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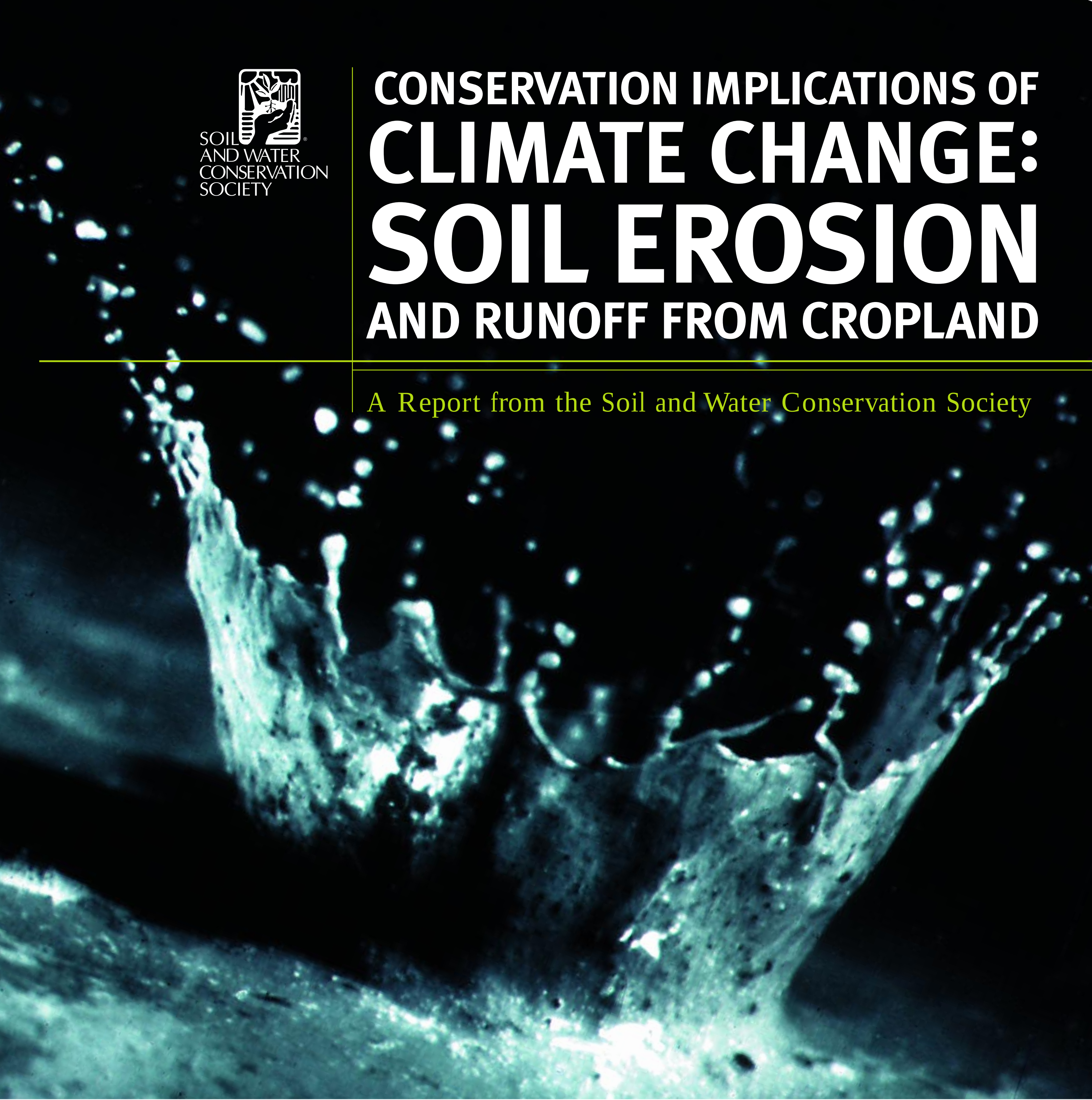
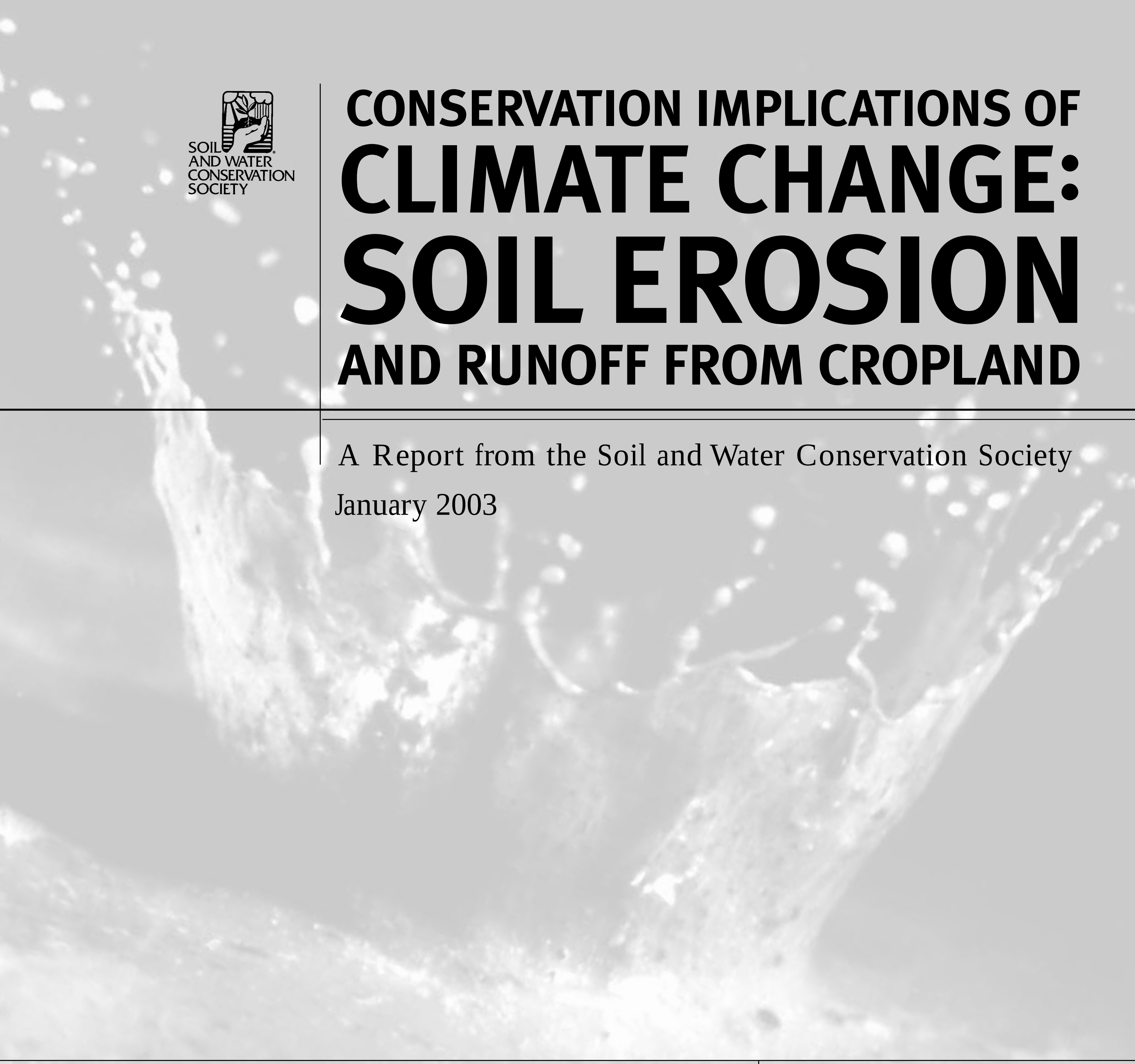
# CONSERVATION IMPLICATIONS OF CLIMATE CHANGE: SOIL EROSION AND RUNOFF FROM CROPLAND

A Report from the Soil and Water Conservation Society





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The Soil and Water Conservation Society (SWCS) is a nonprofit scientific and educational organization that serves as an advocate for conservation professionals and for science-based conservation policy. SWCS seeks to advance the science and art of soil, water, and related natural resource conservation to achieve sustainability. Members practice and promote an ethic that recognizes the interdependence of people and their environment.

SWCS has about 10,000 members around the world. They include researchers, administrators, planners, policymakers, teachers, students, farmers, and ranchers. Nearly every academic discipline and many different conservation institutions are represented within the membership.

Member benefits include the widely respected *Journal of Soil and Water Conservation*; representation in policy circles; opportunities for leadership and networking; and discounts on books and conference registrations.

SWCS chapters throughout the United States, Canada, and the Caribbean Basin conduct a variety of activities at local, state, and provincial levels and on university campuses. These 75 chapters represent the grassroots element of the organization. Each chapter elects its own officers, organizes conservation forums, and formulates local recommendations on land and water conservation issues.

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## EXECUTIVE SUMMARY

A changing climate will affect soil and water resources on agricultural land in many ways, but will the effect of climate change on soil and water resources on agricultural land be large enough to warrant changes in U.S. conservation policy or practice? To answer this question, the Soil and Water Conservation Society (SWCS) reviewed the literature and engaged members of an expert panel in a discussion of quantitative estimates of the effects of climate change on soil and water resources in agricultural landscapes. We chose to focus on one climatic variable, precipitation; two primary conservation effects, soil erosion and runoff; and one type of agricultural land, cropland.

In the end, our answer to this question was an emphatic yes. Conservationists should be seriously concerned about the implications of climate change—as expressed by changes in precipitation patterns—for the conservation of soil and water resources in the United States. The magnitude and extent of increased rates of soil erosion and runoff that could occur under simulated future precipitation regimes are large. More importantly, analyses of the climate record in the United States show that changes in precipitation patterns are occurring now. In fact, the magnitude of observed trends in precipitation and the bias toward more extreme precipitation events are, in some cases, larger than simulated by global climate change models, particularly since 1970. Extrapolating those relationships to the changes in precipitation observed over the past century suggests increases in soil erosion ranging from 4 percent to 95 percent and increases in runoff from 6 percent to 100 percent could already be evident on cropland in some locations.

Unless additional protective measures are taken, such increases in soil erosion and runoff from cropland—if widespread—could reverse much of the progress that has been made in reducing soil degradation and water pollution from cropland in the United States.

The potential for climate change—as expressed in changed precipitation regimes—to increase the risk of soil erosion, surface runoff, and related environmental consequences is clear. The actual damage that would result from such a change is unclear. Regional, seasonal, and temporal variability in precipitation is large both in simulated climate regimes and in the existing climate record. Different landscapes vary greatly in their vulnerability to soil erosion and runoff. Timing of agricultural production practices creates even greater vulnerabilities to soil erosion and runoff during certain seasons. The effect of a particular storm event depends on the moisture content of the soil before the storm starts. These interactions between precipitation, landscape, and management mean the actual outcomes of any particular change in precipitation regime will be complex.

In sum, a change in precipitation regime also produces a change in the level of risk to which agricultural land is exposed. In general, a regime with greater annual precipitation—particularly if increased storm intensity changes more than storm frequency—heightens the risk of soil erosion, runoff, and related environmental and ecological damages. In general, the risk increases at a greater rate than precipitation amount or intensity increases. Whether that new, more risky baseline condition translates into greater soil degradation, pollution of surface water, pollution of groundwater, or a combination of all three outcomes is highly dependent on other factors.

We identified three particularly promising approaches to begin adapting soil and water conservation policies and practices to a changing precipitation regime.

1. *Immediately update climatic parameters in critical conservation planning tools*. Two key efforts already are underway. The Natural Resources Conservation Service (NRCS) is currently updating the climate components of its primary erosion prediction and conservation planning tool using precipitation and temperature data covering the period 1971-1999. The National Oceanic and Atmospheric Administration's National Weather Service (NOAA-NWS) Hydrometerological Design Studies Center is updating precipitation frequency studies used in engineering applications, with support from NRCS, the U.S. Army Corps of Engineers, and others. These two efforts should be completed as soon as possible and then updated more frequently in the future.

2. *Undertake targeted investigations to firm up estimates of the damage that would likely occur under simulated or observed climate regimes*. Those investigations should include the following: (1) replicating studies at more locations and more land uses to develop better estimates of the variability in soil erosion and runoff responses to an altered precipitation regime; (2) utilizing the NRCS National Resources Inventory framework to update national and regional estimates of soil erosion, runoff, and related environmental outcomes based on updated climate parameters in the Universal Soil Loss Equation or the Revised Universal Soil Loss Equation; (3) utilizing the NRCS National Resources Inventory framework to conduct sensitivity analyses and simulate the effect of simulated climate scenarios on national and regional estimates of soil erosion, runoff, and related environmental outcomes; and (4) completing targeted evaluations and studies to better understand the causes of and future trends in changes in precipitation regime, particularly those portions of the regime of most concern for soil erosion, runoff, and related environmental effects.

3. *Evaluate the benefits of building the risk of damage from severe rainstorms into the conservation planning process through risk-based assessments targeted to key conservation systems and environmental outcomes*. In current practice, conservation systems applied to agricultural land are usually designed, planned, and implemented to address soil erosion, runoff, and related effects under estimates of expected average annual climate regimes. Conservation planning approaches based on annual average precipitation should be reevaluated in light of the evidence that future—or current—climate regimes are characterized by increased frequency of extreme events. Such a change in conservation planning would require (1) identifying and quantifying thresholds of soil erosion, runoff, or transport of pollutants above which damage at some specified frequency is unacceptable; (2) identifying critical times during the year when the nature and timing of agricultural production practices increase the risk of damage; (3) determining the probability of occurrence of storms of sufficient intensity and timing to cause damage that exceeds threshold levels; and (4) designing conservation systems to be protective at vulnerable times and during particular events.

Conservationists should take these three foregoing steps quickly. Policymakers and program managers need answers soon so they can begin to make the investment decisions and changes in operational policy needed to ensure U.S. soil and water resources are protected under a changing climate.

# INTRODUCTION

A changing climate will affect soil and water resources on agricultural land in many ways. Will the effect of climate change on soil and water resources on agricultural land be large enough to warrant changes in U.S. conservation policy or practice? To answer this question, we reviewed the literature and engaged members of an expert panel in a discussion of quantitative estimates of the effects of climate change on soil and water resources in agricultural landscapes.

Climate change will affect soil and water conservation through multiple pathways because many climatic variables have important effects on conservation outcomes. Those variables include precipitation, temperature, wind, solar radiation, and atmospheric carbon dioxide, among others. Change in any single variable also is complex. A change in temperature, for example, will affect conservation differently if that change primarily affects minimum, maximum, or mean temperature. A change in a climatic variable also may differ seasonally or geographically.

The interaction between and among climatic variables and conservation outcomes is dynamic and often nonlinear. Climatic variables interact to magnify or dampen conservation effects. Likewise, conservation effects feed back into the system and modify the influence of climatic variables.

Those interactions could have profound effects on soil, water, and related natural resources. Water budgets, streamflow, and frequency and severity of floods and droughts may be altered. Biotic communities, plant growth and development, and land use patterns may shift. Those changes, in turn, may have important implications for soil, water, and air quality, as well as fish and wildlife habitat.

From the outset of the project, it was clear that we needed to simplify the problem by focusing only on a few of the multiple factors, interactions, and potential conservation outcomes. Ultimately, we chose to focus on one climatic variable, precipitation; two primary conservation effects, soil erosion and runoff; and one type of agricultural land, cropland. More specifically, we attempted to summarize quantitative estimates of the effects that changes in precipitation amounts, frequency, and intensity might be expected to have on rates of soil erosion and volumes of runoff from cropland. Even with this limited focus, the interactions among variables and effects are numerous (Figure 1).

We elected to focus our work on the effects of changes in precipitation on soil erosion and runoff from cropland because (1) quantitative estimates were available in the published literature for these factors, (2) erosion and runoff are among the most important factors influencing agriculture's effects on soil and water resources, and (3) scientific understanding of the processes underlying the conservation implications of climate change suggest that precipitation would be a dominant factor affecting conservation outcomes and that soil erosion and runoff would be particularly sensitive to changes in precipitation.

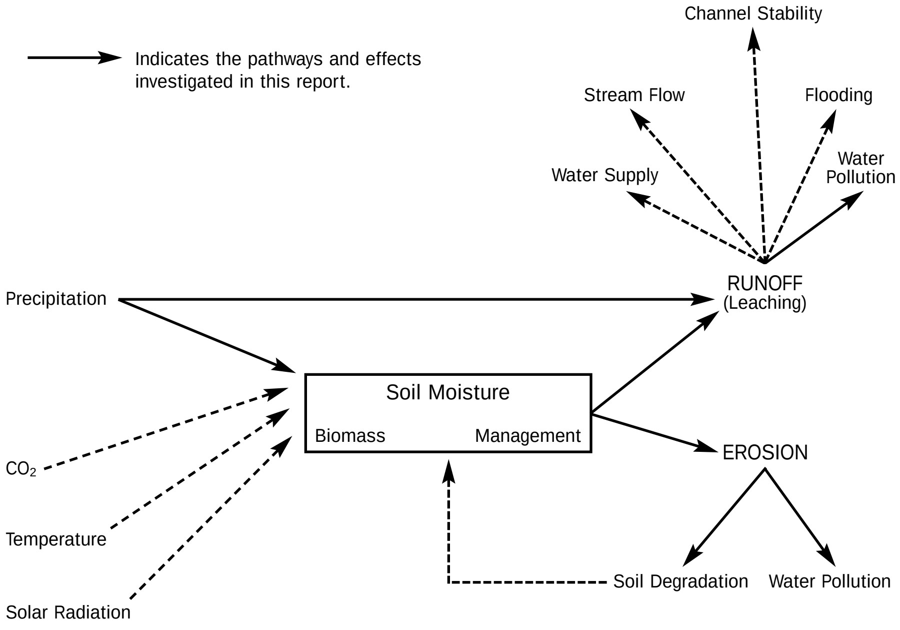
We approached our work in three steps. First, we sought to determine the range of effects that climate change might have on precipitation regimes. We did this by looking at the work of various climate change assessment projects—primarily those conducted by the Intergovernmental Panel on Climate Change (IPCC) and the U.S. National Assessment Synthesis Team (U.S. NAST)—for indications of the large-scale changes in precipitation regimes that model simulations and related analyses have produced. We also reviewed, in some detail, recent analyses of observed changes in precipitation regimes in the United States during the 20th century.

Our second step was to review published studies that would help us assess, quantitatively, the changes in rates of soil erosion and runoff that could occur under such changed precipitation regimes.

Finally we relied on the professional judgment of our expert panel and Soil and Water Conservation Society (SWCS) staff to answer our primary question: Are the effects of changing precipitation regimes on soil erosion and runoff from cropland likely to be large enough to warrant changes in U.S. conservation policy or practice?

**Figure 1**

Effects of climate change on soil and water resources.



## SOIL EROSION, RUNOFF, AND PRECIPITATION

Soil erosion by water remains among the most important forces of soil degradation in the United States and worldwide. Soil erosion on cropland was reduced in the United States by 40 percent between 1985 and 1995, but progress has stalled since. More than 26 million hectares (65 million acres) of cropland in the United States continue to erode at rates greater than the soil loss tolerance, T—a standard generally interpreted to indicate that soil depth is being reduced at a rate that threatens the soil's agricultural productivity (U.S. Department of Agriculture, 1997). Other essential environmental and ecological functions of soil are degraded by soil erosion, but no national estimates exist of the extent to which those functions are being impaired. Accelerated erosion is the dominant cause of soil degradation globally; water erosion affects an estimated 1,094 million hectares (2,706 million acres) (Oldeman, 1994).

Soil erosion and runoff from cropland affects water resources directly by delivering sediment, pollutants attached to sediment, and pollutants in solution to surface water; indirect effects occur through changes in stream channel dynamics and watershed functions. In the United States, nonpoint-source pollution is the single largest cause of surface water pollution. Soil erosion and runoff from agricultural land are major causes and, in many watersheds, the most important causes of nonpoint-source pollution. In addition, the partitioning of precipitation between runoff and infiltration has profound effects on water budgets in watersheds. Runoff volumes, peak flow rates, and timing can dramatically affect stream channels, water supplies, and downstream flooding.

Soil erosion and runoff from cropland will respond to changes in climate for a number of reasons, including climate-induced changes in plant biomass, plant residue decomposition rates, soil microbial activity, evapotranspiration rates, soil surface crusting and sealing, and shifts in land use that occur as adjustments to a changed climate (Williams et al., 1996; as cited by Nearing, 2001). The most important effect of climate change on soil erosion and surface runoff, however, will come from climate-induced changes in the volume and erosive power of rainfall (Nearing, 2001).

The amount and intensity of precipitation affect the amount of soil that can be eroded and the volume and flow rate of surface runoff. As the accumulated quantity of rainfall increases during a precipitation event, the capacity of the soil to absorb the precipitation (infiltration rate) decreases and surface runoff ensues. Initially, runoff water flows uniformly across the surface; soon, however, runoff forms roughly parallel rills that coalesce into small channels of concentrated flow, which, in turn, coalesce into larger channels, eventually entering a stream. Runoff volume, depth, and flow velocity all increase with increasing volume and intensity of precipitation.

Erosion is the process of soil particle detachment and movement. Water flowing across the soil surface—surface runoff—is the most important detachment and transport mechanism. The erosive power of surface runoff is determined by depth of flow, flow velocity, and the number and energy of particles flowing with the water. The capacity for surface runoff to carry soil particles increases as flow depth and velocity increases; this capacity, therefore, increases as the volume and intensity of precipitation increase. Indeed, rainfall erosivity is strongly correlated to the product of total rainstorm energy and the maximum 30-minute rainfall intensity during a storm. Wischmeier and Smith derived this relationship in 1978 (Wischmeier and Smith, 1978). The relationship has proved to be robust and is still used today in the soil erosion prediction equations that are the foundation for erosion control planning in the United States (Nearing, 2001).

## SIMULATED AND OBSERVED CHANGES IN PRECIPITATION

Our first step toward achieving the objectives of this project was to determine the range of effects that climate change might have on precipitation regimes. We did this by looking at the work of two climate change assessment projects—those conducted by the Intergovernmental Panel on Climate Change (IPCC) and the U.S. National Assessment Synthesis Team (U.S. NAST)—for indications of the large-scale changes in precipitation regimes that model simulations and related analyses have produced. Then we reviewed in some detail recent analyses of observed changes in precipitation regimes in the United States during the 20th century.

### Simulated Changes In Precipitation Regime

A great deal of scientific effort has been directed at understanding the effects of increased concentrations of greenhouse gases on a number of climatic variables. The results of that effort have been summarized and synthesized in two documents of particular interest to this project: "Climate Change 2001: The Scientific Basis," prepared by Working Group I of the Intergovernmental Panel on Climate Change (IPCC Working Group I, 2001a), and "Climate Change Impacts on the United States," prepared by the U.S. National Assessment Synthesis Team (U.S. NAST, 2001).

The review by the IPCC working group concluded that the following effects were "virtually certain or very likely" to occur in response to increased concentrations of greenhouse gases in the atmosphere:

- Globally averaged mean water vapor, evaporation, and precipitation increase.
- Mean precipitation increases in most tropical areas; mean precipitation decreases in most sub-tropical areas; and mean precipitation increases in the high latitudes.
- Intensity of rainfall events increases.
- There is a general drying of the mid-continental areas during summer (decreases in soil moisture).

In addition, the working group concluded that new results indicate it is "likely" that precipitation extremes increase more than precipitation means and the return period for extreme precipitation events decreases almost everywhere.

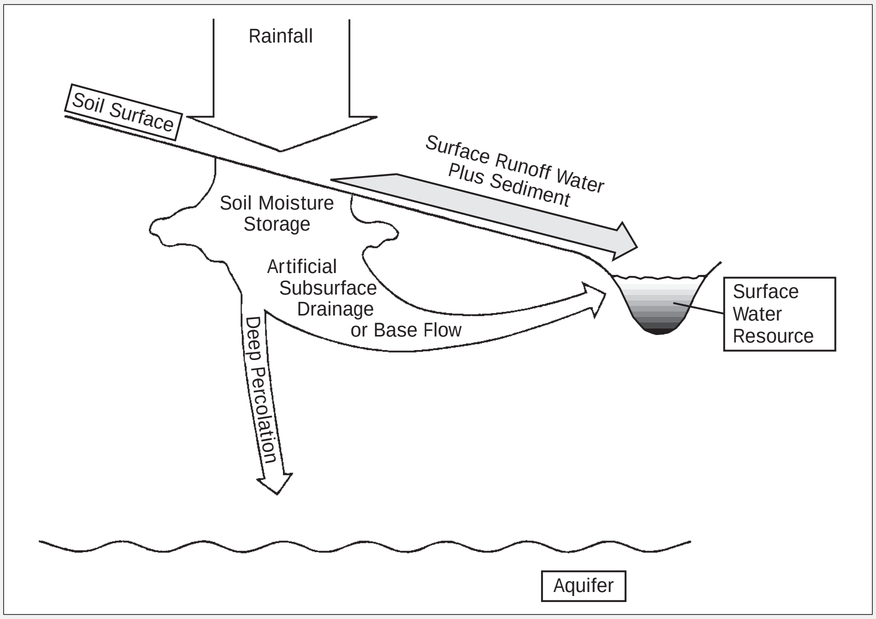
The magnitude of the simulated changes in precipitation differed, depending on which simulation was used. Three ensembles of multiple simulations were used to make projections. An ensemble of simulations based on an idealized 1 percent per year compound increase of carbon dioxide resulted in projections of a global mean temperature increase of 1.1 degree Celsius to 3.1 degrees Celsius, with an average of 1.8 degrees and a standard deviation of 0.4 degree at the point when carbon dioxide concentrations doubled after 70 years. Use of the same ensemble resulted in projected changes in global mean precipitation ranging from –0.2 percent to 5.6 percent, with an average of 2.5 percent and a standard deviation of 1.5 percent. The relative agreement among models using the ensemble was much higher for projected changes in temperature than for changes in precipitation.

A second ensemble was constructed from simulations that use estimates of observed forcing during the 20th century to construct a baseline; future forcing from greenhouse gases and sulfate aerosols is projected from that baseline. Use of this ensemble projected an increase in global mean temperature of 1.3 degrees Celsius, with a range of 0.8 degree to 1.7 degrees. Global average precipitation was projected to increase by 1.5 percent, with a range from 0.5 percent to 3.3 percent. The points of comparison were 30-year averages—2021 to 2050 versus 1961 to 1990.

The third ensemble of simulations used as an initial state the end of 20th century integrations; new forcing scenarios to the year 2100 were then used to project climate effects. The 30-year average temperature response (2071 to 2100 compared to 1961 to 1990) was an increase of 3.0 degrees Celsius or 2.2 degrees Celsius, depending on which of two forcing scenarios was used. Average global precipitation was projected to increase by 3.9 percent, with a range of 1.3 percent to 6.9 percent, or 3.3 percent, with a range of 1.2 percent to 6.1 percent, again depending on which forcing scenario was used.

The working group also reported that new results confirmed projections of precipitation events with increased intensities in a future climate with increased greenhouse gases—a finding that was among the earliest model results and remains a consistent result in a number of regions with improved, more detailed models. The percentage increase in extreme rainfall is greater than the percentage increase in mean rainfall, and the return period of extreme precipitation events is short-

## Erosion, Runoff, and Water Pollution



There are four major pathways through which pollutants are delivered to surface water and groundwater from cropland. Sediment and sediment-adsorbed pollutants, such as phosphorus, ammonium, and strongly adsorbed pesticides, can be transported to surface water by erosion. Soluble pollutants, such as nitrates, soluble phosphorus, and highly soluble pesticides, can be transported to surface water dissolved in runoff water. Soluble pollutants also can be transported to surface water in subsurface flow through the soil profile. Finally, soluble pollutants can be transported to groundwater through subsurface flow to underlying aquifers.

The pathway precipitation follows through the soil system will significantly affect the quantities and types of pollutants delivered to surface water and groundwater. Partitioning of precipitation between infiltration into the soil and surface runoff is the most important factor in determining which of the four pathways dominates during a storm event.

Infiltration is the process of water entering the soil during a rainstorm event, snowmelt, or irrigation. Infiltration rate (quantity/unit time) is influenced by many soil physical and chemical properties. Under most conditions, however, infiltration rate decreases as the soil becomes more saturated. If the soil is dry, water is absorbed inside soil aggregates or adsorbed onto the surface of soil particles. As soil is wetted by rainfall, the cohesive forces (energy holding soil particles together) of the soil become less and less. As the soil approaches its saturation point, cohesive forces reach a minimum. Under these conditions, raindrop energy is dissipated on the soil surface, causing dislodgement and splashing of soil particles. These splashed soil particles return to the soil surface to fill in the low areas of the soil relief and plug soil pores, slowing infiltration. As the soil pores are plugged, forming a soil crust, infiltration rate decreases and soil cohesive forces again begin to increase. Soil particle splash decreases because more energy is required to dislodge the soil particles. Surface runoff increases proportionally to the decrease in infiltration rate.

Water is attracted to soil particles because of the di-polar nature of the water molecule. This attractive force of the soil particle on water molecules becomes less as the water film thickness on soil particles increases. Therefore, water can move downward by gravity more easily from soil particle to soil particle as soil water content increases. In large soil pores, the water films become so thick that water is not influenced by the attractive forces of the soil, and the water flows through vertical pores by gravity. This preferential flow can lead to large volumes of water transmitted through the soil profile rapidly, providing these pores extend to the soil surface and are continuous to deeper depths. Water flowing through large pores in this fashion also can carry dissolved pollutants to surface water via underground tile, or to groundwater.

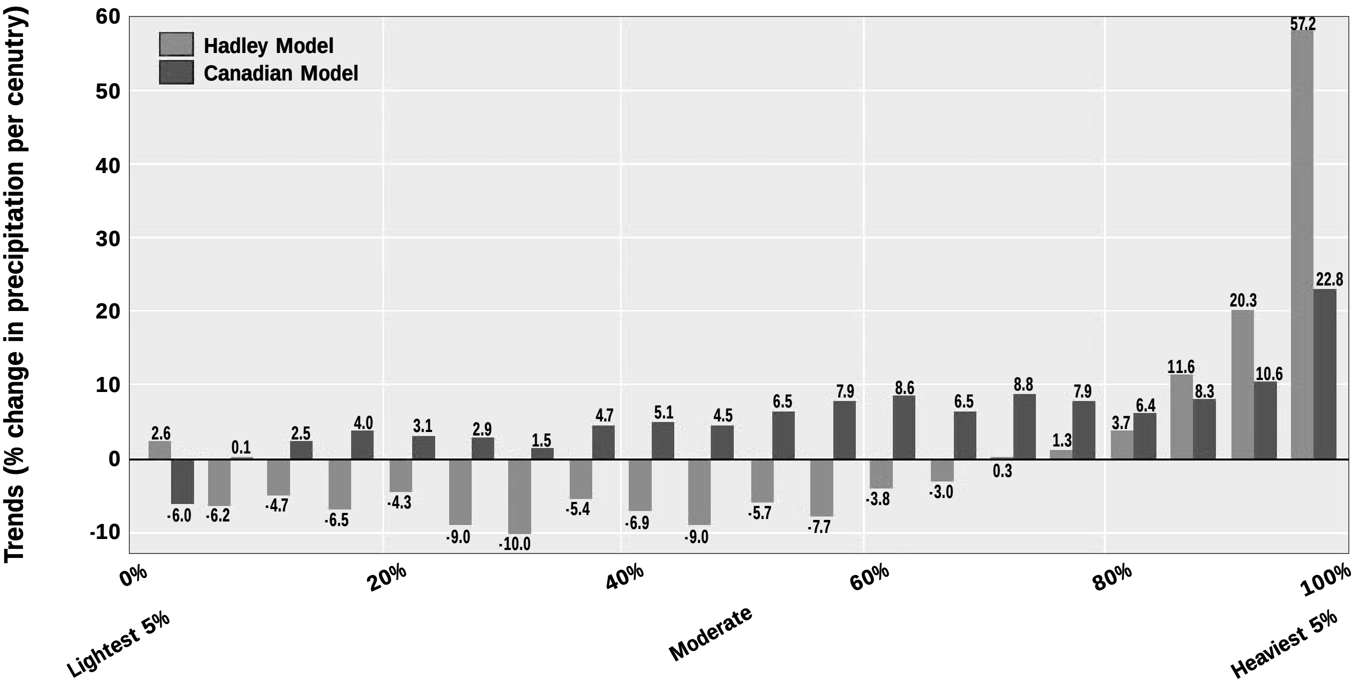
In general, soil erosion and surface runoff are the dominant pathways affected by an increase in precipitation intensity. Delivery of sediment, sediment-absorbed pollutants, and soluble pollutants in runoff water will increase. The processes of erosion and runoff from cropland are described elsewhere in this paper.

Sediment transported to surface water by erosion tends to carry a higher concentration of pollutants than is contained in the topsoil generally. This is because the heavier particles of sand and silt in runoff fall out of suspension more easily than clay and organic matter particles. Because clay and organic matter have high specific surface area and a higher proportion of cation exchange sites, eroded sediment contains a higher proportion of nutrient ions, like phosphate and ammonium, relative to the bulk soil from which it eroded—a process called enrichment. Researchers have studied this process and calculated enrichment ratios for various sediment components and soil management conditions (Sharpley et al., 1995; Young et al., 1986). Young et al. 1986 evaluated nutrient enrichment ratios from soil erosion plots at three locations in the United States. He concluded that nutrient enrichment ratios varied with crop rotation, current crop, tillage system, soil mineralogy, and latitude.

An increase in the number of wet days with no increase in precipitation intensity will tend to emphasize subsurface flow to surface water and groundwater. Hatfield et al 1998, for example, found that delivery of nitrate increased linearly with cumulative weekly precipitation in a tile-drained watershed in Iowa.

**Figure 2**

Projected changes in intensity of U.S. precipitation for the 21st century.



The projected changes in precipitation over the United States as calculated by two models indicate that most of the increase is likely to occur in the locally heaviest categories of precipitation. Each bar represents the percentage change of precipitation in a different category of storm intensity. For example, the two bars on the far right indicate that the Canadian Centre model projects an increase of over 20 percent in the 5 percent most intense rainfall events in each region, whereas the Hadley Centre model projects an increase of more than 55 percent in such events. Because both historic trends and future projections from many global climate models indicate an increase in the fraction of precipitation occurring during the heaviest categories of precipitation events in each region, a continuation of this trend is considered likely. Although this does not necessarily translate into an increase in flooding, higher river flows are likely to be a consequence.

*Source:* U.S. Department of State, 2002.

ened almost everywhere. Over North America, for example, the 20-year return periods are reduced by a factor of two, meaning the probability of extreme events doubles (Zwiers and Kharin, 1998; as cited by the IPCC Working Group I, 2001a).

The U.S. NAST used two general circulation models (GCMs)—the global climate model developed by the Canadian Centre for Climate Modeling and Analysis (CGCM1) and the model developed by the Hadley Centre for Climate Prediction and Research of the Meteorological Office of the United Kingdom (HadCM2)—to create climate change scenarios that could be used to explore potential effects of climate change in the United States. The U.S. assessment was designed to identify vulnerabilities to climate change rather than predict how climate is likely to change in the United States. The climate change scenarios analyzed by the U.S. NAST, however, produced changes in precipitation regimes for the United States that are similar to those the IPCC concluded were likely or very likely to occur at global scales. Both scenarios show increases in temperature and precipitation over the United States, and both show an increase in heavy precipitation events in the United States as the climate warms (Figure 2).

## Observed Changes in Precipitation Regime

Indications of trends in precipitation patterns in the United States found in the observed climate record are particularly interesting because of their immediate implications for conservation. Several published analyses indicate that climate has changed during the past century (Groisman and Easterling, 1994; Karl and Knight, 1998; Kunkel et al., 1999a, 1999b; Peterson et al., 1995; Brown and Braaten, 1998; Changnon, 1998; Frei et al., 1999; Easterling et al., 2000c; Groisman et al., 1994, 1999a and 1999b; and Cayan et al., 2001 as reviewed by Groisman et al., 2001). In the contiguous United States, those general trends include:

- Increase in minimum temperature.
- Decrease in extent of spring snow cover in the West.
- Increase in near-surface humidity and cloudiness.
- Increase in mean precipitation.
- Increase in heavy and very heavy rains in the East.
- Increase in high streamflow events in the East.

The observed changes are consistent with changes projected by the modeling studies summarized above. Observed increases in mean precipitation and rainfall intensity in the United States—climatic factors of particular importance to this project—generally exceed simulated increases.

Annual precipitation, averaged over the contiguous United States, increased about 6 percent over the period 1910 to 1999 (Table 1). Kunkel et al. 1999a estimated a similar upward linear trend—about 1.3 percent per decade—in annual precipitation over the period 1931 to 1996. Both Groisman et al. 2001 and Kunkel et al. 1999a found large regional variation in linear trends in annual precipitation over the periods they studied. Over the period 1900 to 1998, most areas showed increasing trends between 10 percent and 40 percent (Figure 3). Some areas, however, showed decreasing trends in annual precipitation. After about 1970, precipitation tended to remain above the 20th century mean and averaged about 5 percent more over the contiguous United States than in the previous 70 years (Karl et al., 1996).

The general trend toward increased precipitation varied seasonally. Groisman et al. 2001 found that linear trends in mean seasonal precipitation, area weighted over the contiguous United States, were 0 in winter, 10 percent in spring, 7 percent in summer, and 15 percent in autumn for the period 1910 to 1996.

Linear trends in heavy or very heavy precipitation were more pronounced than the trend in total precipitation over the contiguous United States. The proportion of increased annual precipitation occurring in extreme events grew. Precipitation intensity, in other words, increased more than annual precipitation over the period. Karl and Knight 1998, for example, reported that heavy and extreme daily precipitation events accounted for most of the increase in annual precipitation across the contiguous United States. This bias toward increased precipitation intensity has been reported in many locations worldwide (Easterling et al., 2000a, 2000b, 2000c).

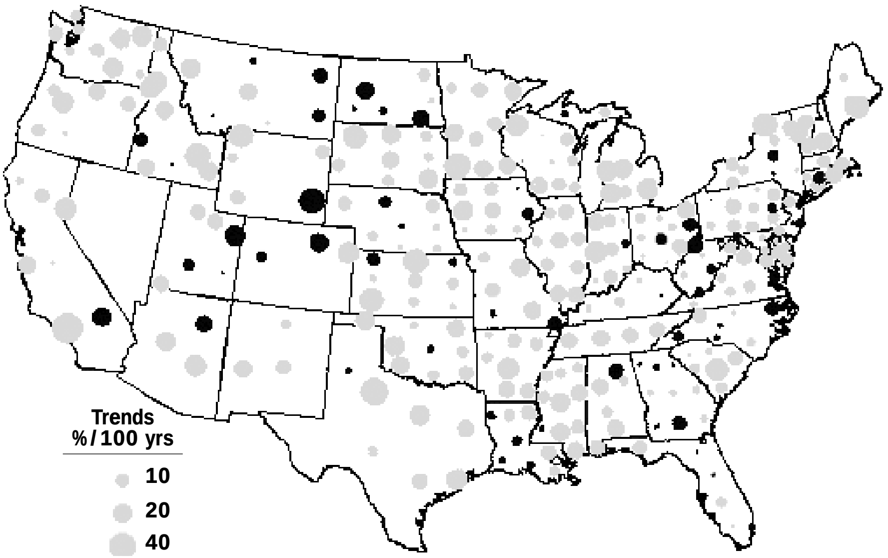
Table 1 shows the linear trend in the share of total precipitation accounted for by heavy, very heavy, and extreme daily precipitation events in the contiguous United States. The linear trend in total precipitation over the period 1910 to 1999 was 0.6 percent per decade. The linear trend in the amount of precipitation occurring during heavy precipitation events (precipitation greater than the 95th percentile for the location) was 1.7 percent per decade; for very heavy events (precipitation greater than the 99th percentile for the location), the linear trend was 2.5 percent per decade; and for extreme events (precipitation greater than the 99.9th percentile for the location), the linear trend was 3.3 percent per decade.

Data regarding the number of days on which heavy and very heavy precipitation events occurred showed a similar trend (Table 2a). The linear trend in total number of days on which precipitation greater than 1 mm (0.04 inch) occurred over the period 1910 to 1999 was 0.5 percent per decade; the linear trend in the number of days on which heavy precipitation events occurred was 1.5 percent per decade; the linear trend in the number of days on which very heavy events occurred was 2.2 percent per decade. The same pattern was apparent if heavy and very heavy precipitation events were defined on the basis of the absolute value of precipitation occurring on that day (Table 2b).

Kunkel et al. 1999a found the same upward trend in heavier precipitation events defined as 7-day duration events with a 1-year return interval or a 5-year return interval (Figure 4). The overall trend in 7-day, 1-year occurrence events was upward at a rate of about 3 percent per decade over the period 1931 to 1996. The

**Figure 3**

Linear trends in annual precipitation over the contiguous United States, 1900 to 1998.



*Source:* Groisman et al. 2001. Linear trends (percent/100 years) of annual precipitation (1900-98) over the contiguous United States (updated from Karl and Knight, 1998). Individual trends from 1221 U.S. Historical Climatology Network stations (Easterling et al. 1996) have been area-averaged inside the U.S. climatic divisions (Guttman and Quayle, 1996). Gray dots indicate increasing trends; black dots indicate decreasing trends.

**Table 1. Trend characteristics in share of total precipitation occurring in heavy, very heavy, and extreme daily precipitation events over the contiguous United States, 1910-1999.**

| | **Annual Precipitation** | | | **Contribution to Annual Totals** | | |
|---|---|---|---|---|---|---|
| **Precipitation** | **Mean** *Value (mm)* | **Linear Trend** | | **Fraction** | **Relative Change** | |
| | | *Estimate (%/10 yr)* | *Variance (%)* | | *Estimate (%/10 yr)* | *Variance (%)* |
| Annual Total | 750 | 0.6 | 5* | 1.00 | — | — |
| Heavy (> 95th percentile) | 195 | 1.7 | 12* | 0.26 | 1.0 | 20* |
| Very heavy (>99th percentile) | 62 | 2.5 | 15* | 0.08 | 1.9 | 17* |
| Extreme (> 99.9th percentile) | 12 | 3.3 | 11* | 0.016 | 2.7 | 9* |

*** Statistically significant at the 0.05 or higher level.**

*Source:* P. Y. Groisman, U.S. National Climatic Data Center.

**Table 2a. Trend characteristics in number of days with heavy and very heavy precipitation events over the contiguous United States, 1910-1999 (percentile definition).**

| | **Days with Precipitation** | | | **Contribution to total days with precipitation above 1mm** | | |
|---|---|---|---|---|---|---|
| **Events** | **Mean** *(days / yr)* | **Linear Trend** | | **Fraction** | **Relative Change** | |
| | | *Estimate (%/10 yr)* | *Variance (%)* | | *Estimate (%/10 yr)* | *Variance (%)* |
| Total days with precipitation above 1mm | 75 | 0.5 | 6* | 1 | — | — |
| Heavy (above 95th percentile) | 4.4 | 1.5 | 12* | 0.06 | 1.0 | 11* |
| Very Heavy (above 99th percentile) | 0.88 | 2.2 | 14* | 0.012 | 1.7 | 13* |

**Table 2b. Trends characteristics in number of days with heavy and very heavy precipitation events over the contiguous United States, 1910-1999 (absolute value definition).**

| | **Days with Precipitation** | | | **Contribution to total days with precipitation above 1mm** | | |
|---|---|---|---|---|---|---|
| **Events** | **Mean** *(days / yr)* | **Linear Trend** | | **Fraction** | **Relative Change** | |
| | | *Estimate (%/10 yr)* | *Variance (%)* | | *Estimate (%/10 yr)* | *Variance (%)* |
| Total days with precipitation above 1mm | 75 | 0.5 | 6* | 1 | — | — |
| Heavy (above 50.8 mm) | 1.4 | 3.3 | 30* | 0.02 | 2.8 | 33* |
| Very Heavy (above 101.6 mm) | 0.13 | 4.9 | 22* | 0.002 | 4.4 | 21* |

*** Statistically significant at the 0.05 or higher level.**

*Source:* P. Y. Groisman, U.S. National Climatic Data Center.

**Table 3. Trends in share of total annual precipitation occuring in heavy, very heavy, and extreme daily precipitation events in the contiguous U.S., 1910-1970 versus 1970-1999.**

| | **1910 - 1970** | | | **1970 - 1999** | | |
|---|---|---|---|---|---|---|
| **Precipitation** | **Mean** *(mm)* | **Linear Trend** | | **Mean** *(mm)* | **Linear Trend** | |
| | | *Estimate (%/10 yr)* | *Variance (%)* | | *Estimate (%/10 yr)* | *Variance (%)* |
| Total Annual precipitation | 737 | -0.4 | 1 | 772 | 1.2 | 2 |
| Heavy (> 95th percentile) | 188 | -0.1 | 0 | 208 | 4.6 | 12* |
| Very Heavy (> 99th percentile) | 59 | 0.9 | 1 | 67 | 7.2 | 15* |
| Extreme (> 99.9th percentile) | 12 | 1.5 | 1 | 14 | 14.1 | 22* |

*** Statistically significant at the 0.05 or higher level.**

*Source:* P. Y. Groisman, U.S. National Climatic Data Center.

trend in 7-day, 5-year occurrence events was greater—about 4 percent per decade over the same period. Both trends were statistically significant at the 0.5 percent level. The precipitation contributed in 7-day, 1-year recurrence events contributed about one-third of the upward trend in annual precipitation.

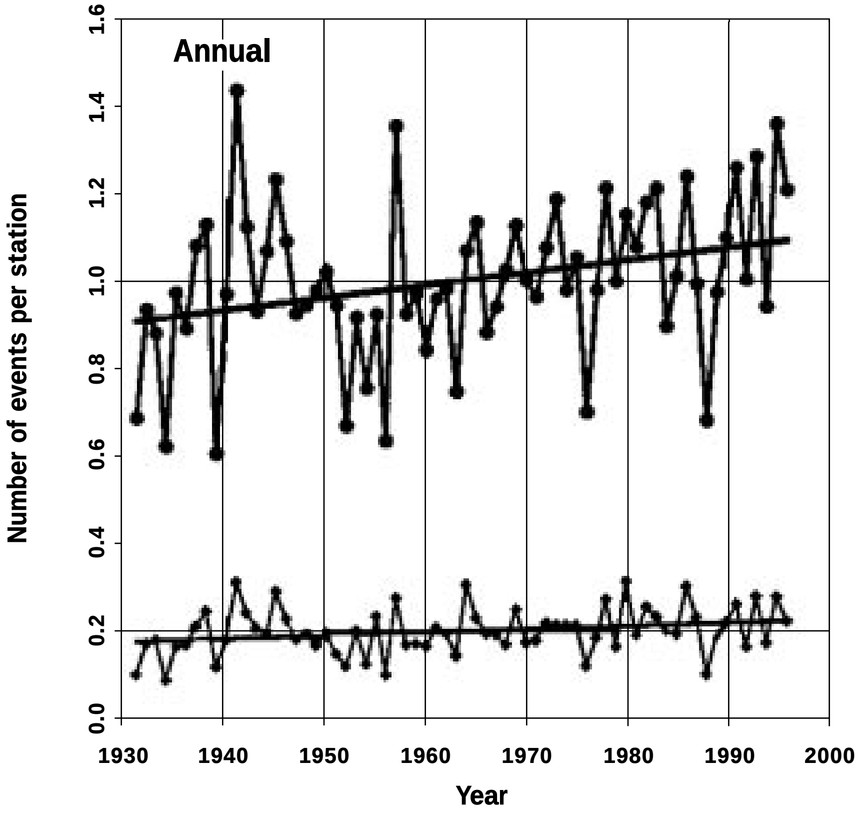
Table 3 presents data indicating that the positive trend in heavy and very heavy precipitation events was much more pronounced between 1970 and 1999 than from 1910 to 1970. The linear trend in total annual precipitation, for example, was –0.4 percent per decade over the period 1910 to 1970, but 1.2 percent per decade between 1970 and 1999. The linear trend in the proportion of precipitation occurring in heavy precipitation events was –0.1 percent per decade between 1910 and 1970, but 4.6 percent per decade between 1970 and 1999. The differences between the two periods were more pronounced for very heavy and extreme events. The same pattern was apparent if the number of days with heavy and very heavy precipitation events were analyzed, but only trends in heavy and very heavy precipitation events were significant at the 0.05 level or higher.

Regional variation within the United States in the trend toward more intense precipitation also is apparent in the climate record. Kunkel et al. 1999a found large regional variation among trends in 7-day, 1-year recurrence precipitation events (Figure 5). The largest upward trends—25 percent to more than 100 percent relative to the 1931-1996 mean—occurred over the southwestern United States and over a broad region from the central Great Plains, across the Mississippi River, and into the southern Great Lakes Basin. Only a few climate divisions showed downward trends. Those divisions were in the northwestern United States and Florida. Climate division trends for 1-day and 3-day events were very similar to those for 7-day events with a 1-year recurrence. Regional variation also was apparent if the trend in relative contribution to total annual precipitation made by differing rainfall intensity classes was analyzed.

Trends in frequency of heavier precipitation events varied seasonally as well as geographically. Kunkel et al. 1999a, for example, reported that 7-day, 1-year recurrence events occurred most frequently in the summer in the Midwest and Great Lakes Basin, but also occurred with some frequency in the spring and fall. In the Great Plains, most events

**Figure 4**

Trend in heavy precipitation events in the United States, 1931-1996.



Nationally averaged annual U.S. time series of the number of precipitation events of 7-day duration exceeding 1-year (dots) and 5-year (diamonds) recurrence intervals.

*Source:* Kunkel et al. 1999a. Copyright held by American Meteorological Society.

occurred in the summer, while events occurred more evenly across the seasons in the Northeast and the South. No climate divisions showed significant trends during the winter. On a national average, 37 percent of the 7-day, 1-year recurrence events occurred in the summer, 25 percent in the fall, 21 percent in the spring, and 16 percent in winter.

Global trends in 1-day and multiday heavy precipitation events showed a similar tendency toward more days with heavy precipitation totals over the 20th century (Easterling et al., 2000c). Nine regions showed statistically significant positive trends in the average number of days with heavy rain—(1) eastern United States, (2) European part of the former USSR, (3) Asian part of Russia, (4) southern Canada, (5) coastal regions of New South Wales and Victoria, Australia, (6) northern Japan, (7) southwestern South Africa, (8) Natal, South Africa, and (9) and Nord-Este, Brazil. Four of those regions showed statistically significant increases in heavy precipitation even when total precipitation stayed the same or decreased. Three regions showed statistically significant negative trends—(1) Ethiopia and Eritrea, (2) equatorial east Africa, and (3) Thailand.

### Key Findings

*Upward trends in total precipitation, coupled with a bias toward more extreme precipitation events, are indicated in both simulated and observed climate regimes.* The general circulation models used by the IPCC and U.S. NAST to simulate climate responses to greenhouse gas forcing generally agree that an increase in annual precipitation and in the frequency of more extreme precipitation events are the most likely outcomes of climate change resulting from increasing greenhouse gas concentrations. Analyses of the historic climate record show a similar general upward trend in annual precipitation and precipitation intensity in the United States, particularly since 1970.

The difficulties and uncertainties in modeling climate response to greenhouse gas forcing are well known and described in the reports of the IPCC 2001a and the U.S. NAST 2001. At the global level, uncertainties arise from uncertainties in sensitivities to greenhouse gas emissions and uncertainties about the emissions themselves.

It is possible that the upward trends in precipitation amounts and intensities observed in the historic climate record will not continue into the future. It is also possible that those trends could accelerate. We did not try to conclude in this project whether changes in the observed climate record are a result of anthropogenic forcing; neither did we try to evaluate the likelihood that simulated climate change in response to greenhouse gas forcing will actually occur. The concurrence of simulated and observed changes is striking, however, and statistical analyses of the observed climate record indicate that there is less than a 1 in 1,000 chance that the observed changes in precipitation regime could have occurred under a stable climate (Karl et al., 1996). The IPCC Working Group 1 conclusion that "there is new and stronger evidence that most of the warming observed over the last 50 years is attributable to human activities" suggests the observed trends could signal the beginning of a long-term trend (IPCC Working Group 1, 2001b. p. 10).

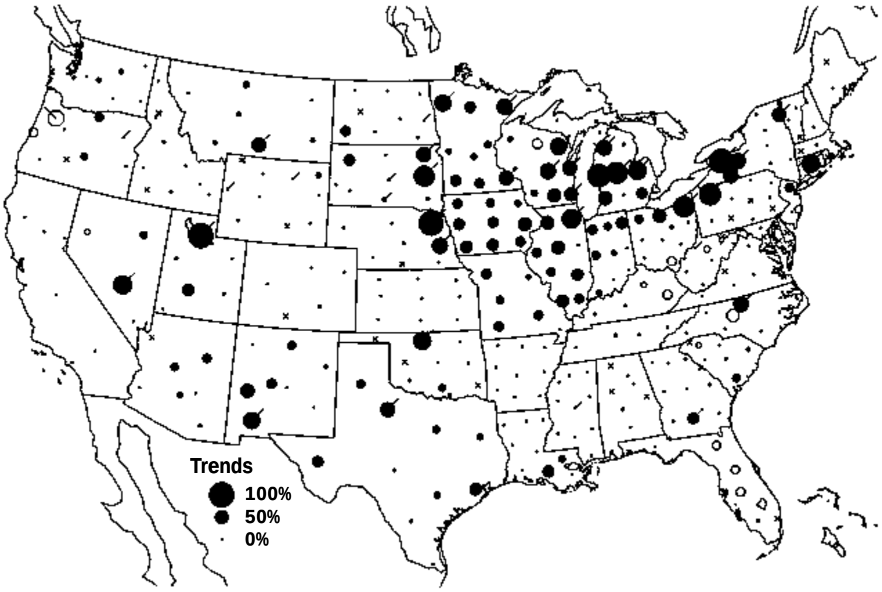
Conservationists should be concerned about the potential effects of changes in precipitation patterns on soil erosion and runoff regardless of whether those changes are attributed to specific forcings—anthropogenic or natural.

*Regional, seasonal, and temporal variability in precipitation is large in both simulated and observed climate regimes.* Regional deviations from simulated global responses are likely to be quite large, even at fairly large scales. Analyses of the historic climate record clearly show that variability in change in precipitation regimes is large. That variability includes:

- Geographic variability in trends of both annual precipitation and precipitation intensity.
- Seasonal variability in trends of both annual precipitation and the frequency of more extreme precipitation events.

**Figure 5**

Linear trends in frequency of heavy precipitation events over the contiguous United States, 1931 to 1996.



United States climate division trends in frequency of precipitation events of 7-day duration exceeding a 1-year recurrence interval. Shaded circles indicate upward trends while open circles indicate downward trends. The magnitude of the trend is given in terms of the percent increase or decrease over the period 1931-1996 relative to the 1931-1996 mean. As indicated in the key, the magnitude of the trend is linearly proportional to the radius of the circle. A tail attached to the upper right indicates positive trends with local significance at the 5 percent level. A tail attached to the upper left indicates locally significant negative trends. An "x" indicates a climate division with no stations with complete records for the period 1931-1996.

*Source:* Kunkel et al. 1999a. Copyright held by the American Meterological Society.

- Decadal variability in trends of both annual precipitation and precipitation intensity.
- Geographic variability in the absolute amounts of rainfall occurring in events defined as heavy, very heavy, or extreme.

Such variability means that general upward trends in annual precipitation and precipitation intensity will be expressed very differently in different locations, years, and seasons. The risk posed to soil and water resources will be just as variable.

Our understanding of the role of climate variability and forcing factors on precipitation is incomplete, but there is clear evidence that known oscillations have important impacts on precipitation regimes. Climate simulations and analyses of the historic climate record suggest a change in baseline conditions characterized by a general trend toward increased total annual precipitation and precipitation intensity. Local and regional variations from that new baseline will be large.

## ESTIMATED EFFECTS ON SOIL EROSION AND RUNOFF

Our second step toward achieving the objectives of this project was to review published studies that would help us assess, quantitatively, the changes in rates of soil erosion and runoff that could occur under changed precipitation regimes. We focused on studies that attempted quantitative estimates of change in soil erosion and runoff caused by changes in precipitation patterns. (Please see the appendix for more information about the nature of the models used by the authors cited below to estimate soil erosion and runoff).

### Estimated Effects on Soil Erosion

Several studies have attempted to quantify the effects of change in precipitation amounts, frequency, and intensity on soil erosion from cropland. Two studies used output from general circulation models to estimate the effect of simulated changes in climate on soil erosion rates at the national scale in the United States. These studies estimated the effect of climate change on erosivity by estimating the effect of a new, simulated precipitation regime on the R-factor (rainfall-runoff erosivity factor) in the Universal Soil Loss Equation (USLE) or Revised Universal Soil Loss Equation (RUSLE).

Nearing 2001 used monthly and annual precipitation output from the UK Hadley Centre model (HadCM3) and the Canadian Centre for Climate Modeling and Analysis model (CGCM1) to modify the R factor in RUSLE for the contiguous United States. The period 2080-2099 was compared to the baseline period 2000-2019. Erosivity was calculated from statistically derived relationships between the R factor and the modified Fournier coefficient (Renard and Freidmund, 1994) and between the R factor and total average annual precipitation. Effects on erosivity varied geographically among grid cells for which model output was generated. The calculated changes in erosivity using the HadCM3 model for individual grid cells ranged from –59.5 percent to +118.3 percent. Calculated changes in erosivity among grid cells using the CGCM1 model ranged from –65.1 percent to +802.8 percent. The absolute changes in erosivity averaged over all grid cells ranged from 15.9 percent to 20.9 percent for the HadCM3 model and 53.4 percent to 58.3 percent for the CGCM1 model, depending on which method was used to estimate the new R-factors.

Phillips et al. 1993 used four global climate models—the National Oceanic and Atmospheric Administration (NOAA) Geophysical Fluid Dynamics Laboratory model (Manabe and Wetherald, 1987), the NASA Goddard Institute for Space Studies model (Hansen et al., 1988), the Oregon State University model (Schlesinger and Zhao, 1989), and the United Kingdom Meteorological Office model (Mitchell et al., 1987)—to generate climatic scenarios, assuming a doubling in atmospheric carbon dioxide concentrations from simulated baseline conditions. Estimates of annual precipitation from each model were used to estimate changes in county-averaged USLE R-factors for each U.S. National Resource Inventory (NRI) sample point. Model simulations of annual precipitation were assumed to occur either (1) through a change in storm frequency only or (2) through a change in storm intensity only. In the first case, a new R-factor was calculated by multiplying the baseline, county-averaged R-factor by the ratio of simulated-to-baseline annual precipitation. In the second case, a new R-factor was calculated by multiplying the baseline, county-averaged R-factor by the square of the ratio of simulated-to-baseline annual precipitation, adapted from Foster et al. 1985.

Estimated changes in annual soil erosion on cropland, averaged over all U.S. NRI sample points, ranged from 2 percent to 8 percent, depending on which model was used if only storm frequency changed, and from 5 percent to 16 percent, depending on which model was used if only storm intensity changed. Estimated changes in annual average soil erosion ranged from –2 percent to 10 percent on pasture and from –5 percent to 22 percent on rangeland, again depending on which model was used and whether storm frequency or storm intensity was adjusted. For all land uses, estimated changes in soil erosion varied greatly from the national averages reported above, depending on the geographic location of the sample points.

Three studies looked at the effects of changed precipitation regimes on soil erosion at smaller geographic scales in the United States. Those studies shed light on the relative effects of changes in precipitation frequency and/or intensity, in addition to changes in total precipitation.

Savabi et al. 1993 used the Water Erosion Prediction Project (WEPP) model to estimate the effect of increased precipitation intensity on soil erosion simulated for cropland growing corn in Minnesota, Illinois, and Texas. They found that linearly increasing the amount of daily precipitation by 5 percent or 10 percent over 50 years increased soil erosion by 10.7 percent and 35.6 percent respectively. In their study, the amount of precipitation received per day (precipitation intensity) was increased while the number of days receiving precipitation remained constant.

Pruski and Nearing 2002 compared directly the effects of changes in frequency and/or intensity by allocating a –20, -10, 0, 10, and 20 percent change in annual precipitation to changes in intensity alone, changes in frequency alone, or a combination of changes in intensity and frequency. They simulated the results of these precipitation regimes using the WEPP model for three soil types, three slopes, and four crops at three locations in the United States—West Lafayette, Indiana; Temple, Texas; and Corvallis, Oregon. They found that a change in intensity had significantly greater effect on soil erosion than a change in frequency of precipitation. Specifically, a 1 percent change in precipitation resulted in an average 2.38 percent change in soil erosion if precipitation intensity alone was changed. An average 0.85 percent change in soil erosion resulted if precipitation frequency alone was changed. Simulating a combination of change in frequency and intensity resulted in an average 1.66 percent change in soil erosion for each 1 percent change in precipitation.

Lee et al. 1996 used the Erosion Productivity Impact Calculator (EPIC) (Sharpley and Williams, 1990) model to simulate the effect of a change in mean monthly precipitation if the frequency of events (number of wet days) or intensity of events (amount of precipitation per day) changed. In contrast to the Pruski and Nearing 2002 and Phillips et al. 1993 results, they found little difference (generally less than 1 percent) in the mean soil erosion rate resulting from increases in frequency compared to increased intensity of precipitation. They also found the mean water erosion rate was linear to precipitation volume for the range of precipitation change in their study—a –20 percent to 20 percent change in precipitation volume led to a –37 percent to 37 percent change in soil erosion. They did find, however, that the variability among the estimates of soil erosion rates resulting from a change in precipitation was less if the frequency of days receiving precipitation was increased than if storm intensity was increased. This reduced variability was caused by the effect of the antecedent moisture content of the soil. Soils under a precipitation regime of increased number of wet days will more likely be wetter and, therefore, more apt to produce soil erosion and runoff. Soils under a precipitation regime of fewer wet days but more intense precipitation events may or may not produce soil erosion and runoff, depending on the antecedent moisture status of the soil.

Studies at locations outside the United States show similar results. Two studies simulated the effects of a change in mean monthly precipitation on erosion rates at the national scale in Great Britain. Boardman and Favis-Mortlock 1993 used the EPIC model to estimate that increases in mean monthly precipitation of 5, 10, and 15 percent from current conditions in Great Britain would result in 10, 26, and 33 percent increases in soil erosion respectively. In a similar study, Favis-Mortlock et al. 1991 simulated the effect of a –10, -5, 5, 10, and 15 percent change in mean monthly precipitation from current conditions in Great Britain. They based their simulated changes in mean monthly precipitation on a literature review of anticipated climate change by 2050. Their study used the EPIC model to estimate changes in soil erosion rates ranging from –7 percent to 64 percent.

Favis-Mortlock and Guerra 1999 estimated soil erosion changes in Mato Grosso State, Brazil, using precipitation regimes generated by three different GCMs and a modified version of the WEPP model (WEPP-CO2 as described by Favis-Mortlock and Savabi, 1996). They reported increases in soil erosion ranging from 27 percent to 55 percent, based on model output from two of the GCMs. Output from the third GCM produced a 9 percent reduction in soil erosion.

### Estimated Effects on Surface Runoff

Three of the previously cited studies also estimated the effects of precipitation change on surface runoff. Savabi et al. 1993 reported that a 5 percent to 10 percent increase in precipitation intensity (average daily precipitation) resulted in a 3.7 percent to 15.9 percent change in runoff at their three study locations. Lee et al. 1996 reported the same linear relationship between precipitation volume and runoff that was reported between precipitation and soil erosion. A –20 percent to 20 percent increase in precipitation resulted in an estimated –40 percent to 40 percent change in runoff.

Pruski and Nearing 2002 found the same relationship between runoff and precipitation intensity and frequency as they did between soil erosion and precipitation intensity and frequency. They also found that rainfall intensity had a greater effect than rainfall frequency on runoff. Each 1 percent change in precipitation amount resulted in an average 2.5 percent change in runoff if a change in intensity accounted for all of the change in amount; an average 1.28 percent change in runoff occurred if a change in frequency accounted for all of the change in precipitation amount; and an average 1.97 percent change in runoff occurred if a combination of change in intensity and frequency accounted for the change in precipitation volume.

In addition to the foregoing studies, Nicks 1993 used the Simulator for Water Resources in Rural Basins (SWRRB) model (Arnold et al., 1990) to estimate the effect of changes in precipitation patterns simulated using the climate generator model (CLIGEN) (Nicks and Gander, 1994) on runoff. He reported that a 16 percent increase in annual precipitation produced a 70 percent to 73 percent increase in water yield in three study watersheds in central Oklahoma under predominately rangeland use. A 12 percent increase in precipitation frequency (number of wet days) produced a 47 percent increase in runoff in the same study watersheds.

Pruski and Nearing (in press) used mean monthly precipitation outputs from the HadCM3 model to estimate the effect of changes in precipitation regime on runoff in eight locations in the United States—Atlanta, Georgia; Cookeville, Tennessee; Corvallis, Oregon; Pierre, South Dakota; Syracuse, Nebraska; Temple, Texas; West Lafayette, Indiana; and Wichita, Kansas. Half of the change in mean monthly precipitation was simulated by increasing precipitation frequency (number of wet days) and half by increasing precipitation intensity (precipitation per day). They reported that changes in mean annual precipitation ranging from –9.6 percent to 10.6 percent produced changes in runoff from –24.5 percent to 41.0 percent.

## Key Findings

*Changes in precipitation regimes clearly have the potential to produce profound effects on soil erosion and runoff from cropland*. Simulated changes in total annual precipitation or mean monthly precipitation expressed as either changes in storm frequency, intensity, or some combination of both all produce large changes in estimated rates of soil erosion and surface runoff. In all cases, the percentage change in soil erosion or surface runoff was larger than the simulated percentage change in precipitation. Soil erosion and surface runoff are highly sensitive to changes in precipitation regimes.

*An increase in storm intensity—all other factors being equal—will increase soil erosion, runoff, and related environmental damage more than an increase in the number of wet days in a year.* Changes in storm intensity have greater effects on soil erosion and runoff than changes in storm frequency. All of the reviewed studies that directly compared the results of a change in total precipitation allocated to either storm frequency or storm intensity—with one exception—reported larger effects from changes in storm intensity.

As indicated above, Lee et al. 1996 reported a linear relationship between precipitation volume and soil erosion or runoff with little difference between a change in storm frequency or intensity. The methods used by Lee et al. 1996, however, would not be expected to distinguish effectively between the effects of frequency and intensity. The model used—the Erosion Productivity Impact Calculator (EPIC)—estimates soil erosion using a version of the Modified Universal Soil Loss Equation (MUSLE). Because the model does not contain the Green-Ampt infiltration model, which estimates water infiltration into the soil based upon the physical condition of the soil and the rainfall intensity, it is less capable of estimating the effects of precipitation intensity than the physically based models used in the other studies, particularly Pruski and Nearing 2002. In addition, runoff in EPIC is calculated using the NRCS runoff curve number method. The curve number method is an empirical formula and cannot account for changes in rainfall intensity.

Pruski and Nearing used the more physically based Water Erosion Prediction Project (WEPP) model to simulate soil erosion and runoff. WEPP also contains the Green-Ampt infiltration model. Although both studies consider the effects of individual rainfall events on runoff and erosion, WEPP accounts for the physical processes of infiltration, soil roughness, and antecedent moisture. Therefore, the Pruski and Nearing study should give a better indication of the effects of changing rainfall intensity versus rainfall frequency.

In general, increased precipitation intensity means a greater proportion of annual precipitation is apportioned to runoff rather than to infiltration. Surface transport of pollutants via soil erosion and runoff will increase markedly—all other factors being equal—and surface transport of pollutants generally will threaten water resources more than subsurface transport. In addition to the direct threats to water quality from increased delivery of sediment and other pollutants (both sediment attached and in solution) from cropland, increased storm intensity will magnify the effects of runoff on channel stability and flooding. Increased storm intensity likely would accelerate both ephemeral and incised gully erosion—erosion processes that are particularly damaging to soil and water resources. The amount of sediment produced by ephemeral gully erosion, for example, can equal the amount of sediment produced by rill and interrill erosion in the same field (Foster, 1986;Thomas et al., 1986). None of the studies we reviewed include estimates of ephemeral or incised gully erosion. Water budgets and water supplies will be affected in important ways if more annual precipitation is allocated to surface runoff through increases in precipitation intensity.

Alternatively, an increase in the number of wet days—all other factors being equal—will cause less of an increase in erosion and runoff compared to an increase in precipitation intensity, but will likely increase the importance of subsurface flow in delivering soluble nonpoint-source pollutants to surface water and groundwater. Hatfield et al. 1998, for example, found that delivery of nitrate increased linearly with cumulative weekly precipitation in a tile-drained watershed in Iowa.

*Geographic, seasonal, and temporal variability in effects will be large*. All of the studies we reviewed suggest that effects of a changed precipitation regime will vary a great deal in space and time. Nearing 2001, for example, estimated changes in erosivity ranging from –65.1 percent to +802.8 percent among different geographic regions in the United States. In large part, the variability in effects reflects the large geographic, seasonal, and temporal variability in precipitation patterns described earlier. But other factors, also highly variable, will influence the effect of changes in precipitation patterns.

Different landscapes vary greatly in their vulnerability to soil erosion and runoff. Soil type, slope, and cover all have profound effects—both positive and negative—on the effect of a change in precipitation regime on soil erosion, surface runoff, and other environmental consequences. Spatial and temporal variability in those factors magnifies the spatial and temporal variability in precipitation patterns.

In addition, row-crop production systems are especially vulnerable to rainfall events that occur at particular times of the year. Those times are (1) when the soil is most exposed because crops are not present or crop residues are minimal and (2) when potential pollutants in the soil system are at high levels and crops are not actively growing. For example, Kramer 2001 documented the seasonality and year-to-year variability of sediment yield from a small watershed in southwestern Iowa from 1975 to 1991. In this study, there was a distinct tendency for maximum soil erosion and runoff to occur in the early plant growth period (spring). Thurman et al. 1991 documented the "spring flush" phenomenon of herbicide concentrations and frequency of detections of herbicides in the post-planting sampling dates of surface water in the midwestern United States. Squillace and Engberg 1998 hypothesized that surface water containing those elevated concentrations of herbicides may contribute significantly to alluvial aquifer contamination as a result of the reverse groundwater flow gradient (i.e. surface water from the stream flowing into the alluvial aquifer). A precipitation increase in Iowa after nitrogen has been applied in the spring will result in more nitrogen in streams than if a similar increase in precipitation occurs in August (Schuman et al., 1973).

If the seasonal distribution of precipitation changes so that more precipitation occurs during vulnerable periods, then the effects on soil degradation and water pollution will be magnified. Groisman et al. 2001 found that the largest linear trends in precipitation in the United States occurred in spring and autumn. The spring season is particularly vulnerable because of the lack of crop residues and/or a growing crop and the fact that fertilizers and pesticides have been applied to agricultural fields.

In sum, a change in precipitation regime also produces a change in the level of risk to which agricultural land is exposed. In general, a regime with greater annual precipitation—particularly if storm intensity increases more than storm frequency—heightens the risk of soil erosion, runoff, and related environmental and ecological damages. The actual damages that occur because of the new, more risky baseline conditions are highly dependent on additional factors.

*Interactions with other components of climate change could mitigate or exacerbate the effects of changes in precipitation patterns.* The effect of a change in precipitation on soil erosion and runoff and the consequent effects on the environment can be reduced or intensified by interactions with other factors. Biomass is a particularly influential factor. The increased risk to soil erosion and water pollution from an increase in annual precipitation could be mitigated by the increase in biomass expected from an increase in carbon dioxide concentrations in the atmosphere. Similarly, the reduced risk to soil erosion and water pollution from a decrease in annual precipitation could be negated by a reduction in biomass caused by a reduction in soil moisture.

Pruski and Nearing (in press) evaluated these interactions at eight U.S. locations. They found that biomass production, as affected by soil moisture, carbon dioxide concentration, temperature, and solar radiation, was a key factor that sometimes overshadowed the direct effects of rainfall increases or decreases on soil erosion and runoff. Different types of changes occurring in different periods of the year also complicated system responses. Overall, they found that these interactions tended to be more important when precipitation decreased than when precipitation increased. Significant increases in precipitation, they found, could be expected to lead to increased soil erosion. Decreases in precipitation could produce reductions or increases in soil erosion, depending on the interaction of plant biomass with erosion and runoff.

*Feedback mechanisms could magnify the long-term effects of a change in precipitation regime.* Over time, the soil's capacity to resist the effects of extreme or, in some cases, mean events can be reduced. In some cases, this loss in resilience or resistance can happen suddenly in response to a particularly damaging event. Runoff from an infrequent but large-magnitude event, for example, can destabilize gully sidewalls, increasing the soil's vulnerability to future, much smaller runoff events (Toy et al., 2002). An extreme erosion episode that removes a large portion of the organic matter-rich topsoil likely would decrease the rate water infiltrates into the damaged soil, leading to accelerated surface runoff, less biomass production, less soil cover and greater risk of erosion in future events of a smaller magnitude.

Such losses in resistance or resilience leave soils and landscapes more vulnerable to subsequent events. In the worst case, this can lead to a downward spiral characterized by accelerated degradation of soil and related water resources (Seybold et al., 1999). Degradation of soil, stream channels, and other watershed features can lead to a similar downward spiral in watershed functions.

# CONSERVATION IMPLICATIONS

The key findings from our review of (1) simulated and observed changes in precipitation regime and (2) quantitative estimates of the effect of changes in precipitation on soil erosion and runoff formed the factual basis for discussion and debate among our expert panel and staff. We also relied on the professional judgment of the panel and SWCS staff to answer our primary question: Are the effects of changing precipitation regimes on soil erosion and runoff from cropland likely to be large enough to warrant changes in U.S. conservation policy or practice?

Our answer was, emphatically, yes. Conservationists should be concerned. That answer led to further discussion about how conservationists should respond to the risk posed by climate change in the form of an altered precipitation regime.

## Conservationists Should Be Concerned

Conservationists should be seriously concerned about the implications of climate change—as expressed by changes in precipitation patterns—for the conservation of soil and water resources in the United States. The magnitude and extent of increased rates of soil erosion and runoff that could occur under simulated future precipitation regimes are large. More importantly, analyses of the climate record in the United States show that changes in precipitation patterns are occurring now. In fact, the magnitude of observed trends in precipitation and the bias toward more extreme precipitation events are, in some cases, larger than simulated by global climate change models, particularly since 1970. The soil degradation, water pollution, and other environmental effects noted in Figure 1 that could occur as a result of the more pronounced increases in precipitation amounts and intensities would be severe enough that conservation policies and practices would need to change and adapt to the increased risk of soil erosion and surface runoff.

Pruski and Nearing 2002, for example, quantified the relationship between a 1 percent change in precipitation and the resulting change in soil erosion and runoff, depending on whether precipitation increased in frequency, intensity, or a combination of both. Extrapolating those relationships to the changes in precipitation observed over the past century suggests increases in soil erosion ranging from 4 percent to 95 percent and increases in runoff from 6 percent to 100 percent could already be evident in some locations (Table 4).

Unless additional protective measures are taken, such increases in soil erosion on cropland—if widespread—could reverse much of the progress that has been made in reducing soil degradation on cropland in the United States.

Changes of this magnitude in soil erosion and runoff likely would have profound effects on water resources, although published estimates are few. Nicks 1993 estimated that a 16 percent average annual increase in precipitation, using mean monthly precipitation quantities from global climate change model estimates, would produce a 128 percent or 103 percent increase in sediment yield and a 70 percent or 73 percent increase in water yield within an Oklahoma watershed depending on what method was used to estimate montly precipitation trends . Favis-Mortlock and Guerra 1999 used mean monthly precipitation outputs from three global climate models for 2050 to estimate changes in sediment yield in Sorriso, Brazil. They reported an increase in sediment yield of 27 percent under the first model in which change in mean monthly precipitation ranged from –10 percent to 38 percent, a decrease in sediment yield of 9 percent under the second model in which change in mean monthly precipitation ranged from –20 percent to 4 percent, and an increase in sediment yield of 55 percent under the third model in which change in mean monthly precipitation ranged from –5 percent to 95 percent. Transport of soluble pollutants, such as nitrates, some pesticides, and salts, could be accelerated by changes in precipitation patterns that are significantly smaller than those needed to induce accelerated erosion. Hatfield et al. 1998, for example, reported that monitoring of subsurface drainage in an Iowa watershed indicates that 67 percent of the nitrate loadings could be accounted for by considering the effects of precipitation patterns in the watershed.

The potential for climate change—as expressed in changed precipitation regimes—to increase the risk of soil erosion, surface runoff, and related environmental consequences is clear. The actual damage that would result from such a change is unclear. That uncertainty is largely the result of variability in precipitation patterns and variability in the landscape features and management that ultimately determine the outcome of a change in a precipitation regime.

**Table 4. Potential effects on soil erosion and runoff from cropland of observed changes in precipitation.**

| | Increase in Mean Annual Precipitation | | | |
|---|---|---|---|---|
| | 5% | 10% | 20% | 40% |
| **Change in Erosion** | | | | |
| Increase only frequency of precipitation | 4% | 9% | 17% | 34% |
| Increase only intensity of precipitation | 12% | 24% | 48% | 95% |
| Increase frequency and intensity equally | 8% | 17% | 33% | 66% |
| **Change in Runoff** | | | | |
| Increase only frequency of precipitation | 6% | 13% | 26% | 51% |
| Increase only intensity of precipitation | 13% | 25% | 50% | 100% |
| Increase frequency and intensity equally | 10% | 20% | 39% | 79% |

*Source:* Derived from Pruski and Nearing 2002.

Regional, seasonal, and temporal variability in precipitation is large in both simulated climate regimes and the existing climate record. Different landscapes vary greatly in their vulnerability to soil erosion and runoff. Timing of biomass production and harvest, tillage operations, and applications of nutrients and pesticides combine to create greater vulnerabilities to soil erosion and runoff during certain seasons. The effect of a particular storm event depends on the moisture content of the soil before the storm starts and, therefore, on the amounts and intensities of previous storm events. These interactions between precipitation, landscape, and management mean the actual outcomes from any particular change in precipitation regime will be complex.

In sum, a change in precipitation regime also produces a change in the level of risk to which agricultural land is exposed. In general, a regime with greater annual precipitation—particularly if increased storm intensity changes more than storm frequency—heightens the risk of soil erosion, runoff, and related environmental and ecological damages. In general, the risk increases at a greater rate than precipitation amount or intensity increases. Whether that new, more risky baseline condition translates into greater soil degradation, pollution of surface water, pollution of groundwater or a combination of all three outcomes is highly dependent on interactions among precipitation patterns, landscape features, and management.

We focused our work on the effects of increased precipitation amounts and intensities on soil erosion and runoff from cropland. It is important to note, however, that increases in the amount and intensity of precipitation are not the only—and in some cases probably not the most important—risks posed by climate change. Decreases in precipitation, for example, can accelerate erosion as much as increases in precipitation because of reduced biomass production. Pruski and Nearing (in press) reported that soil erosion increased in about half of the cases in which a decrease in total precipitation was simulated. More importantly, change in the seasonal distribution of precipitation, coupled with increased minimum temperatures, could have profound effects on water budgets in the western United States. Those effects could be more important than effects on erosion, runoff, and related environmental endpoints. Similarly, a change in precipitation regimes in arid areas could lead to major shifts in plant communities on rangeland. Such shifts could have profound effects on the environment and on the sustainability of agricultural production in those regions. We did not attempt to assess the magnitude of such changes, but such an assessment would likely increase the reasons conservationists should be concerned about climate change.

Work to identify the most effective ways in which soil and water conservation policies and practices can be adapted to a changing precipitation regime should, therefore, be undertaken with some urgency.

## How Should Conservationists Respond?

The primary objective of this project was to answer one question: Are the effects of changing precipitation regimes on soil erosion and runoff from cropland likely to be large enough to warrant changes in U.S. conservation policy or practice? Our answer was, emphatically, yes. Conservationists should be concerned. In the process of coming to that conclusion, we developed ideas regarding the most promising responses to the risk posed by an altered precipitation regime. Three particularly promising responses include:

1. Immediately update climatic parameters in critical conservation planning tools.
2. Undertake targeted investigations to firm up estimates of the damage that would likely occur under simulated or observed climate regimes.

3. Evaluate the need to build the risk of damage from severe storms into the conservation planning process used to determine if recommended conservation practices and systems adequately protect soil and water resources.

*Update Climatic Parameters*

A step that could and should be taken quickly is to adjust the critical parameters in conservation planning tools to reflect the most current climate data. Key climate components of the Revised Universal Soil Loss Equation (RUSLE), for example, are currently derived from climatic data for the period 1936 to 1957 over much of the contiguous United States. NRCS already is working on a new version of RUSLE (RUSLE2) that will feature updated algorithms for computing soil loss on cropland.

New precipitation and temperature data covering the period 1971-1999 are now being prepared for RUSLE2 implementation, including updated R-factors for all parts of the continental United States. Interpolated R-factors, as well as other required climate elements, will be derived for counties, agricultural regions, or other homogeneous areas using the PRISM spatial climate modeling system from Oregon State University. NRCS managers expect to have this new climate information integrated into RUSLE2 sometime in 2003.

Precipitation frequency studies are being updated by the NOAA-NWS Hydrometerological Design Studies Center with support from NRCS in the U.S. Department of Agriculture, the U.S. Army Corps of Engineers, and others. The original precipitation frequency studies were developed for the eastern United States and published as Technical Paper-40 (Hershfield, 1961). Technical Paper-40 was superseded in the West by NOAA Atlas 2 (Miller et al., 1973) and Technical Memorandum NWS Hydro 35 (Frederick et al., 1977). Various other documents extended the precipitation frequency studies to specific geographic areas of the United States. Data used in these documents are what were available immediately prior to publication.

An updated precipitation frequency study for the southwestern United States (Nevada, Arizona, Utah, New Mexico, and southeastern California) was scheduled for release in 2002. An updated precipitation frequency study for the Ohio River Valley region is to be released in 2003. A nationwide update of precipitation frequency is planned to begin in 2003 or 2004.

## Regional Thresholds for Heavy, Very Heavy, and Extreme Precipitation Events

The absolute amount and intensity of rainfall that occurs in events defined as heavy or extreme vary across the United States. In general, smaller absolute amounts of precipitation occur during heavy, very heavy, or extreme events in regions with less annual rainfall.

**Amount of 24-hour Precipitation by Region (mm)**

| Type of Precipitation Event | Southwest | Missouri River Basin | Midwest | Southeastern Coastal region | Nationwide Average |
|---|---|---|---|---|---|
| Heavy (above 95th percentile) | 20 | 20 | 35 | 45 | 30 |
| Very heavy (above 99th percentile) | 34 | 37 | 59 | 82 | 52 |
| Extreme (above 99.9th percentile) | 56 | 64 | 99 | 151 | 89 |

*Source:* P.Y. Groisman, U.S. National Climatic Data Center.

In the table above, for example, the nationwide average rainfall for an event defined as heavy (95th percentile) is 30 mm and ranges from 20 mm to 45 mm among the four regions analyzed. The range in absolute amounts of rainfall is larger for events defined as heavy (99th percentile) or extreme (99.9th percentile).

The same pattern occurs if heavy precipitation events are defined in terms of duration and return period. Kunkel et al. 1999a, for example, reported that thresholds for 7-day, 1-year recurrence rainfall events ranged from less than 25 mm in the desert regions of the southwestern United States to more than 150 mm along the coasts of the Gulf of Mexico, southern Atlantic Ocean, and northern Pacific Ocean. The thresholds for 3-day, 1-year recurrence events were about 80 percent of those for 7-day, 1-year events; thresholds for 7-day, 5-year recurrence events were about 150 percent of those for 7-day, 1-year events.

The absolute intensity and duration of rainfall events are the most important factor in determining whether an increasing trend in such events will result in increased erosion, runoff, and related environmental damage. A large upward trend in heavy precipitation events could cause little damage if the events remain very rare or if the absolute amount of rainfall during the events is small. On the other hand, even very rare events can cause serious and long-lasting damage if rainfall intensities and duration are large.

*Improve Damage Estimates*

The factors determining the actual outcomes from a change in precipitation regime on soil erosion, runoff, and related environmental resources is complex, as noted above. Targeted investigations should be undertaken to reduce the uncertainties in damage estimates that arise from those complexities. Such investigations would provide a much firmer foundation on which to evaluate the changes in U.S. conservation policies and practices that are warranted, feasible, and cost-effective.

Our expert panel members discussed a number of such investigations that would help inform policymakers and program managers. They included:

- Replicating studies, such as those currently in the literature that specifically evaluated the effect of precipitation patterns on soil erosion and runoff, at more locations and land uses to develop better estimates of the variability induced by differences in geography, hydrology, season, and agricultural production systems.
- Utilize the NRCS National Resources Inventory framework to update national and regional estimates of soil erosion, runoff, and related environmental outcomes based on updated climate parameters in USLE or RUSLE.
- Utilize the NRCS National Resources Inventory framework to conduct sensitivity analyses and simulate the effect of simulated climate scenarios on national and regional estimates of soil erosion, runoff, and related environmental outcomes.
- Complete targeted evaluations and studies to better understand the causes of, future trends in, and expected magnitudes of changes in precipitation regime, particularly those portions of the regime of most concern for soil erosion, runoff, and related environmental effects.

## Conservation Planning as Risk Management

There is strong agreement among modeled climate projections that precipitation intensity will increase at a rate greater than the rate of increases in mean or total annual precipitation. This trend toward more precipitation occurring in more extreme events and shorter return periods for heavy precipitation events is evident in the existing U.S. climate record, particularly since 1970.

The erosivity of heavy precipitation events can be very large because erosivity is strongly correlated to the product of total rainstorm energy and maximum 30-minute rainfall intensity. Even small increases in mean precipitation, therefore, could result in much greater damage if most of that precipitation increase comes in more intense storms. Storm intensity also increases the risk of ephemeral gully erosion, incised gully erosion, and stream channel erosion. These forms of erosion can cause severe and lasting damage to soil and water resources and require more intensive and often costly conservation treatments. Heavy precipitation events also can increase the vulnerability of landscapes and watersheds to future, less intense, and more frequent precipitation events.

In current practice, conservation systems applied to agricultural land are usually designed, planned, and implemented to address soil erosion, runoff, and related effects under estimates of expected average annual climate regimes. Several critiques of current practice (Larson et al., 1997; Kramer, 2001) suggest that conservation systems should instead be designed to resist the effects of extreme events of some designated return period. This approach is currently used when designing engineering structures to resist 25-year, 24-hour storm events, for example.

Proponents who desire a more risk-based approach to conservation planning point out that most damage to soil resources occurs during infrequent but severe events. Larson et al. 1997, for example, reported that 60 percent of the total soil erosion that occurred in their Minnesota study location over 10 years occurred during one cropping season. Precipitation amounts and intensities during that cropping season increased the erosivity of the study area by almost fourfold over the long-term average. Similar results were reported by Burwell and Kramer 1983 in Missouri; Hjemfelt et al. 1986; Edwards and Owens 1991; Zuzel et al. 1993 in Oregon; Moldenhauer and Wischmeier 1960; and Barnett and Hendrickson 1960 in Georgia. Similar arguments can be made for the disproportionate effect of extreme events on water resources, particularly with respect to sediment delivery, channel stability, and other watershed processes.

The adequacy of current conservation planning approaches based on annual average precipitation should be reevaluated in light of the evidence that future—or current—climate regimes are characterized by increased frequency of extreme events. Such a change in conservation planning would require:

- Identifying and quantifying thresholds of soil erosion, runoff, or transport of pollutants above which damage at some specified frequency is unacceptable.
- Identifying critical times during the year when the nature and timing of agricultural production practices increase the risk of damage.
- Determining the probability of occurrence of storms of sufficient intensity and timing to cause damage that exceeds threshold levels.
- Designing conservation systems to be protective at vulnerable times and during particular events.

Such an approach is routinely used when engineering structural solutions to soil erosion and runoff, such as terraces or grassed waterways. Such approaches are not routinely used when planning conservation systems that rely more on annual conservation practices, such as conservation tillage or nutrient management. The environmental performance of agricultural production systems depends heavily on how well such annual practices perform.

Research and technology development will be required to provide the necessary understanding and tools to make a risk-based approach to conservation a reality at the field level. Current field-based models may need to be updated or replaced with alternatives that allow planners to incorporate the probability of extreme events into their recommendations for reducing soil erosion, runoff, and water pollution. Similarly, the performance of existing and new conservation systems would need to be assessed regarding their performance during extreme events. Such an assessment might, for example, enhance the importance of conservation systems that encourage continuous soil cover; utilize filter strips, riparian buffers, or vegetative barriers; or minimize the concentration of nutrients, pesticides, salts, or other potential pollutants during vulnerable seasons.

The first step in that effort should be a series of initial risk-based assessments of the relative contribution of severe storms to soil degradation and water pollution. These assessments should be targeted at quantifying how well key conservation systems protect key environmental endpoints under severe storms. The results of these assessments should be used to determine (1) if a shift to a more risk-based conservation planning approach is warranted based on the risk of environmental damage in the absence of such a shift, (2) to what extent such a risk-based conservation planning approach would change the conservation practices and systems recommended for implementation on U.S. farms and ranches, (3) the steps needed to implement such an approach, and (4) a preliminary estimate of the cost of implementing such an approach.

The initial assessments should be undertaken quickly. The updated and improved climate databases that are being assembled should facilitate such evaluations. The basic modeling and prediction capability needed for such assessments is already available in continuous-simulation, storm-based models. Resources should be made available to conduct the assessments. Those resources will leverage the investments already made in assembling data and improving models. Policymakers and program managers need answers soon so they can begin to make the investment decisions and changes in operational policy needed to ensure that U.S. soil and water resources are protected under a changing climate.

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# APPENDIX

## Predicting Soil Erosion and Runoff from Cropland

The studies cited in this report used one of three basic models to estimate the effects of a change in precipitation regime on soil erosion and runoff from cropland. The RUSLE2 model is briefly described here because it will supercede RUSLE. It is provided for comparative and informational purposes.

### Revised Universal Soil Loss Equation (RUSLE)

Abstract (empirical), deterministic, continuous, lumped, annual time step

RUSLE is the primary field tool used by Natural Resources Conservation Service field staff in conservation planning in the United States. RUSLE is based on the Universal Soil Loss Equation (USLE)—an empirical equation developed by Wischmeier and Smith 1965, 1978. USLE was first published in 1965 and later updated in 1978. The 1978 version is documented in Agricultural Handbook 537. This equation was developed to estimate the long-term sheet and rill erosion rates on cropland and pasture in the eastern two-thirds of the contiguous United States. Later, it was adapted for use in other areas of the world and on rangeland and forestland.

*Model Components*

The Revised Universal Soil Loss Equation (RUSLE) (Renard et al., 1997) is described in Agriculture Handbook No. 703. RUSLE has the same factors as USLE, but it expands the adaptability and utility of USLE. The RUSLE equation is:

$$A = R * K * LS * C * P$$

where:

A = estimated average annual soil loss, t/ha

R = rainfall and runoff factor, $MJ*mm*ha^{-1}*h^{-1}*y^{-1}$

K = soil erodibility factor, soil loss per unit of rainfall erosivity index from bare fallow on a 9% slope 22.1 m long, $t*h*MJ^{-1}*mm^{-1}$

LS = slope length and steepness factor, the ratio of soil loss from a slope of specified steepness and length to that of a 9% slope 22.1 m long, dimensionless

C = cropping and management factor, the ratio of soil loss from a specified cropping sequence and tillage system to that of a bare fallow condition, dimensionless

P = erosion control support practice factor, the ratio of soil loss from a slope using a soil erosion control support practice (i.e. contouring) to the same slope conditions tilled up and down the slope, dimensionless

*Factors Impacted by a Change in Rainfall Intensity*

Factors of RUSLE that may need to be modified or adjusted due to a change in rainfall intensity for a given geographic location could include the R-factor, the K-factor, the C-factor, and the P-factor.

*The R-factor.* Raindrops striking the surface of the soil have kinetic energy because of their mass and velocity. Observations by Wischmeier and Smith determined that the product of total storm energy (E) and the maximum 30-minute rainfall intensity ($I_{30}$) was proportional to the soil erosion rate. The $EI_{30}$ for an individual storm is the R-factor for that storm. The annual average of the long-term summed $EI_{30}$ values of rainstorms at a locale equals the R-factor for that specific locale. Precipitation occurring as snow is not included. In the western United States, all rainstorms are included to calculate the R-factor. In the eastern United States, only storms exceeding 13 mm are used in calculating the R-factor unless the maximum 15-minute intensity exceeds 25 mm $h^{-1}$.

A sufficient increase in rainfall intensity will increase the $I_{30}$ value and probably the E value as well. An increase in the $I_{30}$ value will increase the R-factor proportionally. The amount of rain produced by a given storm will affect the E value. Increasing the number of wet days will increase the average R-factor, assuming rainfall quantity or intensity exceeds the thresholds listed above.

*The K-factor.* The soil erodibility factor is a measured (or estimated) value of the average annual amount of soil loss per unit of R-factor. The conditions required to measure a K-value include a bare fallow plot tilled up and down the hill at the same time of year as continuous row-cropped fields with subsequent secondary tillage to control weeds and eliminate serious crust formation. The K-factor is a lumped parameter representing the average annual response of the soil and soil profile to a large number of erosion and hydrologic processes. A change in the rainfall intensity could also affect the long-term response of the soil and soil profile, thus changing the K-factor. It also is anticipated that changes in the seasonality of rainfall or the number of wet days could also affect the soil erodibility factor as well.

*The C-factor.* The cropping and management factor is expressed as the ratio of the soil loss expected from a specified crop/crop rotation/tillage/residue system relative to the soil loss expected from a clean-tilled, continuous fallow condition tilled up and down the slope. This soil loss ratio (SLR) is calculated on a 15-day time step. During a time step, it is assumed no appreciable changes occur in the erosive condition of the soil. This time step can be segmented into shortened time intervals if a sudden change occurs that affects the soil/vegetation/residue system (e.g. tillage operation). The SLR is calculated as a function of five subfactors. These subfactors are prior land use, canopy cover, surface cover, surface roughness, and soil moisture. Each of these subfactors can affect the soil/vegetation/residue system that influences the SLR. A change in rainfall intensity may directly influence the surface roughness and soil moisture subfactors. Surface roughness will tend to decrease as the $EI_{30}$ value increases and lead to more runoff. As antecedent moisture increases, surface runoff will tend to increase.

*The P-factor.* The soil conservation support factor is affected by practices that modify the surface runoff pattern, direction or velocity and/or affect total runoff volume and/or peak rate of runoff. Previous field studies (Moldenhauer and Wischmeier, 1960; Jasa et al., 1986) indicate that contouring is less effective for large storms compared to smaller storms due to a combination of total runoff volume and rainfall intensity. Renard et al. 1997, p. 191, suggested that the P-factor rating given a support practice be based upon the storm erosivity value of a specific probability of recurring rather than the long-term rainfall erosivity factor. Therefore, under a climate change scenario that includes increased rainstorm intensity or volume of runoff, the effectiveness of conservation support practices would decrease, causing an increase of soil erosion.

### Revised Universal Soil Loss Equation, version 2 (RUSLE2)

Abstract (empirical) and physically-based, deterministic, continuous, daily time step

RUSLE2 is the new field tool to be used by the Natural Resources Conservation Service in 2003. It is a Windows-based model that will be placed in field offices for use by field personnel for conservation planning. This soil loss equation estimates long-term sheet and rill erosion, but calculates factors in a daily time step. Because of the daily time step, the stand-alone R, K, LS, C, and P factors that were the basis for the USLE and RUSLE are no longer viable as more physically-based science is used.

*Factors Impacted by a Change in Rainfall Intensity*

The erosivity factor (R) consists of monthly values that are disaggregated into daily values. The erodibility factor (K) varies seasonally, based on daily temperature and precipitation. The cover and management factor (C) uses subfactors similar to those in RUSLE; those subfactors are affected by daily temperature and precipitation. The support practice factor (P) is upgraded from RUSLE. For example, the 10-year, 24-hour storm values are used to compute runoff and the reduction in erosivity by ponding. It is used indirectly to compute factors for contouring, critical slope length, sediment transport capacity, deposition, and detached soil particle size information.

### Modified Universal Soil Loss Equation (MUSLE)

Abstract (empirical), deterministic, event-based, lumped

The MUSLE equation was developed by J. R. Williams 1975 as a method to estimate sediment delivered from small watersheds for individual storms. This equation replaces the R-factor of the USLE (or RUSLE) with a total runoff and peak runoff rate term for an individual storm event. The MUSLE is written as:

$$A = 11.8 * (Q_{surf} * q_{peak})^{0.56} * K * LS * C * P$$

where:

$A$ = tons of sediment delivered to the nearest permanent channel, t
$Q_{surf}$ = surface runoff depth, mm
$q_{peak}$ = peak runoff rate, $m^3\ s^{-1}$

The constant 11.8 is a unit conversion factor. All other factors in the equation are defined the same as in the USLE.

*Factors Impacted by a Change in Rainfall Intensity*

Because MUSLE estimates runoff and sediment delivery produced by individual storms, a change in rainfall quantity will be accounted for in the equation with the $Q_{surf}$ and $q_{peak}$ factors. The Soil Conservation Service Curve Number Method is used to estimate $Q_{surf}$ and is not sensitive to rainfall intensity. Like the USLE, however, the K-, C-, and P-factors also may be affected by a change in rainfall, requiring their adjustment.

### Water Erosion Prediction Project (WEPP)

Physically-based, deterministic, continuous or event-based, distributed, daily time step

The Water Erosion Prediction Project was initiated in 1986 (Foster et al., 1989). It incorporates the latest technology and soil erosion research information. WEPP can be used to predict sheet and rill erosion on hillslopes and sediment delivery from fields and small watersheds. The six major components of WEPP are climate generation, hydrology, plant growth, soils, irrigation, and soil erosion.

The climate generator model (CLIGEN) (Nicks and Gander, 1994) can use existing weather records to simulate physical processes, or it can generate site-specific rainfall amount, duration, maximum intensity, time to peak intensity, maximum and minimum temperature, solar radiation, wind speed, wind direction, and dew point temperature. If weather records are provided, WEPP can use breakpoint precipitation data or daily rainfall amounts. If daily rainfall amounts are entered, WEPP will disaggregate the rainfall into a simple single-peak storm pattern. The rainfall amount and intensity data are used to estimate the amount of infiltration and runoff for each storm.

The hydrology component includes infiltration, runoff, evapotranspiration, interception, lateral flow, and deep percolation. The water balance is computed daily. Infiltration is modeled using the Green-Ampt equation (Green and Ampt, 1911). Leaf area index calculated by the crop growth model is used to estimate transpiration losses. Soil water is routed through the soil layers, eventually to percolate through the soil profile, to enter tile drains, or to be extracted by plants. Currently, the water quality subroutines are not incorporated in WEPP to simulate nutrient and pesticide movement and transformations.

The plant growth component is patterned after the Erosion Productivity Impact Calculator (EPIC) crop growth model (Williams et al., 1984). The complete plant growth cycle, from seed to senescence, and residue decomposition is simulated. Annual and perennial plants can be simulated.

The soils component is the SOILS-5 database. This database includes the soil parameters necessary for calculating hydrologic and erosion inputs. The model changes these parameters on the daily time step to account for temporal changes of these properties due to tillage operations, freezing and thawing, compaction, and precipitation.

The irrigation component can simulate sprinkler or furrow irrigation. The schedule of irrigation is user-defined by one of three methods. Sprinkler irrigation is modeled as a rainfall event of even intensity.

The erosion component uses the steady state sediment continuity equation as the basis for computing erosion. Soil detachment and interrill sediment delivery to the rills are modeled as a function of rainfall intensity and slope. Interrill detachment and transport and rill erosion are modeled separately. Soil detachment in rills occurs if the hydraulic shear stress of the water is greater than the critical flow shear stress of the soil and the sediment load of the flow is less than the flow's transport capacity. Deposition occurs if the sediment load exceeds the capacity of the flow to carry it. Sediment is characterized by particle size based upon the soil profile from which it eroded. The preferential sorting and transport of soil particles that are smaller and lighter is the basis for enrichment ratios for clays, organic matter, and nutrients.

*Factors Impacted by a Change in Rainfall Intensity*

The WEPP model should be well-suited for simulating or accounting for an increase in rainfall intensity. Because the model is process-based, a change of rainfall intensity should be able to be simulated. If measured breakpoint precipitation intensity is available, the effects of this storm intensity could be inputted into the model using proper format and units. The output could then be easily read, either for an individual storm or for the time period for which records are available. If non-breakpoint data are available, then simply changing the amount of rainfall on a given day is all that is necessary. The rainfall amount will be automatically disaggregated in a statistically representative manner simulating a single-peaked storm.

If rainfall intensity is to be modified but not the rainfall quantity, then changing the ip (peak intensity index) parameter in the input file would be necessary to simulate a storm with the desired peak intensity.

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