground cover change by −20%, −10% 0, +10%, and +20%, rainfall unchanged; OR Manning's *n* change by −20%, −10% 0, +10%, and +20% where ground cover information was not available or not used by a model, rainfall unchanged.
3B	canopy cover	Plant canopy cover change by −20%, −10% 0, +10%, and +20%, rainfall unchanged.
3C	ground and canopy cover	Both ground cover (or Manning's *n*) and canopy cover change by −20%, −10% 0, +10%, and +20%, rainfall unchanged.

and only a sensitivity analysis was performed. These and other limitations are discussed below in the description of the models.

2.4. Model descriptions

2.4.1. LISEM

The Limburg Soil Erosion Model (LISEM) was constructed at the end of the 1980s for the Provincial Government of Limburg (De Roo et al., 1989; Jetten et al., 1998). Limburg is the area in the Netherlands where off-site effects (mud flows) often cause damage to houses and infrastructure. LISEM was developed specifically for this problem by simulating the effect of on-site anti-erosion measures such as grass strips (Jetten and de Roo, 2001) and spatial changes of tillage practices (mulch, crop cycle changes). The Limburg Waterboard currently uses LISEM to design several hundred rainwater buffers to protect the villages. Outside the Netherlands it has been used mostly to simulate land use change scenarios in several countries in north-west and Mediterranean Europe, East Africa, and Asia. The model is event based and designed for small scale areas (50 m^2 to 5 km^2). To this end LISEM is linked to a GIS and all input and output data are in the form of raster maps (grid cell resolution usually between 2 and 20 m). Hydrological processes included are spatially distributed rainfall, interception and throughfall, and infiltration using a two-layer Green and Ampt or a solution of the Richard's equation. Erosion includes splash erosion and flow erosion based on transport capacity using unit streampower. Water and sediment are routed with a kinematic wave over a raster based flow network, which is based either on steepest slope or tillage direction (Takken et al., 1999). The use of a raster GIS has advantages and disadvantages. On the one hand the detailed spatial variability of many parameters is available and erosion patterns can be compared directly with field observations (see, e.g., Takken et al., 2001). On the other hand many processes are based by the characteristics of the individual cells, and this sometimes leads to unrealistic alternating patterns of erosion and deposition over short distances which influence the net soil loss (Jetten et al., 2003).

In order to correctly simulate the Ganspoel events, LISEM had to be calibrated for each storm separately, since a single calibration set for all events could not be found. The saturated hydraulic conductivity (K_{sat}) was decreased between 10% and 80% of the database values, assuming a certain degree of crusting, to arrive at the measured total runoff. For instance, for the smallest event of 21 May, 1997, a decrease in K_{sat} of 80% had to be assumed to predict the measured discharge, while the K_{sat} was decreased by 10% for the larger event of 19 May, 1997, indicating a strong increase in crusted surface. A Manning's n of 0.4 had to be assumed for the main channel (which was in fact a ditch with dense grass) to arrive at the correct hydrograph shapes and response time of approximately 60 min. This influences the results considerably: while LISEM normally is sensitive to changes in Manning's n, the channel obscures the changes in Manning's n on the fields in scenarios 3A and 3C. Normally this parameter has much more influence on the results. The cohesion had to be increased considerably to predict the measured net soil loss. The Lucky Hills events also had to be calibrated separately using the same process. Simulated soil loss was consistently too high compared to measured rates and a high cohesion had to be assumed. Possibly LISEM has some problems simulating the stony sandy soils since the transport capacity is based on the median of the soil texture, which may not be a good measure for the suspended matter behaviour in this catchment. Again, K_{sat} had to be decreased, and Manning's n had to be increased for this catchment, which could be correct since the surface is quite rough and stony.

2.4.2. MEFIDIS

MEFIDIS (Nunes and Seixas, 2004) is the Portuguese acronym for Physically Based Spatially Distributed Erosion Model. The model was developed at the Department of Environmental Sciences and Engineering, New University of Lisbon as a storm erosion research model for the Portuguese Ministry of Agriculture.

The model was designed to take advantage of spatially distributed data by dividing the simulation area into the smallest possible homogenous units, and using simple physically based equations to simulate runoff and erosion yield within each unit. The equations were chosen based on parameter availability, either directly from existing databases or indirectly via estimation from existing values. The model is event-based (tested from 20 min to 72 h). The area of application is one small- or medium-sized watershed (tested from 0.05 to 120 km^2).

MEFIDIS divides the area of simulation into a quadrangular grid, depending on the resolution of available spatial information. Typical resolutions used range from 5×5 m to 30×30 m, but the model has been applied to simulate laboratory flumes with 0.3×0.3 m cells. Runoff generation and sediment detachment/deposition are simulated for each cell using physically based equations; runoff and suspended sediment are then routed throughout the watershed. The equations are solved with a finite difference approach, using a forward-time backward-space explicit scheme (Chow et al., 1988). The model is dynamic, and the explicit approach used in solving the equations requires short time-steps, usually 0.1 s to 0.3 s × cell size in meters (or 1 s to 10 s).

The model takes into account rainfall, infiltration, and surface storage for runoff generation. Infiltration is calculated using the Green–Ampt equation (Chow et al., 1988). MEFIDIS also simulates saturation excess runoff by accounting for ground water inside each grid cell. Surface water storage is dependent on surface roughness. The runoff routing direction for each grid cell is that which presents the steepest slope; runoff flow is computed using a kinematic wave approach via the Manning–Strickler equation (Chow et al., 1988).

Sediment detachment from interill areas is assumed to result only from rainfall splash. Vegetation and ground cover are assumed to protect the soil from detachment; rainfall falling on unprotected soil detaches sediment as a function of kinetic energy and soil erodibility computed from soil cohesion and percentage of clay particles (Sharma et al., 1993). All sediment detachment in interill areas is assumed to reach the runoff flow.

Sediment detachment from rill areas is simulated using the transport capacity approach, following Govers (1990). The sediment transport capacity of the flow is computed from the flow velocity and soil particle size. If this capacity in a given grid cell exceeds the sediment in suspension, more soil particles are detached from the soil surface. The rill detachment rate is a function of excess transport capacity and soil detachability computed from soil cohesion (Rauws and Govers, 1988). When the sediment in suspension exceeds the flow's transport capacity, the excess sediment deposits.

2.4.3. RUSLE

The Revised Universal Soil Loss Equation (RUSLE) is an upgrade from the empirically based USLE (Renard et al., 1997). It was developed by the USDA-Agricultural Research Service for use as a conservation planning and assessment tool. RUSLE was designed to predict long-term annual averages of soil loss. It does not have the capability for routing sediment through channels, hence its application is limited to small areas. Therefore, the model was not applied to the larger Ganspoel watershed. In the current application the model was calibrated to individual storm events by assigning values for the erosivity (R) and cropping (C) factors, and adjusting the value of the multiple of erodibility, slope length and steepness, and conservation practices factors (KLSP) until the value of the measured erosion was obtained. Sensitivity analysis was then performed for scenarios 1A, 1B, and 2 by making the appropriate adjustments to the R-factor and for scenarios 3A, 3B, and 3C by adjusting the C-factor. The value of KLSP remained constant. In this way the relative effects of the various scenarios could be assessed. Relationships from USDA Handbook 703 (Renard et al., 1997) were used to estimate the R- and C-factors.

2.4.4. STREAM

STREAM is a non-dynamic model that uses a raster-based, distributed approach to calculate runoff volume and soil loss within an agricultural watershed for a given rainfall event. It is based on an 'expert system' type approach which classifies and combines the dominant parameters on the basis of laboratory and field experimental data. It explicitly takes into account soil surface characteristics (i.e., crusting and roughness) to derive infiltration rates and soil erodibility. By incorporating crusting sensitivity as a key parameter, STREAM is particularly adapted to the context of the loess belt of north-western Europe where it was validated on two catchments of 100 and 1000 ha (Normandy, France).

STREAM operates at both the plot and watershed scales (Cerdan et al., 2002a,b; Souchère et al., 1998). At the plot scale seven integrative factors that embrace the dominant processes (rainfall amount and duration, surface sealing, random and oriented roughness, vegetation cover, and an antecedent rainfall index) are combined to define the infiltration capacity, soil water storage, and the potential sediment concentration of the flow. As long as the soil characteristics are uniform, the agricultural plot is considered as a homogeneous response unit, the factors taken into consideration being homogenised by cultural operations. Potential sediment concentration in the interrill flows range from 0–5 g/l to 25–35 g/l, depending upon soil surface and rainfall intensity parameters (Cerdan et al., 2002b).

At the watershed scale the flow network is calculated according to the topography, but also takes into account agricultural features that have an influence on flow direction such as the furrows or ditches. The flow is accumulated at the pixel level, the size of which is dictated by the DEM resolution. Sediment is routed with the flow in each pixel as a function of inflow from upslope and the potential sediment concentration.

For the Ganspoel watershed, all the parameters necessary to run STREAM were present in the input database except for the parameters related to the calculation of the flow network (e.g., wheel tracks, dead furrows, and headlands). No parameters were therefore estimated. However, some of the values for the parameters, including "crusting" and "roughness" that were given as inputs, were adjusted, as they were inconsistent with our expertise using the model in the environment simulated. For Lucky Hills all the input data needed for STREAM were not available. More experimental data would have helped in terms of deriving better parameters for STREAM to describe soil infiltration capacity and soil erodibility. The inputs were not statistically distributed for Lucky Hills.

In STREAM the vegetation cover is characterized in three classes (0–20%, 21–60%, 61–100%) and no distinction is made between ground and canopy cover. Therefore, only scenario 3C could be simulated, and in that case it could only be done shifting from one vegetative class to the next, rather than by percent cover.

2.4.5. KINEROS

The model KINEROS, developed by Smith et al. (1995) for the USDA Agricultural Research service, is a distributed, event-oriented, deterministic and physically based model. This model is primarily useful for predicting surface runoff and erosion over small agricultural and urban watersheds. Runoff is calculated based on the Hortonian approach and infiltration is calculated by Smith and Parlange (1978) infiltration model. KINEROS requires the watershed to be divided into homogeneous overland flow planes and channel segments, and models water movement over these elements in a cascading fashion. One-dimensional flow discharge per unit width is expressed in terms of the storage of water per unit area through the kinematic approximation. In KINEROS, the kinematic wave equations are solved numerically by a four-point implicit method.

Unsteady, free surface flow in channels is also represented by the kinematic approximation to the equations of unsteady, gradually varied flow. Channel segments may receive water and sediment uniformly from either or both sides of the channel, from one or two channels at the upstream boundary, or from a plane at the upstream boundary. The dimensions of planes are chosen to completely cover the watershed, so rainfall on the channel is not considered directly.

The general equation used in KINEROS to describe the sediment dynamics at any point along a surface flow path is a mass balance equation similar to that for kinematic water flow (Bennett, 1974). For upland surfaces, the rate of erosion of the soil bed is partitioned into two parts: splash erosion rate caused by the splash of rainfall on bare soil and hydraulic erosion rate due to interplay between shear force of water on the loose soil bed and the tendency of soil particles to settle under the force of gravity. Splash erosion rate is approximated as a function of rainfall rate and depth of flow. Hydraulic erosion rate is related to the difference between equilibrium concentration and the existing sediment concentration as a kinetic transfer process.

Kineros offers several options for the sediment transport relation to estimate the transport capacity of flow in channels or on a plane element. Julien and Simons (1985) showed that each could be represented by a generalized relation. The equations for each transport relationship are discussed in detail in the User Manual (Woolhiser et al., 1990).

The general approach to sediment transport simulation for channels is nearly the same as that for upland areas. The major difference in the equation is that splash erosion is neglected in channel flow, and the rate of lateral sediment inflow becomes important in representing lateral inflows.

2.4.6. SWAT

The Soil Water Assessment Tool (SWAT) was developed by the USDA-Agricultural Research Service. SWAT is a process model that incorporates a methodology to integrate land use and field-scale management practices within a watershed and evaluate the impacts that can be expected from their implementation over a long period of time (Arnold et al., 1999). It is a watershed-scale, continuous, daily time-step model that simulates the water, nutrient, chemical, and sediment movement in a watershed resulting from the interaction of weather, soil properties, stream channel characteristics, agricultural management, and crop growth. This model provides an analysis of water quality (nutrients, pesticides, and sediments) at the sub-basin outlets resulting from these factors.

Only the Lucky Hills watershed was simulated using SWAT. The watershed was modeled as one sub-basin with the McNeal soil and typical Southwest range vegetation. Soil properties in addition to what was specified in the data supplied for the exercise were taken from the Map Unit Use File (MUUF) database (Baumer et al., 1994). The crop properties of a generic land representation of southwestern US (arid) rangeland found in the SWAT crop file were used. The model uses daily precipitation, maximum/minimum temperatures, radiation, wind speed, and relative humidity. The daily precipitation values at the gauge stations 83 and 80 were used in the model. We obtained measured daily temperature data from the Douglas airport weather station. The other weather parameters were generated by the model using monthly characteristics from the Douglas airport station.

The runoff in SWAT is estimated with the Curve Number method and the sediment yield from watersheds is estimated with the Modified USLE (MUSLE) (Williams and Berndt, 1977). The Curve Number and the MUSLE C factor are adjusted on a daily basis based on the soil water content and the canopy and ground cover, respectively. Since MUSLE requires the peak flow rate for runoff, it is calculated by the model as a function of the maximum half-hour rainfall. The maximum half-hour rainfall is itself calculated by the model using the monthly maximum half-hour rain over the entire period of record, and a random number. These parameters (the monthly maximum half-hour rain) are provided by the user and are part of the monthly weather characteristics. The model then assumes a triangular rainfall distribution during each day. This causes problems when comparing specific storm results with measured data during storms that have a distribution different from the triangular distribution. In this exercise we used the maximum half-hour rainfall values given for the Douglas airport station.

SWAT has the capability to estimate the impact of an increase/decrease of canopy cover and ground cover combined, but it is difficult to separate the two given how it is represented in SWAT. Therefore, the scenarios for plant cover were not reported for the SWAT model.

2.4.7. WEPP

The Water Erosion Prediction Project (WEPP) model is a process-based model developed by the USDA-Agricultural Research Service for predicting spatial and temporal distributions of soil erosion and sediment yield from single hillslopes, agricultural fields and watersheds up to approximately 400 ha in size (Flanagan and Nearing, 1995). WEPP is composed of sub-models for stochastic weather generation, Green and Ampt infiltration, surface runoff, erosion mechanics, plant growth, residue management, tillage effects on the soil, and soil consolidation. Soil detachment, transport, and deposition processes are represented in the model using a steady-state sediment continuity equation which represents rill and interrill processes. Rill detachment rate is dependent upon the ratio of sediment load to transport capacity, rill erodibility, hydraulic shear stress, surface cover, below ground residue, and consolidation. Net deposition is calculated when sediment load is greater than transport capacity. Interrill erosion is represented as a function of rainfall intensity, ground cover, canopy cover, and interrill soil erodibility. The model is designed to accommodate spatial and temporal variability in topography, surface roughness, soil properties, hydrology, and land use conditions on hillslopes. The model has been validated against approximately thousands of plot years of natural runoff and erosion data from many sites in the United States and in other parts of the world.

The Geospatial interface to the WEPP model (GeoWEPP) (Renschler, 2003) was used to delineate the watershed configuration of WEPP channels and representative hillslopes for both watershed sites. The GeoWEPP delineation procedure is based on integrated software code of the topographic analysis tool TOPAZ developed by Garbrecht and Martz (2000). TOPAZ uses two key parameters to initiate channel delineation and its contributing areas: the critical source area (CSA) and minimum source channel length (MSCL). There was no clear identification of the points where concentrated flow in channels at the Lucky Hills site starts. Therefore a topographic analysis of the provided

Digital Elevation Model (DEM) was used to determine a single channel for the entire watershed. The CSA and MSCL appeared to be 0.5 ha and 100 m, respectively. In case of the much larger and more humid Ganspoel site, there was a longer channel indicated in the provided land use information as well as a road that functions as a contributory of temporarily occurring concentrated runoff to the main channel. The delineation with 20 ha for the CSA and 200 m for the MSCL resulted in a simple channel network with one contributory (the road) in a main channel with representative hillslopes for contributing areas from top and either side of the channel. The version of GeoWEPP used at the time of the modeling exercise allowed only delineating a single representative hillslope for each contributing area with a single soil and land use along the entire hillslope. However, the automatic delineation procedure of the drainage networks and slope shapes with the same objective method was favored to a manual delineation of hillslopes and channels in both watersheds.

2.5. Analyses of data

This basic methodology used to interpret the results of the study was linear sensitivity analysis. All of the results of the models were analyzed in terms of relative changes in runoff volume and erosion from the zero change, or baseline, conditions. Specifically, the ratios of predicted runoff and erosion for the −20%, −10%, +10%, and +20% cases to the corresponding values for the zero change condition were calculated for each model for each storm and each change scenario. This was done because the models were calibrated with data provided for those baseline conditions, and since we were interested in this study to look at changes in model response as a function of storm and cover inputs rather than absolute estimates of runoff and erosion. After the change ratios were calculated, linear sensitivity values were calculated using linear regression between the percent change of response variable to the percent change of input variable for each model and each scenario.

We used the median values of sensitivities between the models as an index to represent the sample set of model responses for each storm and scenario. It was apparent that the model results followed a skewed, though unknown, distribution type, and attempts to use standard means testing between model results did not give sensible results. Coefficients of variation (standard deviation divided by the mean) were used to quantify differences in variability between models, that is, under which scenarios and storms the models were predicting more similarly or differently.

3. Results and discussion

3.1. Lucky Hills watershed results

Table 4 shows the linear sensitivities (non-dimensional) of model sediment predictions relative to changes in inputs for the various scenarios for the Lucky Hills watershed. These results represent the average percent change in sediment response to each percent change in the respective input values for each scenario (Table 3).

Table 4
Sensitivities (non-dimensional) of model sediment predictions relative to changes in inputs for the various scenarios for the Lucky Hills watershed, expressed as percent change in sediment response to each percent change in input values calculated using linear regression

Scenario	Storm	RUSLE	STREAM	LISEM	WEPP	MEFIDIS	KINEROS	SWAT	Median of model sensitivities	Magnitude of change (kg ha^{-1})
1A	1-Sep-84	2.17	6.30	2.26	1.68	5.07	1.96	4.47	2.26	69.57
	10-Sep-82	2.29	12.50	5.81	2.71	10.58	4.98	9.34	5.81	41.90
	12-Aug-82	2.25	36.02	15.64	9.92	19.88	5.52	1.29	9.92	8.12
1B	1-Sep-84	1.00	2.83	1.60	1.94	3.43	1.46	4.37	1.94	59.60
	10-Sep-82	1.00	7.40	2.95	2.00	3.94	2.41	9.02	2.95	21.29
	12-Aug-82	1.00	28.50	9.51	5.83	9.02	3.78	1.28	5.83	4.78
2	1-Sep-84	1.17	4.35	0.69	0.80	1.31	0.47	0.12	0.80	24.60
	10-Sep-82	1.28	7.10	2.98	0.70	6.26	2.73	0.25	2.73	19.69
	12-Aug-82	1.25	9.50	4.84	1.88	4.52	1.48	0.21	1.88	1.54
3A	1-Sep-84	−2.60	NA*	−0.03	−0.55	−1.31	−0.45	NA	−0.55	−17.04
	10-Sep-82	−2.60	NA	−0.09	−1.15	−1.75	−0.60	NA	−1.15	−8.33
	12-Aug-82	−2.60	NA	−0.27	0.00	−2.95	−1.86	NA	−1.86	−1.53
3B	1-Sep-84	−0.23	NA	−1.18	−0.09	−0.10	−0.06	NA	−0.10	−3.10
	10-Sep-82	−0.23	NA	−1.58	−0.09	−0.31	−0.13	NA	−0.23	−1.64
	12-Aug-82	−0.23	NA	−2.79	0.00	−0.77	−0.44	NA	−0.44	−0.36
3C	1-Sep-84	−2.85	NA	−1.20	−0.66	−2.10	−0.51	NA	−1.20	−37.00
	10-Sep-82	−2.85	NA	−1.67	−1.24	−2.06	−0.75	NA	−1.67	−12.03
	12-Aug-82	−2.85	NA	−3.08	0.00	−3.81	−2.34	NA	−2.85	−2.335

Magnitude of change is the erosion change for each 1% change in input, and was calculated based on the median model results and measured storm sediment from Table 2.
NA: not available.
STREAM gives total catchment erosion instead of sediment yield.

3.1.1. Erosion

All of the models responded with positive sensitivities to scenarios 1A, 1B, and 2, which means that predicted erosion increased with increases in both precipitation amount and precipitation intensity (Table 4). All of the models responded with negative sensitivities to scenarios 3A, 3B, and 3C, which means that predicted erosion decreased with increases in both ground cover and canopy cover. These results are consistent with expectation that erosion should increase as the driving force (rainfall) increases and decrease with more protection to the soil surface in the form of plant leaves, residue or litter, and rocks.

The models overall were most sensitive to scenario 1A, which was an increase in storm rainfall amounts by way of an increase in rainfall intensity. Median sensitivity values ranged from 2.3 to 9.9 for the three storms (Table 4). This would indicate that, according to the model predictions, rainfall increases associated with increased rainfall intensity are quite important relative to potential changes in erosion rates under climate change. The exceptions in the model predictions were for RUSLE, for which ground cover (scenarios 3A and 3C) had higher sensitivities than did rainfall intensity. This may be due to the fact that RUSLE was designed as an average annual erosion model, and that we have applied the model to individual storms. The second most sensitive scenario was that for increase in rainfall amount by way of an increase in rainfall duration (scenario 1B), with median sensitivities ranging from 1.9 to 5.8 for the three storms. It was interesting that the models were also sensitive to scenario 2, wherein rainfall intensity changes were evaluated without associated changes in total rainfall depths for the storms. These results point out the importance of rainfall relative to climate change impacts on soil erosion, and the potential implications of historically observed increases in intense precipitation events (IPCC Working Group I, 2001; Easterling et al., 2000a,b,c; Karl and Knight, 1998) and predictions of a continued increase in intense precipitation during the 21st century (IPCC Working Group II, 2001).

The models were all sensitive to cover changes, also. With the exception of LISEM, all of the models showed much greater sensitivity to ground cover (scenario 3A) that was in contact with the soil surface than to plant canopy cover (scenario 3B). This result makes sense in terms of the processes affected by the two types of cover. Both ground and canopy cover reduce the energy of falling raindrops, which will effect a decrease in soil erosion by splash. Ground cover, though, also acts as a significant deterrent to rill erosion by both protecting the soil surface from the forces of flowing water and by dissipating energy of flow that would otherwise be available to transport sediment.

In almost every case sensitivity values were greater for the smaller storms (see Table 2; storms in Table 4 are listed in order from largest to smallest). The only exception to this was for scenario 2 where storm intensity was increased with no change in total rainfall. In that case the RUSLE, MEFIDIS, KINEROS, and SWAT models showed a higher sensitivity to intensity for the medium storm than for the smallest storm. The other significant exception to this was for the sensitivity of the RUSLE model to cover changes. The RUSLE model is limited by its structure to a multiplicative form with no interaction between rainfall erosivity and cover effects. Hence, the sensitivities of the RUSLE model to cover changes were the same irrespective of storm size. The more process-based models did predict such an interaction.

Note that while the models predicted a greater relative change (i.e., sensitivity) for the smaller storm, the absolute changes in magnitude of erosion was greater for the larger storms (Table 4). For example, for scenario 1A, the median of the model results would indicate a 9.9% increase in erosion for every 1% change in rainfall amount and intensity for the storm of 12 August, 1982, and only a 2.3% change in erosion for the storm of 1 September, 1984. However, a 9.9% change in erosion for the storm of 12 August, 1982 (see Table 2) translates to 8.1 kg ha^{-1}, while a 2.4% change in erosion for the storm of 1 September, 1984 translates to 69.6 kg ha^{-1}.

There was a great deal of coherence between the seven models in terms of their relative responses of predicted runoff and erosion as a function of the simulated changes in rainfall and cover. As mentioned above, most of the models showed the greater sensitivity to rainfall changes, particularly to changes in the combination of rainfall amount and intensity (scenario 1); and most of the models showed a greater influence of ground cover as compared to canopy cover. All of the models showed a general tendency to have a greater relative influence, though a lesser absolute difference, on the smaller storms.

Of the process-based models, STREAM and MEFIDIS tended to be the most sensitive to rainfall changes, and MEFIDIS the most sensitive to cover changes. Results for STREAM relative to cover changes are not reported here, because STREAM uses a categorization scheme to account for cover differences. In STREAM, cover is categorized into one of three general levels of low, medium, and high. This is a reasonable approach for predicting erosion, given the natural variability in the data. However, it did not allow us to perform the exercise here and hence we were not able to execute STREAM as a function of percent changes in cover. The WEPP and KINEROS models tended to be the least sensitive of the process-based models in this exercise.

The RUSLE model exhibited perhaps the least differences between treatments than did the other models. This was probably due to the fact that it is an empirical model designed to show linear trends as a function of individual factors affecting erosion. For example, for four of the six scenarios RUSLE showed no differences in response among the three storms. In general the RUSLE model showed a lesser sensitivity to rainfall, and a greater sensitivity to cover, than did the process-based models.

As measured by the coefficient of variation between relative model responses, the models tended to behave more coherently for cover than for rainfall, and for the larger storms as compared to the smaller ones (Table 5).

3.1.2. Runoff

Sensitivities for runoff response of the models followed many of the same patterns as did sensitivities for erosion, but in nearly every case the median values of sensitivity for the models were less for runoff than for erosion (Tables 4 and 5). This makes sense in terms of the processes. Erosion is affected by the runoff amounts as well as directly by rainfall energy and cover, thus the overall response to rainfall and cover changes will be greater for erosion than for runoff amounts.

Most of what was discussed above for erosion was also true for the runoff. The median sensitivities were greater for rainfall than for cover, the greatest overall sensitivity was to scenario 1, sensitivities were greater for the smaller storms, magnitudes of change were greater for the larger storms, and ground cover had a much greater effect on runoff response than did canopy cover.

Table 5
Coefficients of variation, CV (%), between the model results for the relative changes in sediment and runoff from the baseline (zero change) conditions for the Lucky Hills watershed

Scenario	1A	1B	2	3A	3B	3C	Average over scenarios
Sediment							
1-Sep-84	31.8	20.1	24.2	14.8	16.9	14.1	20.3
10-Sep-82	59.7	47.7	45.8	14.6	9.2	11.5	31.4
12-Aug-82	93.4	85.2	50.9	20.6	11.3	20.3	46.9
Average of storms	61.6	51.0	40.3	16.7	12.5	15.3	32.9
Runoff							
1-Sep-84	30.4	12.3	26.8	3.6	0.7	4.1	13.0
10-Sep-82	50.1	40.4	43.7	9.2	1.1	9.3	25.6
12-Aug-82	104.0	87.9	55.9	10.8	6.2	10.8	45.9
Average of storms	61.5	46.8	42.1	7.9	2.7	8.1	28.2

Each storm average CV is an average of four values of CV related to the four levels of input change: −20%, −10%, +10%, and +20% input change for each scenario.

3.2. Ganspoel watershed results

Tables 6 and 7 show the linear sensitivities (non-dimensional) of model runoff and sediment predictions relative to changes in inputs for the various scenarios for the Ganspoel watershed. These results represent the average percent change in runoff and sediment response to each percent change in the respective input values for each scenario (Table 3). Note that for various reasons, only four models worked this data set: LISEM, WEPP, MEFIDIS and STREAM. Also, not all of those four models were able to give results for all of the storms studied. This led to some limitations in the analyses. For example, because the results of certain models tended to have higher sensitivities in general than other models, the exclusion of a particular model for a particular storm led in some cases to a lack of trend in the data that may have been present had all the models produced results for all the storms. In other words, the results for Ganspoel were more variable than those for Lucky Hills (Tables 6 and 7). Nonetheless, many of the same basic trends in the results were evident.

The reason for the difficulty for the models to simulate the storms at Ganspoel is in part due to the fact that Ganspoel is a much larger and more complex watershed than is Lucky Hills. While Lucky Hills was a single land use watershed of under 4 ha, Ganspoel

Table 6
Sensitivities (non-dimensional) of model runoff volume predictions relative to changes in inputs for the various scenarios for the Lucky Hills watershed, expressed as percent change in runoff volume response to each percent change in input values calculated using linear regression

Scenario	Storm	STREAM	LISEM	WEPP	MEFIDIS	KINEROS	SWAT	Median of model sensitivities	Magnitude of change (mm)
1A	1-Sep-84	6.31	1.94	1.80	2.68	1.91	2.60	2.27	0.341
	10-Sep-82	12.50	3.97	3.05	5.50	4.38	5.23	4.80	0.156
	12-Aug-82	35.98	8.60	7.63	9.53	5.38	1.30	8.11	0.027
1B	1-Sep-84	2.83	1.46	2.22	2.04	1.47	2.54	2.13	0.319
	10-Sep-82	7.40	2.05	2.21	2.58	2.18	5.12	2.40	0.078
	12-Aug-82	28.50	5.96	4.38	5.52	3.94	1.30	4.95	0.016
2	1-Sep-84	4.35	0.50	1.06	0.64	0.45	0.07	0.57	0.085
	10-Sep-82	7.10	1.94	0.78	3.15	2.31	0.14	2.13	0.069
	12-Aug-82	9.49	3.33	1.38	3.44	1.40	0.00	2.36	0.008
3A	1-Sep-84	NA*	−0.02	−0.57	−0.20	−0.12	NA	−0.16	−0.025
	10-Sep-82	NA	−0.06	−1.35	−0.25	−0.39	NA	−0.32	−0.010
	12-Aug-82	NA	−0.19	0.00	−1.33	−1.37	NA	−0.76	−0.002
3B	1-Sep-84	NA	−0.02	−0.10	0.00	−0.03	NA	−0.03	−0.004
	10-Sep-82	NA	−0.16	−0.10	0.00	−0.15	NA	−0.13	−0.004
	12-Aug-82	NA	−0.88	0.00	0.00	−0.32	NA	−0.16	−0.001
3C	1-Sep-84	NA	−0.08	−0.68	−0.20	−0.15	NA	−0.18	−0.027
	10-Sep-82	NA	−0.22	−1.45	−0.25	−0.54	NA	−0.39	−0.013
	12-Aug-82	NA	−1.07	0.00	−1.33	−1.70	NA	−1.20	−0.004

Magnitude of change is the runoff change for each 1% change in input, and was calculated based on the median model results and measured storm runoff from Table 2.
NA: not available.

Table 7
Sensitivities (non-dimensional) of model sediment predictions relative to changes in inputs for the various scenarios for the Ganspoel watershed, expressed as percent change in sediment response to each percent change in input values calculated using linear regression

Scenario	Storm	STREAM	WEPP	MEFIDIS	LISEM	Median of model sensitivities	Magnitude of change (kg ha[1])
1A	14-Sep-98	5.19	7.46	2.07	5.24	5.22	31.52
	11-July-97	NA	15.67	NA	5.78	10.73	42.16
	19-May-97	5.94	NA	4.18	9.07	5.94	4.95
	21-May-97	2.80	NA	3.91	10.89	3.91	0.97
1B	14-Sep-98	1.64	4.88	1.74	2.52	2.13	12.88
	11-July-97	NA	10.12	NA	13.57	11.85	46.56
	19-May-97	4.31	NA	2.57	6.32	4.31	3.59
	21-May-97	2.03	NA	3.60	10.14	3.60	0.90
2	14-Sep-98	3.81	3.30	0.41	2.40	2.85	17.23
	11-July-97	NA	0.52	NA	0.80	0.66	2.59
	19-May-97	2.17	NA	1.18	3.74	2.17	1.81
	21-May-97	0.81	NA	0.51	1.11	0.81	0.20
3A	14-Sep-98	NA	0.00	−0.84	−1.95	−0.84	−5.08
	11-July-97	NA	0.00	NA	−0.32	−0.16	−0.63
	19-May-97	NA	NA	−0.51	−1.84	−1.18	−0.98
	21-May-97	NA	NA	−0.76	−3.60	−2.18	−0.54
3B	14-Sep-98	NA	−1.89	−0.02	−0.54	−0.54	−3.26
	11-July-97	NA	−0.04	NA	−1.79	−0.92	−3.60
	19-May-97	NA	NA	−0.26	−0.12	−0.19	−0.16
	21-May-97	NA	NA	−0.36	−0.23	−0.30	−0.07
3C	14-Sep-98	NA	−1.89	−0.87	−2.83	−1.89	−11.43
	11-July-97	NA	−0.04	NA	−2.20	−1.12	−4.40
	19-May-97	NA	NA	−0.78	−1.97	−1.38	−1.15
	21-May-97	NA	NA	−1.13	−3.43	−2.28	−0.57

Magnitude of change is the erosion change for each 1% change in input, and was calculated based on the median model results and measured storm sediment from Table 2.
NA: not available.

contained 80 fields with some roads, buildings, grassland, forest, a grassed main channel, and multiple crops with differing planting and harvesting schedules.

Despite the variability for this modeling exercise, the models showed surprisingly similar relative behavior for the different scenarios. One important finding from the Lucky Hills results was that scenario 1A had the greatest overall level of sensitivity, which implies that change in rainfall intensity is more important in terms of runoff and erosion than change in rainfall amount alone (scenario 1B). For Ganspoel, all of the models also generally showed the greatest sensitivity to scenario 1A, followed by scenario 1B, with generally less sensitivity to the other scenarios. Thus the results indicated that predicted erosion and runoff were most sensitive to changes in rainfall amount that comes in the form of rainfall amount changes due to intensity (scenario 1A), followed by change in rainfall amount due to rainfall duration (scenario 1B). There were a couple of exceptions, the most evident being the response of LISEM to the storm of 11 July, 1997. In that storm LISEM gave much greater sensitivity for runoff to scenario 1B than to scenario 1A (Table 8). The results for erosion followed accordingly (Table 7). It is not clear why this result

Table 8
Sensitivities (non-dimensional) of model runoff volume predictions relative to changes in inputs for the various scenarios for the Ganspoel watershed, expressed as percent change in runoff volume response to each percent change in input values calculated using linear regression

Scenario	Storm	STREAM	WEPP	MEFIDIS	LISEM	Median of model sensitivities	Magnitude of change (mm)
1A	14-Sep-98	4.25	4.68	2.03	2.24	3.25	0.31
	11-Jul-97	NA	5.53	NA	3.39	4.46	0.10
	19-May-97	5.97	NA	5.30	7.94	5.97	0.01
	21-May-97	2.89	NA	4.85	5.21	4.85	0.01
1B	14-Sep-98	1.49	4.07	1.53	1.33	1.51	0.14
	11-Jul-97	NA	4.11	NA	6.42	5.27	0.12
	19-May-97	4.30	NA	3.72	5.32	4.30	0.01
	21-May-97	2.07	NA	4.61	4.78	4.61	0.01
2	14-Sep-98	2.93	0.74	0.51	0.94	0.84	0.08
	11-Jul-97	NA	0.52	NA	0.70	0.61	0.01
	19-May-97	2.16	NA	1.36	2.99	2.16	0.00
	21-May-97	0.84	NA	0.49	0.48	0.49	0.00
3A	14-Sep-98	NA	0.00	−0.05	−0.07	−0.05	0.00
	11-Jul-97	NA	0.00	NA	−0.24	−0.12	0.00
	19-May-97	NA	NA	−0.63	−1.26	−0.95	0.00
	21-May-97	NA	NA	−0.93	−1.21	−1.07	0.00
3B	14-Sep-98	NA	−0.56	0.00	−0.24	−0.24	−0.02
	11-Jul-97	NA	−0.04	NA	−0.61	−0.33	−0.01
	19-May-97	NA	NA	0.00	−0.10	−0.05	0.00
	21-May-97	NA	NA	0.00	−0.12	−0.06	0.00
3C	14-Sep-98	NA	−0.56	−0.05	−0.58	−0.56	−0.05
	11-Jul-97	NA	−0.04	NA	−0.86	−0.45	−0.01
	19-May-97	NA	NA	−0.63	−1.36	−1.00	0.00
	21-May-97	NA	NA	−0.93	−1.22	−1.08	0.00

Magnitude of change is the runoff change for each 1% change in input, and was calculated based on the median model results and measured storm runoff from Table 2.
NA: not available.

came about. The storm of 11 July, 1997 had only half the rainfall and one quarter the runoff, yet a measured peak runoff value of nearly the same (85%) as the largest storm of 14 September, 1998. Perhaps the increase in rainfall intensity had a greater impact on the storm of 14 September than on the already relatively intense storm of 11 July.

As was true for the Lucky Hills' results, sensitivities of sediment to input changes were greater than those for runoff (Tables 6 and 7), but this was not true on every case. For example, for the storm of 21 May, 1997, sensitivity of runoff was slightly greater than for sediment to changes in both precipitation intensity and amount (scenarios 1A and 1B). Also as was also true for the Lucky Hills' results, all of the models showed a positive sensitivity to rainfall scenarios (1A, 1B, and 2) and a negative sensitivity to cover scenarios (3A, 3B, and 3C). Also similar to Lucky Hills was the fact that magnitude of sensitivity was generally greater for the rainfall scenarios than for the cover scenarios. The coefficients of variation between model results (Table 9) were also generally greater for the rainfall scenarios than for the cover scenarios, as was true for the Lucky Hills results.

Table 9
Coefficients of variation, CV (%), between the model results for the relative changes in sediment and runoff from the baseline (zero change) conditions for the Ganspoel watershed

Scenario	1A	1B	2	3A	3B	3C	Average over scenarios
Sediment							
14-Sep-98	66.1	41.4	40.4	30.0	33.7	37.8	41.6
19-May-97	94.6	58.2	57.4	11.6	1.5	12.2	39.2
21-May-97	9.4	14.2	4.2	NA	NA	NA	9.3
Average of storms	56.7	38.0	34.0	20.8	17.6	25.0	32.0
Runoff							
14-Sep-98	32.0	25.4	0.5	4.5	4.5	6.8	12.3
19-May-97	71.5	19.1	5.9	1.1	1.1	7.7	17.7
21-May-97	22.1	25.6	9.7	NA	NA	NA	19.1
Average of storms	41.8	23.4	5.4	2.8	2.8	7.3	13.9

Each storm average CV is an average of four values of CV related to the four levels of input change: −20%, −10%, +10%, and +20% input change for each scenario. Values were not calculated for cases where less than three results were available to compute variance, which included all scenarios for the storm of 11 July, 1997.

The results for Ganspoel do not show a clear trend with respect to sensitivity as a function of storm size as was exhibited in the Lucky Hills results. Again, because of the variability in the results, the results were more erratic. Apparently more interactions between processes and water and sediment routing associated with the larger and more spatially complex Ganspoel watershed led to the more variable results. Magnitudes of change tended to be greater for the larger storms, simply because the magnitudes of the runoff and erosion were greater for the those storms while response sensitivities were erratic (Tables 6 and 7). The two larger storms showed greater magnitude of change in runoff and sediment for all scenarios than did the two smaller storms.

3.3. Implications

The results of this study have clear implications for both the use and applicability of erosion models as well as for potential climate change impacts on runoff and erosion. The similarities in the responses of these disparate models, as well as the differing model application styles and calibration criteria, to the basic factors studied here give credibility to the use of erosion models for studying a complex problem such as climate change, and give us some insight into how runoff and erosion might respond under climate change. Past comparisons of soil erosion models as applied to common blind data sets for measured erosion and runoff have resulted in relatively poor predictions in terms of absolute values (Jetten et al., 1999; Favis-Mortlock, 1998). However, results of both of those studies implied that relative results from the models were apparently better than absolute results. All models are based on some combination of process descriptions and measured runoff and erosion data from experiments or data that show the impact of a particular factor on runoff or erosion. In that sense, all of the models are essentially designed to respond in a particular manner to a particular input, for example rainfall intensity. It is also important to note that the models are not all built the same way in terms of process descriptions, nor are they based on the same data for development. This should give some credence to the relative model results if a group of models respond in a similar manner to a given input.

Certainly the seven models used in this study responded in many ways similarly to the various scenarios tested, even though the model responses were often quite different in an absolute sense. Some of the basic conclusions of this study include:

1. Erosion is likely to be more affected by changes in rainfall and cover than runoff, though both are likely impacted in similar ways.
2. On a purely percentage basis, erosion and runoff will change more for each percent change in rainfall amount and intensity of a storm than to each percent change in either canopy or ground cover.
3. Changes in rainfall amount associated with changes in storm rainfall intensity will likely have a much greater impact on runoff and erosion than changes in rainfall amount alone.
4. Changes in ground cover (cover in contact with the soil surface) have a greater impact on both runoff and erosion than changes in canopy cover alone.

It is important to point out that just because the sensitivity values for runoff and erosion were generally greater for rainfall changes as opposed to cover changes, this does not imply that future changes in rainfall will dominate over changes in land use. In fact, the opposite scenario is more likely. Predictions by climate change experts suggest the possibility of rainfall changes on the order of a few percents in rainfall amounts and intensities (though precise numbers are not generally reported). Changes in cover as a function of land use changes can be much more important. Clear cutting a forest during a “slash-and-burn” operation may take cover from near 100% to near 0%, which will obviously have a huge impact on susceptibility to runoff and erosion, making a slight change in rainfall regime pale in comparison. On the other hand, if forested slopes are clear-cut for purposes of farming, the incidence of increased occurrences of intense storms as a function of climate change will certainly exacerbate the erosion problem.

The results of this study are alarming. If the trends reported for precipitation in the United States and Europe over the last century continue, significant consequences will incur. If, as a rough estimate, we compute the average of the sensitivities for scenarios 1A and 1B for all storms on both watersheds, the sensitivity value would be 5.45 (545%). Even using the smallest values of the three or four storms for the two scenarios and two watersheds gives a sensitivity of 2.5 (250%). If rainfall amounts during the erosive times of the year were to increase roughly as they did during the last century in the United States, the increase in rainfall would be on the order of 10%, with greater than 50% of that increase due to increase in storm intensity. If these numbers are correct, and if no changes in land cover occurred, erosion could increase by something on the order of 25–55% over the next century. Correspondent values for runoff are 23–31%. Obviously these are not well-defined values, nor scientifically defendable in an absolute sense, but the trends are clear. Both storm water runoff and soil erosion are likely to increase significantly under climate change unless offsetting amelioration measures are taken.

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