Runoff and Soil-Loss Responses to Changes in Precipitation: A Computer Simulation Study

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ABSTRACT: Changes in precipitation have occurred over the past century and are expected to continue over the next century. These changes will have significant implications for runoff, soil erosion, and conservation planning. This study was undertaken to investigate how runoff and soil erosion by water can be expected to be altered as a function of changes in the average number of days of precipitation per year and changes in the amount and intensity of the rain that falls on a given day. The Water Erosion Prediction Project (WEPP) model was used to simulate erosion for three locations, three soils, three slopes, and four crops. Average annual precipitation was changed ±10% and ±20% by changing either a) the number of wet days per year, b) the amount and intensity of precipitation per day, or c) a combination of the two. Results indicated that, on average, each 1% change in average annual precipitation induced a 1.28%, 2.50%, and 1.97% change in runoff and a 0.85%, 2.38%, and 1.66% change in soil loss for the three types of precipitation changes, respectively. Comparisons of the results of the soil-loss simulations to published relationships for Revised Universal Soil Loss Equation (RUSLE) R-factors in the United States suggest that the third option of changing both the number of wet days per year and the amount and intensity of precipitation per day is the most realistic scenario for representing changes in precipitation for hydrologic studies.

Keywords: Climate change, erosion, global change, hydrology

Climate change resulting from greenhouse gas-induced global warming is expected to affect the extent, frequency, and magnitude of soil erosion by water in several ways. Erosional response will occur with changes in plant biomass production, plant residue decomposition rates, soil microbial activity, evapo-transpiration rates, and soil surface sealing and crusting, as well as shifts in land use necessary to accommodate new climatic regimes (Williams et al. 1996; Rosenzweig and Hillel 1998). Also, any increases in precipitation, whether in amounts of rain per event, storm intensity, or precipitation frequency may directly exacerbate erosion, or vice-versa (Favis-Mortlock and Boardman 1995; Nearing 2001).

There has been a general increase on the order of 5% to 10% in total precipitation for the United States during the past century (National Assessment Synthesis Team of the U.S. Global Change Research Program 2000; Karl et al. 1996). This increase was due to both an increase in the number of wet days and increased precipitation intensity. The historical weather records indicate that, since 1910, there has been a steady increase in the area of the United States affected by extreme precipitation events (>50.8 mm in a 24-hour period), as well as an increase in the proportion of the country experiencing a greater than normal number of wet days. Statistical analysis of the data indicates that there is less than a one in one thousand chance that these two increases (in extreme events and proportion of the country experiencing an increase in number of wet days) could have taken place under a quasi-stationary climate (Karl et al. 1996).

Savabi and Stockle (2000) investigated the impact of CO_2 and temperature changes on soil erosion. Their study indicated sensitivity of erosion to changes in both parameters, but they did not attempt to evaluate the potential impact of precipitation changes on erosion. Favis-Mortlock and Boardman (1995) used

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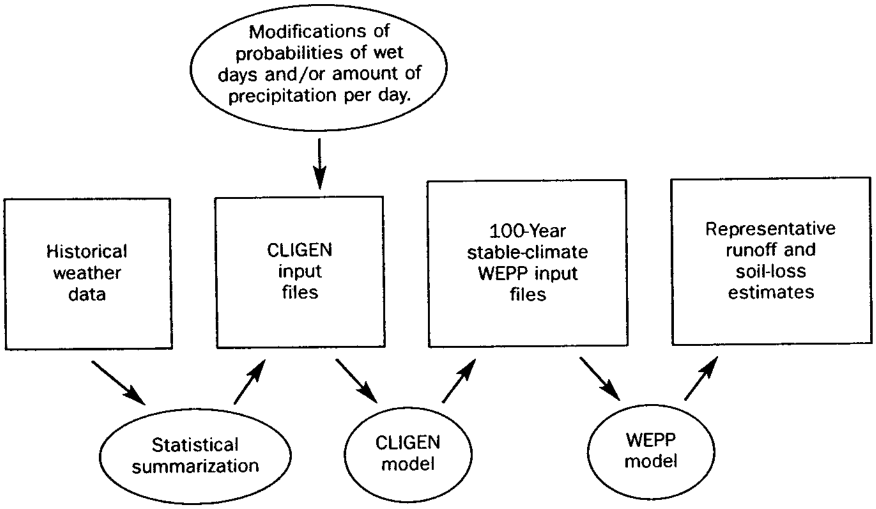
Figure 1
Schematic representation of weather data processing to establish the various precipitation scenarios.



the Erosion Productivity Impact Calculator (EPIC) model to evaluate potential erosion rate changes on the South Downs in the United Kingdom. The EPIC erosion model is based on the Universal Soil Loss Equation, and although precipitation was one of the environmental parameters studied, it is not explicitly clear from that paper how erosivity values were computed based on the precipitation adjustments.

Favis-Mortlock and Savabi (1996) used the WEPP model (Nearing et al. 1989; Flanagan and Nearing 1995) with adjustments coded for atmospheric CO_2 concentration effects on evapo-transpiration rates, water balances, and crop biomass production rates. The authors indicated in that study that precipitation changes were made by changing only the amount of precipitation occurring on a given day of rainfall and by leaving constant the number of wet days and the duration and peak intensity of the rainfall event. It is not clear from their paper whether the authors left constant the true value of the peak intensity or the relative value of peak intensity, which is the actual WEPP input parameter definition. In either case, this methodology does not represent realistic conditions of rainfall changes under global climate change. Favis-Mortlock and Guerra (1999) also used the WEPP model, along with data from a global circulation model, to evaluate erosional response for a case study in Brazil. Their results indicated large potential erosional changes. However, the authors did not document precisely how precipitation changes were represented within the WEPP input files.

Renard and Freidmund (1994) recently developed relationships for estimating erosivity (R-factors) for the Revised Universal Soil Loss Equation (RUSLE). The relationships have important relevance to climate change studies of erosion. They analyzed erosivity data from 155 climate stations across the United States and developed statistical relationships between erosivity and both average annual rainfall and a modified Fournier coefficient (Fournier, 1960). The Fournier coefficient is calculated as a function of distributions of average monthly precipitation. These relationships were used by Nearing (2001) to estimate potential changes in rainfall erosivity across the United States in the next century. These relationships are broad in scope but should give a reasonable idea of the trends in changing rainfall under climate change, and they can act as a check for studies that evaluate the impact of precipitation changes on soil erosion rates.

The objective of this study was to investigate the potential impact of precipitation changes on soil erosion rates for hillslopes such as might be experienced under global climate change. In particular, we investigated the relative differences in soil-loss rate changes as a function of increases in the number of wet days vs. increases in the amount and intensity of rainfall within events. The results indicate that there may be a significant difference in erosion response of a system under the two scenarios, with a much greater response to changes in rainfall amounts and intensities as compared with simply the number of wet days. A combination approach gave results consistent with other data on rainfall erosivity (i.e., Renard and Freidmund 1994), and is suggested for future investigations.

Methods and Materials

Precipitation scenarios. Climate data from three locations were studied: West Lafayette, Indiana; Temple, Texas; and Corvallis, Oregon. Climate files for each of these three locations were generated using the Climate Generator (CLIGEN) model (Nicks and Gander 1994; Flanagan and Nearing 1995) and data from the WEPP database for these locations (Nicks et al. 1993). These data were essentially statistical representations of the historical National Weather Service records from each location. CLIGEN was then used to generate long-term (100-year, in this case) representative, synthetic, stable-climate weather files for WEPP (Figure 1), which were necessary in order to determine representative soil-loss values for each location (Baffaut et al. 1996). The version of CLIGEN included corrections in the coding errors associated with rainfall intensity calculations (Yu 2000), as well as the recently improved random number generator (Flanagan et al. 2001).

Three scenarios of precipitation changes were considered: a) all precipitation change occurring as number of days of precipitation, b) all precipitation change occurring as amount of rainfall in a given day, and c) half the precipitation change occurring from each source. In the first scenario, the number of days of precipitation was increased by changing the probability of wet following wet and the probability of wet following dry days in the CLIGEN input file until the desired change in total precipitation was reached. For lack of better information, the levels of both probabilities were increased or decreased simultaneously such that the proportion between the two was held constant. In this first scenario, the average and variation in the amount of precipitation for a given day of precipitation, as well as average and variation of rainfall intensities, were held constant (Table 1).

For the second scenario, the number of days of rainfall was held constant, while the average amount of precipitation for each wet day was either increased or decreased to obtain the desired change in total precipitation. Under this scenario and using CLIGEN, changes in the amount of precipitation on a given day also change the average and peak intensities of precipitation (Table 1) in a statis-

Table 1. Precipitation characteristics for the first ten years of each weather file for (a) West Lafayette, IN, (b) Temple, TX, and (c) Corvallis, OR.

(a)

Precipitation Scenario	Level of Change in Average Annual Precipitation	Average Number of Wet Days per Year	Average Precipitation Amount per Wet Day	Average Event Precipitation Intensity	Average 5-minute Peak Precipitation Intensity
	%		mm	mm hr^{-1}	mm hr^{-1}
Change in Number of Wet Days	-20	91	8.7	2.80	25.87
	-10	101	8.7	2.78	26.61
	0	113	8.7	2.85	26.99
	+10	126	8.7	2.79	26.07
	+20	138	8.7	2.79	26.32
Change in Amount of Rain per Day	-20	113	7.0	2.29	21.75
	-10	113	7.9	2.59	24.53
	0	113	8.7	2.85	26.99
	+10	113	9.6	3.14	29.62
	+20	113	10.5	3.41	32.08
Combined Changes in Number of Wet Days and Amount of Rain per Day	-20	101	7.7	2.53	24.17
	-10	107	8.3	2.70	25.25
	0	113	8.7	2.85	26.99
	+10	120	9.1	2.98	28.05
	+20	126	9.3	3.07	28.58

(b)

Precipitation Scenario	Level of Change in Average Annual Precipitation	Average Number of Wet Days per Year	Average Precipitation Amount per Wet Day	Average Event Precipitation Intensity	Average 5-minute Peak Precipitation Intensity
	%		mm	mm hr^{-1}	mm hr^{-1}
Change in Number of Wet Days	-20	59	12.2	3.83	45.75
	-10	67	12.1	3.88	45.84
	0	75	12.1	3.85	45.21
	+10	82	11.9	3.84	44.26
	+20	89	11.9	3.84	43.90
Change in Amount of Rain per Day	-20	75	9.7	3.13	36.93
	-10	75	10.9	3.49	41.12
	0	75	12.1	3.85	45.21
	+10	75	13.3	4.20	49.30
	+20	75	14.5	4.54	53.07
Combined Changes in Number of Wet Days and Amount of Rain per Day	-20	67	10.9	3.52	41.70
	-10	70	11.9	3.79	44.52
	0	75	12.1	3.85	45.21
	+10	79	12.9	4.12	47.96
	+20	82	13.2	4.20	48.32

Table 1 continued on following page

tically representative manner based on current knowledge of the relationships between these variables (Nicks and Gander 1994). This is because representative intensities of storms are generated by CLIGEN based on statistical relationships with storm amount and geographic location.

The third precipitation change scenario was a combination of scenarios one and two, with equal change generated by number of days of precipitation and amount of rainfall per event. The five levels of total precipitation changes considered in each case were zero, approximately ±10%, and approximately ±20% of total precipitation, with the same relative proportion of precipitation for the year maintained as a function of month. Thus, with the three precipitation change scenarios and the four change levels, plus the zero change level, there were 13 climate files generated for each of the three locations studied.

Soils, crops, and topography scenarios. Three varying soil textures, four crops, and three slopes were used in the analyses. The soils were a silt loam, a sandy loam, and a clay (Table 2). Simulated crops included grazing pasture, chisel plowed corn and soybean rotation, winter wheat, and disked fallow. Slopes considered were s-shaped with 0% slope at the crest of the hill and 1% at the bottom of the hill. Three hillslopes of 3%, 7%, and 15% maximum gradient halfway down the slope were used. Each of the slopes was 40 meters

Table 1 continued

(c)

Precipitation Scenario	Level of Change in Average Annual Precipitation	Average Number of Wet Days per Year	Average Precipitation Amount per Wet Day	Average Event Precipitation Intensity	Average 5-minute Peak Precipitation Intensity
	%		mm	mm hr^{-1}	mm hr^{-1}
Change in Number of Wet Days	-20	124	7.0	2.31	25.72
	-10	140	7.1	2.36	26.34
	0	154	7.2	2.38	26.67
	+10	169	7.1	2.34	26.32
	+20	184	7.0	2.23	25.97
Change in Amount of Rain per Day	-20	154	5.8	1.92	21.55
	-10	154	6.6	2.15	24.21
	0	154	7.2	2.38	26.67
	+10	154	8.0	2.62	29.30
	+20	154	8.7	2.85	31.63
Combined Changes in Number of Wet Days and Amount of Rain per Day	-20	140	6.5	2.14	23.90
	-10	145	6.8	2.25	25.22
	0	154	7.2	2.38	26.67
	+10	162	7.5	2.47	27.56
	+20	169	7.9	2.59	28.94

Table 2. Properties of the topsoil for the three soil types simulated.

Soil	Sand	Clay	Organic Matter	Cation Exchange Capacity	Rock	Interrill Erodibility, K_i	Rill Erodibility, K_r	Critcal Hydraulic Shear Stress, τ_c	Baseline Green-Ampt Hydraulic Conductivity, K_b
	(%)	(%)	(%)	(meq/100g)	(%)	(10^6 kg s m^{-4})	(s m^{-1})	(Pa)	(mm h^{-1})
Silt Loam	9.8	20.1	2.6	19.6	0.0	4.95	0.0093	3.5	1.71
Sandy Loam	66.5	19.6	0.9	4.8	5.2	3.94	0.0119	3.57	19.76
Clay	16.9	49.5	2.7	35.7	0.5	3.33	0.0069	3.5	0.71

in length. We also initially computed results for slope lengths of 10 and 100 meters for the West Lafayette, Indiana, location. However, the results did not provide additional information, and so the different slope lengths were dropped from further simulations.

With three locations, 13 climate files, four crops, three soils, and three slopes, a total of 1,404 simulations were run. Each erosion simulation was run using the entire 100-year synthetic, steady-climate weather file in order to obtain stable and representative soil-loss estimates. All soil-loss values reported and discussed in this study are given in terms of average erosion rate over the portion of the slope that was predicted to experience net annual average loss of soil. The small areas of net deposition on the bottom of the hills as predicted by the model for these slopes were not relevant to the results of the study and are not discussed.

Results and Discussion

The average annual precipitation amount for the original, zero-change condition was 964 mm for West Lafayette, 868 mm for Temple, and 1070 mm for Corvallis. Table 3 shows averages of the actual values of runoff and soil loss estimated by the model for each of the treatments. Changes in precipitation for the various climate scenarios and locations we studied are listed in Tables 4 and 5, along with values of runoff and soil loss normalized to the results for zero change in precipitation. A value of one in these tables indicates no difference in computed runoff (Table 4) or soil loss (Table 5) between the condition of changed average annual precipitation and zero change in precipitation. A value less than one indicates a reduction in runoff or soil loss compared with the zero-change precipitation condition, and a value greater than one indicates an increase.

Sensitivity of runoff and soil-loss response to changes in average annual precipitation were reported in relative terms as ratios of the percentage of change of the response variable (average annual runoff or soil loss) to the percentage of change in average annual precipitation. Thus, a sensitivity value of one would indicate an average change of 1% in runoff or soil loss for each 1% change in precipitation, and a value of two would indicate an average change of 2% in runoff or soil loss for each 1% change in precipitation. Sensitivity values for runoff and soil loss are reported in Tables 6 and 7, respectively. Actual values of average runoff and soil loss for each treatment and each precipitation scenario and change level can be computed using the sensitivity values from these tables and the runoff and soil-loss values listed in Table 3.

Runoff results. Table 4 indicates that an increase in average annual precipitation always translated to an increase in runoff and vice versa, regardless of how the change in precipitation was modeled. However, the results indicate greater sensitivity of runoff resulting from change in the average amount of rainfall per event than to sensitivity of runoff caused simply by changes in the number of days of rainfall (Table 6). The combined case of changes in both factors resulted in intermediate sensitivities. This result makes sense in terms of processes.

A larger total rainfall in a given day, other conditions being equal, will produce a disproportionately larger increase in runoff because of the exponential decrease in infiltration rate during a rainfall as the surface layer of soil wets downward. A small rainfall will use a greater proportion of its total rainfall depth in this wetting process, whereas a larger rainfall will have a greater proportion of rainfall depth available for runoff after the initial profile wetting period. This change in infiltration rate during a rainfall is both a real phenomenon observed in nature and experiments, as well as a process modeled within WEPP via the Green-Ampt infiltration equations.

In addition to the disproportional effect of the increase in rainfall amount, increase in rainfall intensity also increases runoff at a proportional to the rate of infiltration subtracted from the rate of rainfall. Thus, runoff

1.28% increase in runoff for each percentage point increase in annual rainfall. There appear to be two principal reasons for this result, one having to do with soil surface roughness and the other with soil moisture. As rainfall input is increased, soil surface roughness is decreased because of the energy effect of the rain impacting the soil surface. Decreased roughness causes decreased surface storage during the subsequent rainfall event and, hence, more runoff. Thus, the increase in rainfall causes a disproportionate increase in runoff. This interpretation is evidenced in the WEPP model calculations of soil surface roughness. For the corn and soybean rotation in Corvallis on the roughness for the case of 20% decrease in precipitation was 8.9 mm, and for the case of

smaller sensitivity of runoff to precipitation than did the other management treatments (Table 6). The explanation for this may be caused by differences in this treatment with regard to soil moisture. The fallow treatment had greater average soil moisture and associated lower soil-water suction, in general, because of the fact that plant transpiration was not present. For the Corvallis location on the silt loam soil, for example, mean total moisture in the soil profile for the case of fallow was 488 mm, and for the case corn and soybeans, it was 388 mm. Corresponding soil water-suction values were 70 mm for fallow and 85 mm for corn and soybeans. Other loca- refer back to the discussion regarding runoff rate being equivalent to rainfall rate in excess

Table 4. Mean normalized values of changes in average annual runoff relative to conditions of zero precipitation change for (a) West Lafayette, IN

precipitation and zero change in precipitation. A value less than one indicates a reduction in runoff compared to the zero-change precipitation condition, and a value greater than one indicates an increase.

(a)

West Lafayette, IN	Change in Number of Wet Days	Change in Amount of Rain per Day	Combined Changes in Number of Wet Days and Amount of Rain per Day

Table 5. Mean normalized values of changes in average annual soil loss relative to conditions of zero precipitation change for (a) West Lafayette, IN, (b) Temple, TX, and (c) Corvallis, OR. A value of one indicates no difference in computed soil loss between the condition of changed average annual precipitation and zero change in precipitation. A value less than one indicates a reduction in soil loss compared to the zero-change precipitation condition, and a value greater than one indicates an increase.

(a)

West Lafayette, IN	Change in Number of Wet Days				Change in Amount of Rain per Day				Combined Changes in Number of Wet Days and Amount of Rain per Day			
Normalized Precipitation	0.82	0.90	1.09	1.19	0.80	0.90	1.10	1.20	0.82	0.90	1.11	1.21
Location Average	0.82	0.92	1.03	1.11	0.59	0.78	1.27	1.52	0.72	0.85	1.23	1.30
Silt Loam Soil	0.81	0.91	1.02	1.11	0.57	0.77	1.28	1.54	0.70	0.83	1.25	1.31
Sandy Loam Soil	0.82	0.92	1.02	1.12	0.56	0.76	1.29	1.56	0.72	0.86	1.25	1.32
Clay Soil	0.84	0.93	1.03	1.10	0.63	0.81	1.23	1.46	0.75	0.87	1.19	1.27
Grazing	0.79	0.98	1.05	1.16	0.54	0.74	1.34	1.70	0.77	0.91	1.35	1.44
Fallow	0.79	0.82	1.02	1.08	0.60	0.80	1.24	1.47	0.64	0.77	1.16	1.25
Corn-soybean	0.86	0.94	1.00	1.13	0.60	0.79	1.26	1.49	0.74	0.87	1.22	1.25
Wheat Winter	0.86	0.93	1.04	1.08	0.61	0.80	1.22	1.42	0.74	0.86	1.19	1.26
S-shape(0-3-1%) 40m	0.81	0.93	1.04	1.13	0.57	0.77	1.28	1.56	0.73	0.86	1.25	1.33
S-shape (0-7-1%) 40m	0.82	0.91	1.02	1.10	0.58	0.78	1.27	1.52	0.71	0.85	1.24	1.30
S-shape (0-15-1%) 40m	0.84	0.91	1.02	1.10	0.61	0.80	1.24	1.47	0.73	0.86	1.20	1.27

(b)

Temple, TX	Change in Number of Wet Days				Change in Amount of Rain per Day				Combined Changes in Number of Wet Days and Amount of Rain per Day			
Normalized Precipitation	0.80	0.91	1.09	1.20	0.80	0.90	1.10	1.20	0.82	0.90	1.11	1.21
Location Average	0.83	0.93	1.07	1.19	0.61	0.80	1.22	1.45	0.74	0.86	1.20	1.31
Silt Loam Soil	0.82	0.91	1.07	1.19	0.59	0.78	1.22	1.47	0.72	0.85	1.21	1.32
Sandy Loam Soil	0.83	0.93	1.08	1.21	0.60	0.80	1.24	1.48	0.73	0.86	1.22	1.34
Clay Soil	0.84	0.94	1.07	1.18	0.64	0.82	1.20	1.41	0.77	0.87	1.18	1.29
Grazing	0.86	0.94	1.11	1.29	0.58	0.76	1.26	1.55	0.71	0.85	1.24	1.42
Fallow	0.84	0.90	1.14	1.21	0.63	0.81	1.21	1.43	0.72	0.91	1.25	1.37
Corn-soybean	0.78	0.98	0.99	1.09	0.62	0.81	1.20	1.42	0.81	0.78	1.16	1.21
Wheat Winter	0.83	0.90	1.05	1.19	0.61	0.81	1.21	1.42	0.73	0.89	1.15	1.26
S-shape(0-3-1%) 40m	0.83	0.92	1.08	1.22	0.61	0.78	1.24	1.49	0.73	0.86	1.22	1.34
S-shape (0-7-1%) 40m	0.82	0.93	1.07	1.18	0.60	0.80	1.22	1.46	0.74	0.86	1.19	1.31
S-shape (0-15-1%) 40m	0.83	0.93	1.07	1.18	0.63	0.81	1.20	1.42	0.75	0.86	1.19	1.29

(c)

Corvallis, OR	Change in Number of Wet Days				Change in Amount of Rain per Day				Combined Changes in Number of Wet Days and Amount of Rain per Day			
Normalized Precipitation	0.79	0.89	1.10	1.20	0.80	0.91	1.10	1.20	0.81	0.90	1.10	1.21
Location Average	0.84	0.85	1.12	1.18	0.53	0.76	1.29	1.60	0.65	0.89	1.26	1.43
Silt Loam Soil	0.80	0.84	1.13	1.18	0.53	0.76	1.29	1.60	0.64	0.88	1.24	1.42
Sandy Loam Soil	0.85	0.83	1.16	1.19	0.48	0.73	1.34	1.70	0.61	0.88	1.31	1.52
Clay Soil	0.86	0.87	1.09	1.17	0.59	0.79	1.24	1.51	0.69	0.90	1.22	1.35
Grazing	0.80	0.80	1.19	1.19	0.53	0.76	1.28	1.57	0.61	0.83	1.27	1.51
Fallow	0.84	0.85	1.12	1.22	0.56	0.77	1.26	1.55	0.66	0.88	1.24	1.41
Corn-soybean	0.84	0.90	1.05	1.17	0.48	0.72	1.34	1.72	0.66	0.93	1.30	1.40
Wheat Winter	0.87	0.84	1.13	1.15	0.57	0.79	1.26	1.57	0.66	0.92	1.22	1.40
S-shape(0-3-1%) 40m	0.83	0.84	1.13	1.19	0.54	0.76	1.29	1.61	0.65	0.89	1.26	1.43
S-shape (0-7-1%) 40m	0.84	0.85	1.12	1.18	0.53	0.76	1.29	1.60	0.65	0.89	1.25	1.43
S-shape (0-15-1%) 40m	0.84	0.85	1.12	1.18	0.53	0.76	1.29	1.60	0.65	0.88	1.26	1.44

sensitivity values for soil loss and runoff (Tables 6 and 7). As in the case of runoff, soil loss is more sensitive to changes in the amount and intensity of rainfall in a day as compared with the number of days of rainfall. For the case of changes in the number of days of rainfall, soil loss is indicated to increase only 0.85% on average with each percentage point increase in precipitation, as compared with 2.38% for the case of change in amount of rain per day.

One major reason for the difference between the sensitivity results for runoff and those for soil loss is related to biomass production. Both runoff and soil loss are sensitive to biomass, but soil loss is more so. Soil loss is affected by plant canopy, which reduces the impact energy of rainfall; by crop residues, which protect the soil from raindrop impact and drastically reduce rill detachment rates and sediment transport capacities; and from subsurface roots and decaying residue, which mechanically hold the soil in place and provide a medium for microorganisms to thrive. The increase of biomass production with increased rainfall thus tends to counteract, to some degree, the increased erosivity of the rain. This argument is supported by the results of the simulations for fallow conditions in comparison with the other treatments. The sensitivity values for the three precipitation scenarios for fallow conditions average 1.63 for soil loss (computed from Table 7) and 1.55 for runoff (computed from Table 6). For all other crop treatments, the sensitivities for runoff are always greater than for soil loss.

The difference between a sensitivity of 0.95 for soil loss and 1.06 for runoff for the fallow scenario of change only in the number of days of rainfall (Tables 6 and 7) can be explained in terms of surface sealing and consolidation processes. Surface sealing and consolidation occur as a function of rainfall amount in nature and in the WEPP model (Flanagan and Nearing 1995) so that any increase in rainfall will increase soil resistance to erosion. This process also acts as a feedback effect, similar to, but in lesser degree, the effect of biomass on partially offsetting the impact of increased rainfall on erosion. This explains the lesser sensitivity of 0.95 for soil loss as compared with 1.06 for runoff.

The soil-loss sensitivity value for fallow conditions for the scenario of change in amount of rainfall per day is actually greater (2.22) than that for runoff (1.99) (Tables 7 and 6, respectively). Although the surface sealing

Table 6. Sensitivities of changes in runoff to changes in average annual precipitation. Sensitivity values are calculated as the ratio of the percent change in runoff to the percent change in precipitation. Values represent averages for all simulation runs associated with the soil, crop, slope, or location listed in the first column. Values greater than zero indicate that runoff increases with increased annual precipitation. A value of greater than one indicates a greater percentage change in runoff than the percentage change in precipitation.

Scenarios	Normalized sensitivity of runoff to changes in average annual precipitation		
	Change in Number of Wet Days	Change in Amount of Rain per Day	Combined Changes in Both
Silt Loam Soil	1.32	2.57	2.00
Sandy Loam Soil	1.31	2.80	2.17
Clay Soil	1.15	2.17	1.75
Grazing Pasture	1.54	3.09	2.41
Fallow	1.06	1.99	1.60
Corn and Soybean	1.32	2.51	1.97
Wheat Winter	1.21	2.43	1.91
S-shape (0%-3%-1%) 40 m	1.32	2.59	2.03
S-shape (0%-7%-1%) 40 m	1.29	2.49	1.98
S-shape (0%-15%-1%) 40 m	1.23	2.42	1.91
West Lafayette, IN	1.16	2.61	1.94
Temple, TX	1.19	2.25	1.73
Corvallis, OR	1.50	2.64	2.23
Overall Average	1.28	2.50	1.97

Table 7. Sensitivities of changes in soil loss to changes in average annual precipitation. Sensitivity values are calculated as the ratio of the percent change in soil loss to the percent change in precipitation. Values represent averages for all simulation runs associated with the soil, crop, slope, or location listed in the first column. Values greater than zero indicate that soil loss increases with increased annual precipitation. A value of greater than one indicates a greater percentage change in soil loss than the percentage change in precipitation.

Scenarios	Normalized sensitivity of soil loss to changes in average annual precipitation		
	Change in Number of Wet Days	Change in Amount of Rain per Day	Combined Changes in Both
Silt Loam Soil	0.90	2.45	1.72
Sandy Loam Soil	0.89	2.60	1.82
Clay Soil	0.79	2.10	1.46
Grazing Pasture	1.02	2.66	1.96
Fallow	0.95	2.22	1.71
Corn and Soybean	0.70	2.46	1.48
Wheat Winter	0.77	2.18	1.50
S-shape (0%-3%-1%) 40 m	0.92	2.47	1.71
S-shape (0%-7%-1%) 40 m	0.84	2.40	1.67
S-shape (0%-15%-1%) 40 m	0.82	2.27	1.61
West Lafayette, IN	0.74	2.35	1.56
Temple, TX	0.88	2.10	1.50
Corvallis, OR	0.92	2.69	1.93
Overall Average	0.85	2.38	1.66

and consolidation effect discussed above is present in this case, also, that effect is apparently superceded by yet another process when rainfall amounts and intensities per day are increased. The likely candidates for this are rill and interrill soil-detachment processes. Interrill erosion rates are represented in the WEPP model as proportional to the rainfall intensity and the runoff rate (Flanagan and Nearing 1995). These relationships are based on experimental data (Zhang et al. 1998). Because both of these variables increase with increased rainfall intensity, the effect of increased intensity on interrill erosion is greater than unity. Rill erosion occurs as a threshold process, similar conceptually to the process of runoff occurring as a threshold process. In the case of runoff, as discussed above, the process involved is that of rainfall rate relative to the threshold infiltration rate. Runoff occurs proportional to the excess infiltration rate above the infiltration rate, rather than proportional to the rainfall rate increase. Likewise, soil detachment occurs proportional to the excess shear stress of water flow above the threshold critical shear stress of the soil, rather than to the shear stress of the flow itself. The overall effect is that the sensitivity of the rill erosion rate to runoff rate will be somewhat more than unity, other factors being constant. The effect is not present in the precipitation scenario of changes in the number of rainfall days because, in that case, the average runoff rate is essentially not changing. Instead, only the frequency of runoff events changes.

Comparison of results with RUSLE R-factors. We compared our results from the WEPP model simulations with the results obtained by Renard and Freidmund (1994) for relationships between current rainfall in 155 locations across the United States and the currently used erosivity factors for corresponding locations. Renard and Freidmund (1994) reported two equations for the relationship between erosivity (the RUSLE R-factor) and annual average rainfall: one to be used with values of precipitation less than 850 mm per year and the other for values of precipitation more than 850 mm per year. In our study, the range of precipitation values considered in all of the scenarios ranged from 694 to 1284 mm per year. Hence, the values overlap the range for the two equations presented by Renard and Freidmund (1994, equations 11 and 12). Thus, we calculated sensitivity values of the R-factor using both of the equations. Use of Renard and Freidmund's equation 12 for annual precipitation less than 850 mm resulted in a sensitivity value of 1.61, and use of equation 13 for annual precipitation greater than 850 mm resulted in a sensitivity value of 1.99. These values compare with our average computed sensitivity values from this study of 0.85, 2.38, and 1.66 for the three precipitation scenarios studied. Clearly, using simply a change in number of wet days, which resulted in an average sensitivity value of 0.85, is not consistent with the Renard and Freidmund results and probably not appropriate for climate change studies. Likewise, the sole use of change in the amount of precipitation per wet day will probably tend to overestimate the impact of precipitation change on erosion. The use of a combined approach, with 50% change occurring from each source and an average sensitivity of 1.66, produces apparently reasonable, if slightly conservative, results. Given the variability in the data from the Renard and Freidmund study, a further refinement from the 50% split in effects is not warranted.

Summary and Conclusion

The results of this study illustrate some of the complex interactions that may take place with climate change relative to runoff and soil erosion, even when, as in this study, only rainfall changes are considered. There are complex interactions between rainfall amounts, rainfall frequencies, soil-moisture retention, evapotranspiration rates, soil surface roughness, soil surface sealing and consolidation, plant biomass production rates, infiltration, runoff, and soil loss. It is encouraging that the WEPP model appears to sensibly respond to these various interactions as discussed above. There are undoubtedly also several, perhaps secondary, relationships and interactions that came into play within the WEPP model during the simulations that are not identified or discussed in this paper. This is not to suggest, of course, that the WEPP model accounts for all of the possible complex interactions that take place relative to erosion and precipitation or even that the current relationships are exact. Also, the current study does not attempt to evaluate the effects of changes in atmospheric CO_2 concentrations, solar radiation, or temperature as might occur with climate change. Such studies are in progress.

This study does help identify how best to account for precipitation changes in future climate change studies. It is not sufficient simply to change the number of days of rainfall in order to account for changes in average monthly precipitation. Doing so will cause the investigator to underestimate the potential climate change effects on erosion. It is also not sufficient to simply change the average amount of rainfall that occurs on a wet day, which is often the most expedient method of accounting for total or monthly precipitation changes. This is the method that has apparently been most frequently used in past studies, though some studies do not explicitly state how precipitation was changed. Use of this method will probably tend to overestimate the effects of precipitation changes on runoff and erosion. Based on the results of this study, we suggest a hybrid approach in which 50% of the precipitation change is made via changes in the average amount of precipitation occurring on a wet day and the other 50% change is made via a change in the number of wet days. Also, the change in the amount of rainfall per day must be accompanied by an appropriate estimate of the associated changes in rainfall intensities.

If these changes are not properly taken into account, modeling results can be quite variable and inaccurate. In the current study, we found that on average, a 1% change in total precipitation may cause a 2.38% change in soil loss if only the amount of precipitation per day and the associated intensities are modified. If only the number of days of precipitation is changed, maintaining the average amount and intensity per wet day, the same change in precipitation will cause only a 0.85% change in soil loss. The intermediate, combined approach resulted in an average change of 1.66%. This intermediate result was consistent with empirical relationships for the RUSLE erosivity factor (Renard and Freidmund 1994).

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