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Updated climate database and impacts on WEPP model predictions

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Abstract: CLImate GENerator (CLIGEN) (v5.3), a stochastic weather generator, is widely used in conjunction with the Water Erosion Prediction Project (WEPP) model for runoff and soil loss predictions. CLIGEN generates daily estimates of weather based on long-term observed weather station data statistics. For the United States, the original CLIGEN database released with WEPP in 1995 was derived using inconsistent periods of climate records through 1992 that could lead to significant variations in runoff and soil loss predictions on spatial and temporal scales. To achieve more reliable estimates of runoff and soil loss, an updated climate database was derived from a consistent 40 years of recent climate records of 1974 to 2013 in the United States. The objectives of this study were to (1) examine the spatial patterns in trends of differences in precipitation and maximum and minimum temperatures between the two databases, and (2) evaluate the impacts on WEPP-predicted mean annual runoff and soil loss, from the original to the updated databases. For runoff and soil loss estimates, WEPP simulations were conducted under a tilled fallow condition for 1,600 CLIGEN locations in the contiguous United States for a slope profile of 22.1 m length, 9% slope gradient, and silt loam soil.

Comparison of precipitation and maximum and minimum temperatures between the original and updated databases showed variations in spatial patterns both annually and seasonally. Annual precipitation and minimum temperature generally increased across most of the country while maximum temperature increased in the western half of the United States and parts of the Northeast. Seasonally, increases in precipitation are evident in the Midwest in spring, fall, and winter, the Northwest in spring, and the Southeast in fall. Maximum daily temperature has increased in the western half of United States and parts of the Northeast in the winter, fall, and spring, whereas minimum daily temperature has increased in all seasons across the United States.

Changes in WEPP-simulated mean annual runoff and soil loss from the use of the original to the updated CLIGEN database showed increases in runoff and soil loss in most of the United States. However, some stations showed either increases or decreases in runoff and/or soil loss with the updated database primarily because of differences in monthly precipitation and intensity values in the two databases. Understanding the impacts of the use of the updated database on runoff and soil loss from this study will help in making informed decisions for conservation planning and management when utilizing the WEPP erosion model.

Key words: CLIGEN—climate—runoff—soil loss—weather generator—WEPP

Daily time series of weather data are necessary to drive process-based hydrological models. Although observed historical data could be used in such studies, weather generators are useful inexpensive tools that compensate for the inadequate length of weather records and missing data. Weather generators are stochastic models that generate weather sequences for an infinite time period based on statistical characteristics of observed data recorded at a specific location. These generators produce daily time series of meteorological variables (e.g., precipitation, temperatures, solar radiation, and wind speed) by preserving the monthly or seasonal characteristics of observed historical records.

Several weather generators are available including Advanced Weather GENerator (AWE-GEN) (Fatichi et al. 2011), Climatic Data Generator (CLIMGEN) (Stöckle et al. 1999), Weather Generators (WeaGETS) (Chen et al. 2012), Weather Generator (WGEN) (Richardson et al. 1984), the Long Ashton Research Station Weather Generator (LARS-WG) (Semenov et al. 2002), and CLImate GENerator (CLIGEN) (Nicks et al. 1995). CLIGEN was primarily developed to be used with the Water Erosion Prediction Project (WEPP) (Flanagan and Nearing 1995; Flanagan et al. 2007) model. CLIGEN is a stochastic weather generator that produces daily estimates of precipitation, maximum and minimum temperature, dew point temperature, wind speed and direction, and solar radiation for a single geographic point derived from the monthly statistical parameters, which are based on observed weather data. Unlike other weather generators, it also provides storm shape characteristics, including time to peak, peak intensity, and storm duration, which are utilized by WEPP for runoff and soil loss predictions.

WEPP is a physical process-based, distributed parameter, continuous simulation model that allows prediction of sheet and rill erosion from hillslope profiles, and channel erosion from small field and farm-sized watersheds (Flanagan and Nearing 1995; Flanagan et al. 2007). Recently, the USDA Natural Resources Conservation Service (NRCS) has made plans to adopt WEPP for use in their field offices for soil and water conservation planning and management.

As part of the USDA NRCS implementation project, the use of the original CLIGEN database compiled by Nicks et al. (1995) in the early 1990s raised two concerns. First, this database used observed weather station statistics with variable periods of record through 1992. Such a temporally inconsistent data set could potentially cause different runoff and erosion predictions at adjacent locations, because their monthly statistics

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might be influenced by the variability in the precipitation and temperature data as a result of temporal differences. Second, numerous recent climate change studies have documented the general trends of increasing precipitation depths and extreme precipitation events with rising temperatures in the United States (Karl and Knight 1998; Groisman et al. 2004; Portmann et al. 2009; IPCC 2013). These studies also reported increases in both the frequency and intensity of extreme precipitation events that varied significantly both regionally and seasonally. It is therefore essential that the CLIGEN database be derived from observed data sets that are temporally consistent and include more recently observed records. Improvements to the CLIGEN database were requested by NRCS to allow the WEPP model to provide more realistic and consistent runoff and erosion predictions.

The purpose of the research reported here was (1) to update the CLIGEN database using a consistent 40 years of climate records from 1974 to 2013; (2) to compare and evaluate the changes in precipitation, maximum temperature (T_{max}), and minimum temperature (T_{min}) from the original to the updated CLIGEN databases; and (3) to evaluate the changes in WEPP model runoff and soil loss predictions from the use of the original 1995 to the updated 2015 database.

Materials and Methods

CLImate GENerator. The first version of CLIGEN was developed around 30 years ago by the USDA Agricultural Research Service (ARS) to be used with the WEPP model to predict runoff and soil erosion (Nicks and Lane 1989; Nicks et al. 1995). Later, Charles R. Meyer at the USDA ARS National Soil Erosion Research Laboratory (NSERL) re-coded CLIGEN in 1999 to make it more understandable and maintainable for users (Flanagan et al. 2001b). Meyer also developed, tested, and incorporated quality control abilities within CLIGEN, which helped it to better reproduce strings of generated daily weather (Meyer et al. 2008). During this same time period, other problems in the CLIGEN Fortran code and database were identified, corrected, and evaluated for obtaining reliable estimates of runoff and soil loss from WEPP (Flanagan et al. 2001b).

CLIGEN uses input weather station statistics called parameter files (.PAR) to generate long-term daily weather values. Generated weather variables include daily precipitation depth and its storm characteristics (duration, time to peak, and peak intensity), maximum and minimum daily temperatures (T_{max} and T_{min}), dew point temperature (T_{dp}), solar radiation, and wind speed and direction. The number and distribution of precipitation events are computed using a two-state Markov chain model. The occurrence of precipitation on any day is determined based on the probabilities of wet and dry days in sequence and random number generation. For a wet day, the precipitation depth is generated from a skewed normal distribution function, and the event duration is determined using an exponential function. Peak intensity and time to peak parameters are computed using precipitation amount and duration (Yu 2000). Excluding T_{min}, T_{max}, and T_{dp}, all other variables are generated independently of each other.

The CLIGEN .PAR files containing monthly statistical values of precipitation, maximum and minimum temperatures, dew point temperature, mean maximum 30-minute precipitation intensity, time to peak intensity, solar radiation, and wind speed and direction information are derived using raw data obtained from the long-term historical daily weather records of the National Oceanic and Atmospheric Administration-National Climatic Data Center (NOAA-NCDC). A dat2par program (Scheele and Hall 2000) is used to generate the .PAR files that processes data from several input files, including .DAT, STATIONS, STATPARM, TIMEPEAK, DEWPOINT, IDXALL, and WIND (table 1).

Original and Updated CLImate GENerator Databases. Table 1 summarizes the comparison of raw data inputs used to derive the original and updated CLIGEN databases. All of the required input data for the CLIGEN database were updated and formatted in the .DAT, STATIONS, STATPARM, TIMEPEAK, DEWPOINT, and WIND files. Major changes and updates relevant to each input file are highlighted here.

.DAT File. The most necessary information needed to create a .PAR file for a station is a .DAT file containing observed daily precipitation depth, T_{min}, and T_{max} data for the station. The dat2par program generates .PAR files for each existing .DAT file. For the original 1995 CLIGEN database, daily precipitation, T_{min}, and T_{max} variables were derived from daily historical records available through 1992. For the overall 2,642 weather stations in the original database, the historical number of years of record varied from a minimum of 9 years to a maximum of 117 years. Out of all the available stations, 2,111 utilized more than 44 years of data. For the new updated 2015 CLIGEN database, a consistent period of records from 1974 to 2013 from NCDC were used for daily precipitation, T_{min}, and T_{max}. Stations from those that were available in the original database (2,642) were first updated. However, not all stations could meet the criteria for the desired period of historical records, either because of missing data or because some stations were closed and/or moved to different locations. Additional new stations that were included in the updated database resulted in an overall total of 2,765 stations.

Daily values in the .DAT files were statistically summarized using the dat2par program to obtain monthly values of mean liquid equivalent precipitation on a wet day, standard deviation of daily precipitation on a wet day, skewness of daily precipitation on a wet day, probability of a wet day followed by a wet day, probability of a wet day followed by a dry day, mean daily T_{max}, mean daily T_{min}, standard deviation of daily T_{max}, and standard deviation of daily T_{min}. A wet day is defined as a day with nonzero precipitation.

STATIONS File. The stations file contains a numbered list of stations along with their names, latitude, longitude, elevation, and 24-hour precipitation distribution type for the set of stations used in the .DAT files. The types represent the four synthetic rainfall distributions for different areas in the United States defined in the Soil Conservation Service Technical Release 55 document (Cronshey et al. 1986).

STATPARM File. This input file contains the maximum 30-minute and 6-hour precipitation depths (TP5 and TP6), monthly values of solar radiation and its standard deviation, and monthly maximum 30-minute rainfall intensity. Sets of stations available in the original database (142 stations) were updated and expanded. Mean daily solar radiation and standard deviations for each month were computed from the available measured data for each station. The total amount of direct and diffused solar radiation energy (Watt h m^{-2}) received on a horizontal surface during a 60-minute period ending at a timestamp were available in the National Solar Radiation database (table 1) and were

Table 1
Data inputs used to derive the original and updated CLIGEN databases.

		Period of record		Number of stations				
Parameter	CLIGEN database input file(s)	Original 1995 CLIGEN database	Updated 2015 CLIGEN database	Original CLIGEN database	Updated CLIGEN database	Time scale of raw data in updated database	Units for raw data	Units in CLIGEN .PAR file
P, T_{max}, T_{min}	.DAT	Through 1992	1974 to 2013*	2,642	2,765	Daily	Tenths of mm, tenths of °C	in, °F
Solar radiation	STATPARM	Unknown	1991 to 2005†	142	822	Hourly	Watt h m^{-2}	Langleys
Time-to-peak	TIMEPEAK	Unknown	1974 to 2013‡	1,548	912	15-min	Dimensionless	Dimensionless
Mean maximum 30-min peak intensity; maximum 30-min and maximum 6-h precipitation depths	STATPARM	Unknown	1974 to 2013§	142	822	Precipitation frequency GIS maps, 15-min	in	in hr^{-1}
Dew point temperature	DEWPOINT	Unknown	1974 to 2013‖	273	568	Hourly	°C	°F
Wind	IDXALL and WIND	Unknown	Same set as original database	852	852	Unknown	m s^{-1} (wind speed), percentage of time (wind direction)	m s^{-1} (wind speed), percentage of time (wind direction)

*Available: ftp://ftp.ncdc.noaa.gov/pub/data/ghcn/daily/.

†Available: ftp://ftp.ncdc.noaa.gov/pub/data/nsrdb-solar/.

‡Available: https://hdsc.nws.noaa.gov/hdsc/pfds/pfds_gis.html.

§ Available: ftp://ftp.ncdc.noaa.gov/pub/data/15min_precip-3260/.

‖Available: ftp://ftp.ncdc.noaa.gov/pub/data/noaa/.

used to compute solar radiation values in the updated CLIGEN database. The mean maximum daily 30-minute precipitation intensity (*MX 0.5 P*) for each month was computed from the NCDC 15-minute precipitation information. Stations that did not have a complete 40-years (1974 to 2013) of 15-minute precipitation record were not included in the list of stations in the STATPARM file.

Each CLIGEN station parameter file requires TP5 and TP6 values. The original CLIGEN database obtained these from the NOAA-NCDC return periods geographic information system (GIS) maps derived for the United States (Hershfield 1961). TP5 and TP6 values in the updated CLIGEN database were derived from the NOAA updated precipitation frequency GIS maps for 100 years. The 15-minute NCDC precipitation data were only used in areas of no coverage.

TIMEPEAK File. This file contains monthly values of cumulative distribution of time to peak rainfall intensity (t_p). Days with multiple storms were collapsed by removing zero precipitation values, and t_p was computed as the ratio of elapsed time from the beginning of the first precipitation interval to the middle of the 15-minute interval containing the peak intensity to total time from the beginning of the first precipitation interval to the end of the last precipitation interval. The ratios range from 0 (beginning of storm) to 1 (end of storm). In both the original and updated databases, values were derived from 15-minute precipitation data. However, in the original database the periods of records used are unknown and likely included variable periods of records. For the updated database, the same set of stations in the original database (1,548) were updated and expanded for the desired period. The criterion used to build the TIMEPEAK file in the updated database was a complete 40 years of 15-minute precipitation data that eventually resulted in 921 stations.

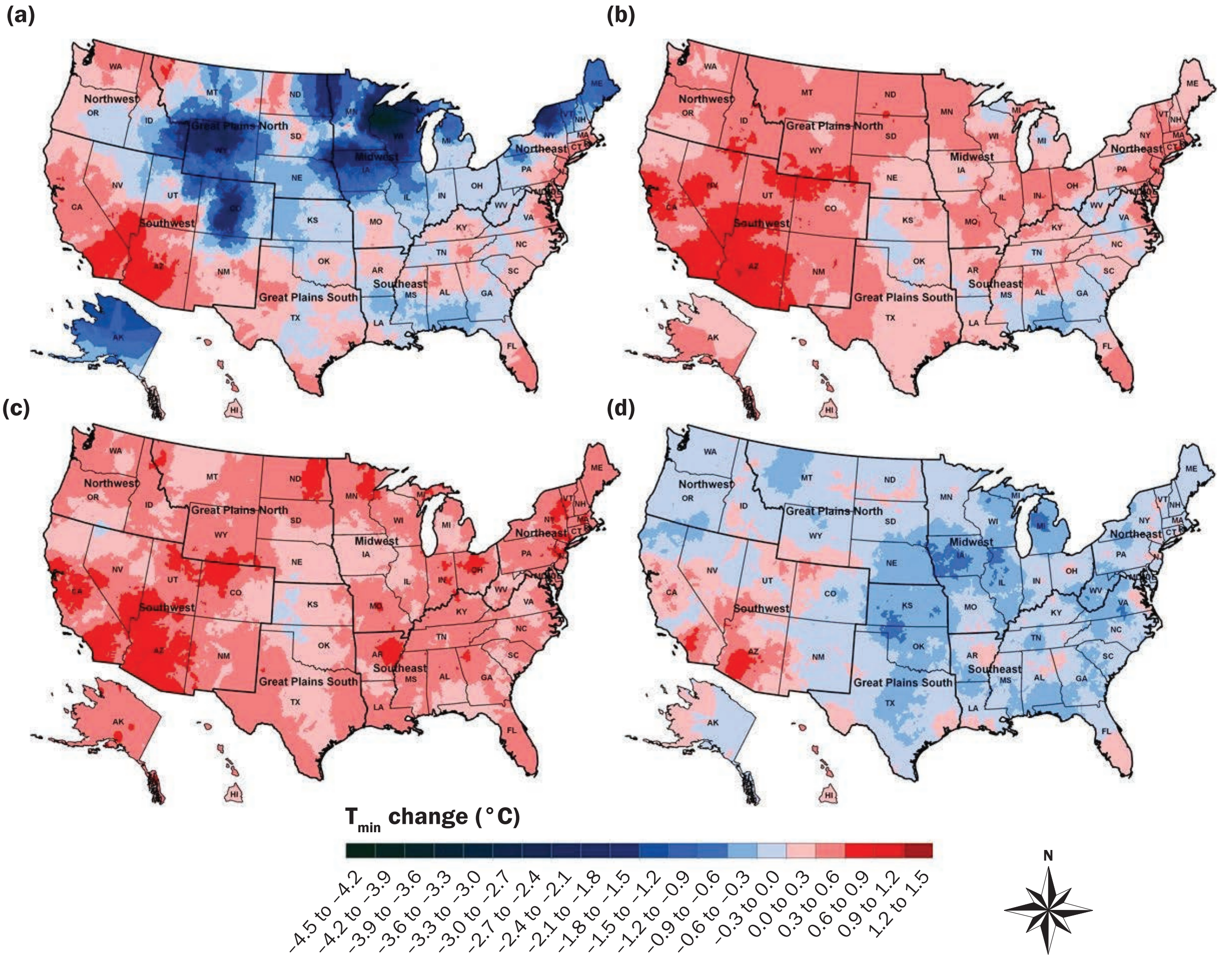
DEWPOINT File. Mean daily dew point temperatures for each month were calculated based on the hourly observed data in the NOAA-NCDC database. The same set of stations as the original CLIGEN database (273 stations) was used and expanded to 568 stations.

WIND File. Monthly wind information for 16 compass directions includes the percentage of time wind is blowing from each direction, mean wind velocity from each direction, standard deviation of speed for each wind direction, and skewness coefficient of speed for each wind direction. Wind parameters from the original CLIGEN database were used in the updated database without any changes or updates of information. WEPP water erosion predictions are not very sensitive to wind inputs, and there was a critical need to update the precipitation and temperature values quickly. Moreover, other models including the Wind Erosion Prediction System (WEPS) do not use the wind data available in the CLIGEN records since they instead use WINDGEN, a separate and more detailed wind generator program (Wagner 2013). Nonetheless, the wind data in the CLIGEN database should be updated sometime in the near future.

The dat2par program uses a triangulation method to interpolate solar radiation, maximum 30-minute precipitation intensity, time to peak, dew point temperature, and wind speed and direction from three nearby weather stations, if that information is not available for the selected station. All of the data for the interpolation procedures cover the same range of years as the daily precipitation and temperature data.

Figure 1

Comparison of minimum temperature (T_{min}) change on a seasonal basis ([a] winter, [b] spring, [c] summer, and [d] fall) from original 1995 (uncorrected) to updated 2015 CLIGEN databases.



Comparison of Original and Updated CLImate GENerator Databases. Comparisons of precipitation, T_{max}, and T_{min} from the original to updated CLIGEN databases were conducted on annual and seasonal bases using the monthly values from the parameter (.PAR) files. Common (1,823) weather stations from both databases were selected across the United States for the evaluation. Annual and seasonal values of precipitation and temperatures were computed for each station for both databases. For seasonal analysis, monthly values were divided into four seasons: winter (December through February), spring (March through May), summer (June through August), and fall (September through November). Seasonal precipitation depths were computed by summing the three monthly values for each season, while seasonal temperatures were computed by averaging the three monthly values for each season.

Precipitation and temperature changes were also computed on an annual and seasonal basis. For the precipitation comparisons, the percentage change was calculated for each common station by subtracting the original 1995 database value from the updated 2015 database value and then dividing the difference by the original 1995 database value and multiplying by 100. For temperature change, the original database values were subtracted from the updated database values. A kriging interpolation method was applied to produce smoothed GIS maps for displaying results. For the contiguous United States, maps were divided into seven major regions (Northwest, Southwest, Northern Great Plains, Southern Great Plains, Midwest, Northeast, and Southeast) to evaluate the changes in precipitation and temperatures.

Preliminary analysis of seasonal changes in T_{min} between the original and updated CLIGEN databases indicated significant reductions of >1°C during the wintertime in the updated database (figure 1). This trend of decreasing temperatures, typically occurring in the Northeast, Midwest, Northern Great Plains, parts of Southwest, and Alaska led us to investigate the temperature values in the .DAT files for possible errors. Errors were identified in the T_{min} values in the original 1995 database because of missing negative signs in the .DAT files on days where observed temperatures were below −17.7°C. Such inconsistencies were noticed for most of the stations. This indicates a potential source of substantial error for users of the original 1995 climate database, particularly for winter processes related to minimum temperatures.

To evaluate the changes in temperature from the original CLIGEN database to the updated one, we first had to correct the minimum temperature values in the original .DAT files and reconstruct the .PAR files. Overall, 2,235 stations were corrected out of the 2,645 stations available in the original 1995 database in the subsequent analysis, which is identified as the "original (corrected)" database. The remaining stations could not be corrected because of relocation of NCDC stations, or they did not require correction because all measured temperatures were above −17.7°C. Changes in precipitation and temperatures from the corrected original 1995 to the updated 2015 CLIGEN databases were evaluated for the 1,635 common stations shown in figure 2.

Water Erosion Prediction Project. WEPP is a process-based, distributed-parameter computer simulation modeling system developed to predict soil erosion and sediment delivery by water from hillslopes and small field-sized watersheds (Flanagan et al. 2007). It is based on fundamentals of stochastic weather generation, infiltration theory, hydrology, soil physics, plant science, hydraulics, and erosion mechanics (Flanagan and Nearing 1995; Flanagan et al. 2001a). It can simulate spatial and temporal distributions of net soil loss and sediment deposition along a hillslope profile and sediment delivery at the bottom of the hillslope. Simulations can be performed for individual storm events, or in a daily-continuous simulation mode (multiple storm events, multiple years).

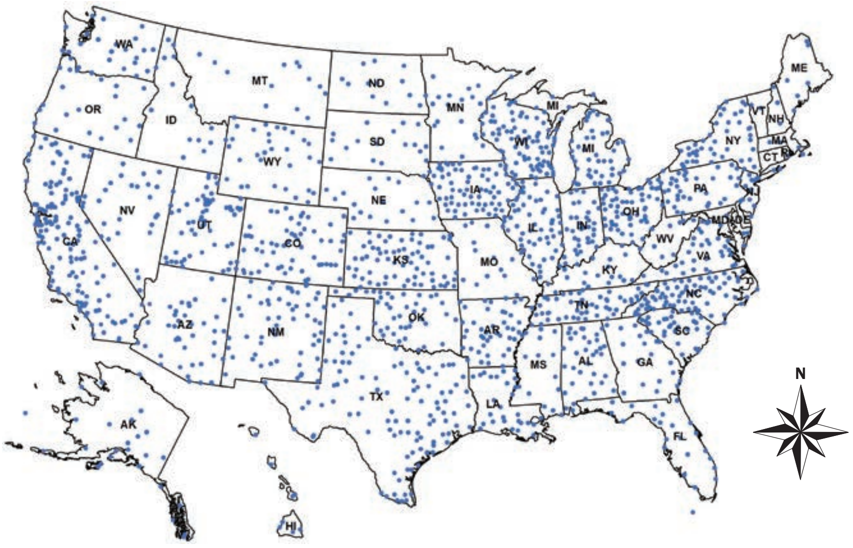
The WEPP modeling system has components for weather generation, irrigation, surface hydrology, water balance, subsurface hydrology, winter processes, plant growth and residue decomposition, and erosion. Detailed descriptions of the individual components can be found in the technical model documentation (Flanagan and Nearing 1995). Briefly, the surface hydrology component computes infiltration, rainfall excess, depressional storage, and peak discharge considering weather, soil, vegetation, and land management information. Infiltration is based on a Green-Ampt Mein-Larson infiltration equation modified for unsteady rainfall (Mein and Larson 1973; Chu 1978). Rainfall excess occurs when the rainfall intensity rate exceeds the soil infiltration rate. Runoff occurs when rainfall excess has been computed and the surface depressional storage is satisfied. Peak surface flow discharge calculations are performed based on solution of the kinematic wave equations. WEPP maintains a continuous water balance within the soil profile by performing snow accumulation and melt, soil frost and thaw, deep percolation, evapotranspiration, and subsurface lateral flow computations. The daily water balance information updates vegetation growth and residue decomposition rates. Temporal adjustments are made to baseline hydraulic conductivity, rill and interrill erodibilities, and critical soil shear stress for temporally changing soil and vegetative conditions due to tillage sequences, soil consolidation, residue addition and/or removal, and harvesting operations.

WEPP separately estimates runoff for rill and interrill areas to compute soil erosion over the hillslope. Erosion in interrill areas is a function of raindrop impact and transport by shallow sheet flow, and in rill channels, erosion is a function of excess flow shear stress. A steady-state sediment continuity equation governs rill detachment down a slope profile, with lateral additions of interrill sediment into the rill.

Water Erosion Prediction Project Simulations. Continuous WEPP (v2012.8) simulations were conducted across the contiguous United States for 1,598 locations common to both the original and updated databases. One hundred-year climate input files were generated using the original (corrected) and updated climate databases and CLIGEN version 5.3. Simulations were performed for the standard Universal Soil Loss Equation (USLE) unit plot conditions of uniform slope profile of 22.1 m length and 9% slope gradient with a generic silt loam soil. Management used was tilled fallow with continuous tillage disturbance and smoothing every 15 days. Changes in the WEPP-predicted mean annual runoff and soil loss from the original (corrected) to the updated CLIGEN databases were evaluated. Percentage change was calculated for each common station by subtracting the original 1995 database value from the updated 2015 database value and then dividing the difference by the original 1995 database value and multiplying by 100. A kriging interpolation was performed to display trends across the United States.

Figure 2

Locations of the 1,635 common CLIGEN stations in the United States in the corrected original 1995 database and updated 2015 database.



Results and Discussion

Precipitation and Temperature Trends from CLImate GENerator Databases. The spatial patterns of mean annual precipitation, maximum temperature, and minimum temperature for the contiguous United States, Alaska, and Hawaii from the original (corrected) and updated climate databases are shown in figures 3 and 4, respectively.

Visual comparisons of precipitation and temperature maps show similar spatial trends. In the contiguous United States, mean annual precipitation for the original database ranges from 58 to 2,865 mm y^{-1} (figure 3a), whereas for the updated database, it ranges from 61 to 2,710 mm y^{-1} (figure 3b). Precipitation in the eastern half of the country (Midwest, Southern Great Plains, Northeast, and Southeast) is greater (>1,000 mm y^{-1}) compared to the western half of the United States (Northwest, Southwest, and Northern Great Plains) except in the Pacific Coastal regions of Washington, Oregon, and northern California where precipitation is higher (>1,500 mm y^{-1}) because of windward effects resulting from the Cascade Range barriers. In Alaska, mean annual precipitation in both the databases ranges approximately from 50 to 5,500 mm y^{-1}, whereas in Hawaii, mean annual precipitation in the original database varies from 1,250 to 2,230 mm y^{-1} and in the updated database ranges from 448 to 3,118 mm y^{-1} (figures 4a and 4b).

Figures 3c and 3d, and figures 3e and 3f present the spatial distribution of mean annual T_{max} and T_{min} trends in the contiguous United States, respectively, for the original and updated databases. T_{max} for both of the databases ranges from 10°C to 31°C. T_{min} varies from −9°C to +19°C for the original database and from −8°C to +21°C for the updated database. Moving from the southern to the northern United States, both T_{max} and T_{min} show decreasing trends in both databases. In Alaska, ranges of T_{max} and T_{min} are similar in both databases (figures 4c and 4d for T_{max} and figures 4e and 4f for T_{min}). In Hawaii, T_{max} and T_{min} in the original database ranges from 22°C to 26°C and 15°C to 17°C, respectively, and in the updated database varies from 19°C to 28°C and 13°C to 17°C, respectively (figures 4c and 4d for T_{max} and figures 4e and 4f for T_{min}).

The spatial pattern trends of mean annual precipitation and mean annual T_{max} and T_{min} changes from the original (corrected) database to the updated database are shown in figure 5. Mean annual precipitation change ranges from −20% to +15% across the United States (figure 5a), with increasing trends across most of the country, except in some parts of the Northwest, Southwest, and Southeast, where there are decreasing trends. Eastern parts of the Northern Great Plains, central parts of the Midwest, and most of the Northeast show up to a 15% increase in average annual precipitation depths. Other parts of the country have slight (5%) increases or decreases in precipitation. Increasing trends in precipitation are observed in Alaska while decreasing trends are noticed in Hawaii. Mean annual T_{max} changes from the original (corrected) to the updated database range from −0.6°C to +0.9°C (figure 5b). The spatial pattern of T_{max} shows decreasing trends in the eastern part of the contiguous United States encompassing parts of the Midwest, Southern Great Plains, and Southeast regions, and increasing trends in the Northeast, Southwest, parts of the Northwest and Northern Great Plains, and Alaska and Hawaii. Figure 5c presents the spatial pattern of mean annual T_{min} change trends with temperatures varying from −0.6°C to +1.5°C. The results show increasing trends of T_{min} across the contiguous United States, Alaska, and Hawaii. The western United States, Northeast, and Alaska have much greater increases in T_{min}, ranging from 0.6°C to 1.5°C relative to other parts of the country.

Care must be taken when interpreting annual trends as they can obscure substantial seasonal changes. Figure 6 shows the spatial distribution of precipitation change trends from the original to the updated CLIGEN database on a seasonal basis. Seasonal change typically varies in the range of −15% to +25% across much of the United States. A cluster of stations in California shows the most significant increasing trends of greater than 25% in winter (figure 6a) and summer (figure 6c). The spatial pattern in winter also shows increasing trends in the Southwest, Southern Great Plains, Midwest, Northwest, and eastern parts of Northern Great Plains (figure 6a). In spring, most of the stations in the northern half of the United States show increasing trends in precipitation (figure 6b), whereas in the fall, increasing trends are seen all across the country except in the west (figure 6d). The greatest decreasing trends occur in the summer and fall in some portions of Nevada, California, and Arizona (figures 6c and 6d). In Hawaii, decreasing trends in precipitation are evident in all seasons.

Figure 7 displays the spatial distribution of seasonal T_{max} changes from the original to the updated climate database. The spatial pattern of seasonal T_{max} in the contiguous United States mostly ranges from −0.6°C to +0.6°C with the exception of a few parts of the Northern Great Plains in the winter, and the Southwest in the spring where there are greater than 0.6°C increases in T_{max}. The spatial pattern consists of both increasing and decreasing trends that vary with season. The eastern half of the United States including parts of the Midwest, Southern Great Plains, and Southeast have decreasing trends in all seasons. The decreasing trends extend into the interior of the western United States in the fall (figure 7d) and winter (figure 7a). In Alaska and Hawaii, the spatial pattern shows increasing trends in all seasons. Increasing trends in T_{max} above 0.9°C are evident during the winter and spring in Alaska.

Figure 8 presents the seasonal spatial patterns of T_{min} changes from the original (corrected) to the updated database. T_{min} is elevated across the contiguous United States in the summer. In the fall, winter, and spring seasons, similar spatial patterns of increasing trends across the continent are observed with some decreasing trends in the range of 0°C to −0.6°C in some parts of the Southeast and the Southern Great Plains. In the fall, the area of decreasing trends expands into some parts of the Midwest and Northeast. Prominent increases in T_{min} of greater than 0.9°C are observed in Alaska during the winter.

Table 2 presents some of the extreme outlier stations identified for precipitation and T_{min} based on 1,635 common stations in the original (corrected) and updated CLIGEN databases. No outliers were found for T_{max}. Stations in Iowa and California showed increasing annual precipitation trends ranging from 41% to 52% in the updated 2015 database compared to the original 1995 database, whereas a station in Hawaii had a decrease in average annual precipitation of 41%. For T_{min}, four outlier stations were in the Southwest where average annual T_{min} had an increase of up to 2.7°C in the updated database. A station in Virginia had a decrease in average annual T_{min} by 1.7°C in the updated database. The seasonal analysis for these outlier stations shows that precipitation and T_{min} consistently either increased or decreased in winter, spring, summer, and fall.

Figure 3

(a and b) Mean annual precipitation (mm y^{-1}), (c and d) mean annual maximum temperature (T_{max}; °C), and (e and f) mean annual minimum temperature (T_{min}; °C), for contiguous United States, when using the (a, c, and e) original (corrected) and (b, d, and f) updated CLIGEN databases, respectively.

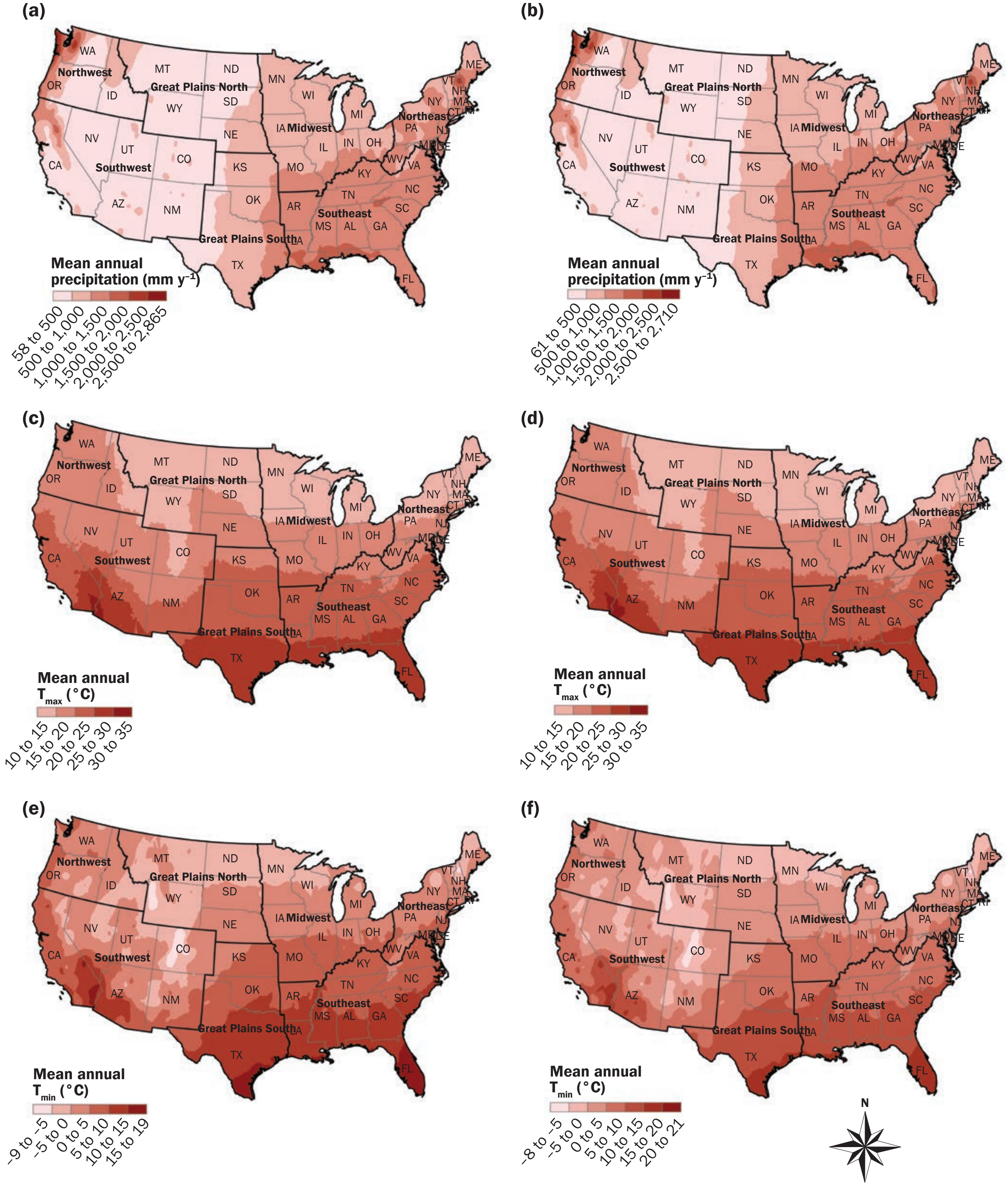
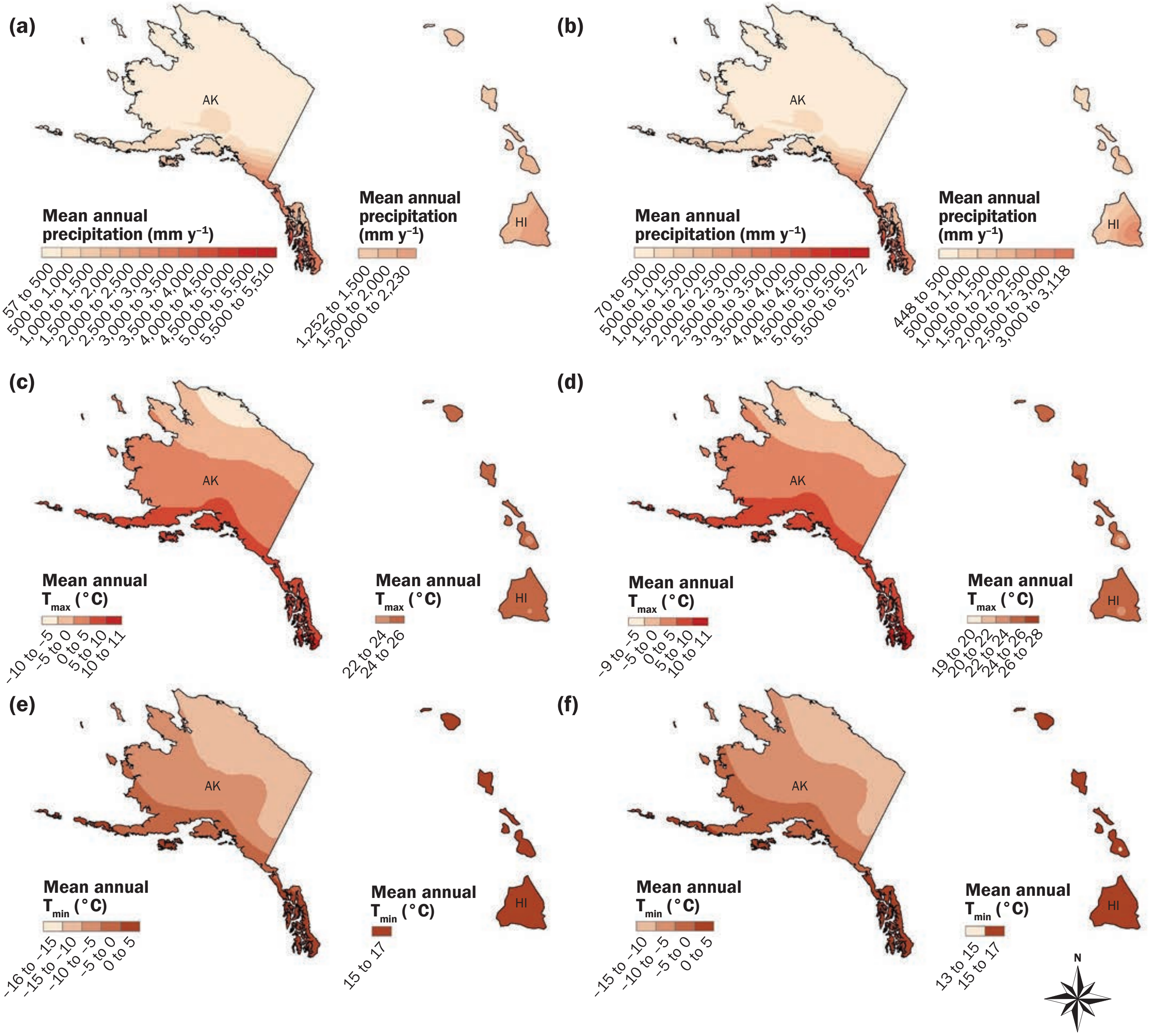


Figure 4

(a and b) Mean annual precipitation (mm y^{-1}), (c and d) mean annual maximum temperature (T_{max}; °C), and (e and f) mean annual minimum temperature (T_{min}; °C), for Alaska and Hawaii, when using the (a, c, and e) original (corrected) and (b, d, and f) updated CLIGEN databases, respectively.

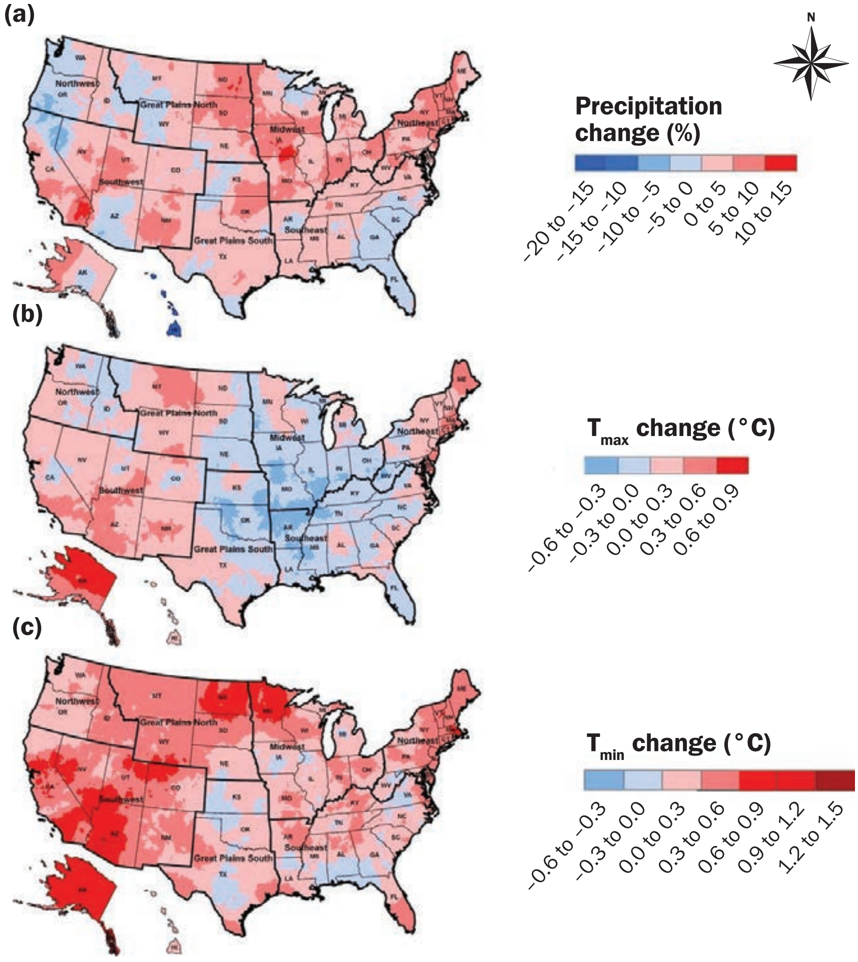


Water Erosion Prediction Project Simulations. The trends and spatial distribution of WEPP-predicted mean annual runoff and soil loss obtained from using the original and updated CLIGEN database for tilled fallow conditions are shown in figure 9. Visual comparison shows similar trends and ranges in runoff (figures 9a and 9b) and soil loss (figures 9c and 9d) from both databases, which follows the pattern of mean annual precipitation shown in figures 3a and 3b. The eastern half of the country has much more variability in runoff and soil loss compared to the western half. In the eastern United States, high values of runoff and soil loss ranging from 400 to 600 mm y^{-1} and 250 to 450 t ha^{-1} y^{-1}, respectively, are located around the Gulf of Mexico where a large amount of precipitation occurs in intense thunderstorms and hurricanes. This high erosion area in the lower portions of the southeastern United States extends from Texas to Florida. Moving from the southeastern United States toward the central or northcentral regions of the United States, runoff decreases to 100 mm y^{-1}, and soil loss decreases to near 100 t ha^{-1} y^{-1}. In the western United States, high values of runoff and soil loss are in the high rainfall regions of the Olympic, Cascade, Sierra Nevada, and Rocky Mountain ranges with orographic effects. The lowest values of runoff and soil loss are in the interior western US regions and southern California due to either scarcity of rainfall or seasonal rainfall mostly in the form of snow.

Figures 10 and 11 show the spatial trends of changes in WEPP-simulated mean annual runoff and soil loss, respectively, for tilled fallow conditions with the original (corrected)

Figure 5

Comparison of (a) mean annual precipitation, (b) mean annual maximum temperature (T_{max}), and (c) mean annual minimum temperature (T_{min}) changes from the original (corrected) to the updated CLIGEN database.



CLIGEN database, as compared to those when using the updated CLIGEN database. Compared to the original database, the use of the updated database generally shows increases in runoff and soil loss in most parts of the United States. In the eastern half of the United States, changes in runoff range from −20% to +35%, and changes in soil loss ranges from −20% to +60% (figure 10). The greatest increases in runoff and soil loss are seen in portions of South Dakota, Wisconsin, Indiana, Michigan, and Ohio, and the greatest decreases are observed in parts of Kansas and Texas. In the western half of the United States, changes in runoff and soil loss are substantially higher compared to the eastern half because the absolute magnitude of the runoff and soil loss values are very low, which tended to greatly affect percentage differences (figure 11). Changes in runoff varied from −15% to +202%, and changes in soil loss ranged from −50% to +315%. The greatest percentage increases in runoff and/or soil loss were in the southwest part of California and eastern part of Oregon.

Percentage changes in WEPP-simulated runoff and soil loss predictions resulting from use of the two climate databases varied by CLIGEN locations and showed a variety of trends in response to using the generated climate inputs. Figure 12 presents the trends in changes of mean annual precipitation, runoff, and soil loss for each common CLIGEN station (1,568) under tilled fallow conditions. We categorized the set of simulation runs into eight groups of observed patterns as shown in table 3 according to either increases or decreases in precipitation, runoff, and soil loss. The number of stations for each corresponding group are presented in table 3. Almost half of the stations fall into Group 1 (827), which correspond to situations with increases in precipitation, runoff, and soil loss. One hundred and seventy-eight stations are attributed to Group 5, which presents situations with decreases in precipitation, runoff, and soil loss. Other observed group patterns (Groups 2 to 4 and Groups 6 to 8) illustrate that increases or decreases in precipitation did not always translate into corresponding increases or decreases in predicted runoff and soil loss. Other factors besides precipitation depth may have also come into play, particularly if the derived precipitation intensity factors in the updated database were modified substantially with the use of 40 years (1974 to 2013) of station information and/or updated parameter interpolations.

Changes in runoff and soil loss from the original to the updated climate database were primarily due to differences in the database records that were used to derive the monthly values in the .PAR file. One important variable that affects runoff and soil loss simulations in WEPP is rainfall intensity (Zhang and Garbrecht 2003; Pruski and Nearing 2002). Given that all other conditions were the same, rainfall of greater intensity would disproportionately generate higher amounts of runoff and erosion. Greater rainfall amounts with other conditions being similar will also produce increased runoff because of an exponential decrease in the infiltration capacity of the soil due to wetter surface conditions. Increased runoff depths and rates resulting from increased rainfall depths and intensities will tend to increase soil detachment rates in rill channels and interrill areas, and also the sediment transport capacity in the rills, all of which effectively will cause increased erosion.

Figure 13 shows differences in the mean monthly precipitation (P_{month}) and mean maximum daily 30-minute precipitation intensity ($MX\ 0.5\ P$) in the original and updated databases for selected CLIGEN stations corresponding to Groups 1, 4, 5, and 8. The monthly trends of precipitation and intensity in the updated database generally follow the trends of the original database; however, there are increases or decreases in precipitation and intensity values in some or all the months. For the WI476678 station (figures 13a and 13b), higher P_{month} and $MX\ 0.5\ P$ in the updated database compared to the original database caused increased run-

Figure 6

Comparison of precipitation changes on a seasonal basis ([a] winter, [b] spring, [c] summer, and [d] fall) from the original to the updated CLIGEN database.

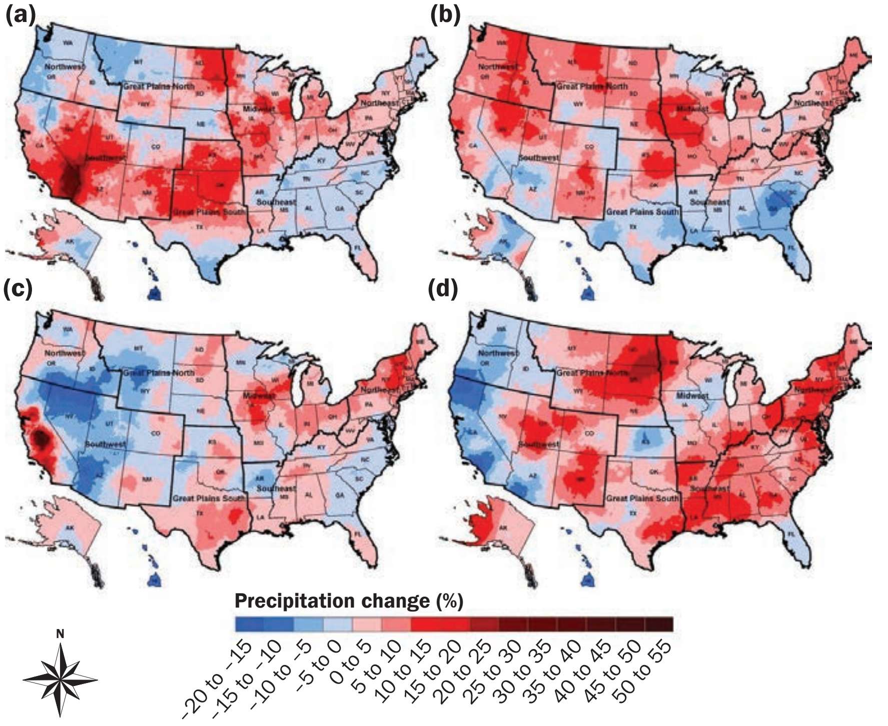
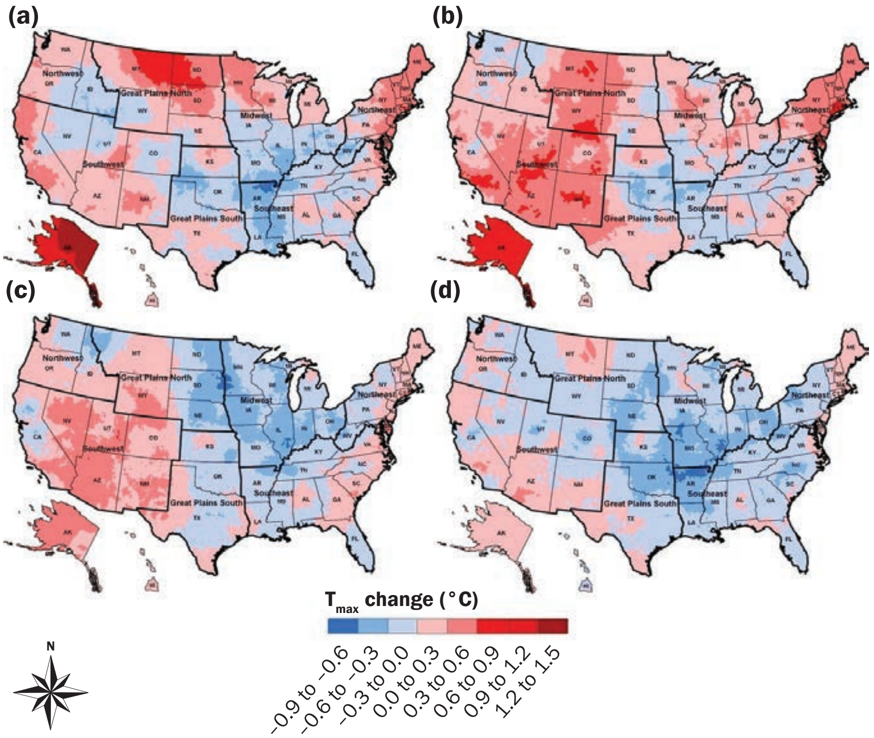


Figure 7

Comparison of maximum temperature (T_{max}) change on a seasonal basis ([a] winter, [b] spring, [c] summer, and [d] fall) from the original to the updated CLIGEN database.



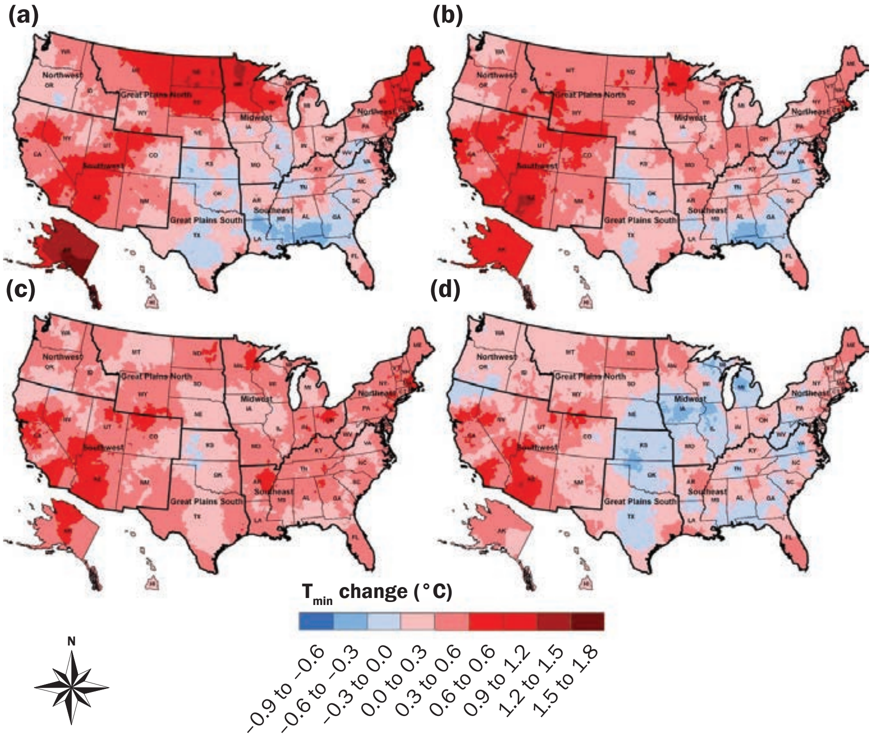
off and soil loss (Group 1). The OK344298 station (figures 13g and 13h) belonging to Group 5 is the opposite of Group 1, where lower P_{month} and *MX 0.5 P* in the updated database produced decreased runoff and soil loss. At IL116910 (figures 13c and 13d), P_{month} is similar in the two databases; however, intensity values in the updated database are lower, and these caused decreased runoff and soil loss (Group 2). In one of western US sites (figures 13i and 13j), monthly precipitation amounts are similar, but intensity values are much higher in the updated database than in the original database, which resulted in increased runoff and soil loss (Group 8). The differences in monthly precipitation amount and/or intensity in the updated and original databases explains the increasing or decreasing runoff and soil loss predictions in locations shown in figure 12 and spatial variations of changes in runoff and soil loss between databases illustrated in figures 10 and 11.

For a given station, CLIGEN simulates the peak rainfall intensity of individual storms based on monthly values of mean maximum 30-minute precipitation intensity (*MX 0.5 P*) (Zhang 2013) following the equation proposed by Arnold and Williams (1989). If a station does not have its own values for this *MX 0.5 P* (due to lack of 15-minute precipitation data), then the monthly *MX 0.5 P* values in the CLIGEN .PAR file are obtained by interpolating the *MX 0.5 P* values from three nearby stations weighted by proximity. Figure 14 shows the distribution of *MX 0.5 P* stations in the contiguous United States for the original and updated CLIGEN databases. The number of stations in the original database with this information was much less, and the stations were sparsely distributed compared to those available in the updated database. Therefore, using the updated database should provide more realistic rainfall intensity values for a site, either because the intensity variables were determined directly from observed station data, or were determined by interpolation from a denser network of available locations.

Other contributing factors of increasing and decreasing trends in runoff and soil loss responses at the CLIGEN stations (figure 12) from the use of the updated to the original database could be changes in trends of other meteorological inputs including T_{min}, T_{max}, and other interpolated variables including solar radiation, T_{dp}, and t_p. For

Figure 8

Comparison of minimum temperature (T_{min}) change on a seasonal basis ([a] winter, [b] spring, [c] summer, and [d] fall) from the original (corrected) to the updated CLIGEN database.



example, warmer temperatures in the northern regions of the United States can cause precipitation to fall more in the form of rain or mix of rain and snow particularly during winter and early spring. Snowmelt during these periods with combined rain and soil frost and thaw conditions can cause severe runoff and soil loss. Another source of variability of mixed responses in runoff and soil loss results might be from the different time periods of climate records in the original database. Nevertheless, the use of temporally consistent updated CLIGEN data sets with denser station networks should provide reliable model predictions for conservation planning and management.

Summary and Conclusions

In this paper, we have presented a method to update the CLIGEN database for 2,700 locations across the United States using a consistent 40 years (1974 to 2013) of recent climate records of precipitation and temperature in the United States as opposed to variable periods of climate records used in the existing (original) CLIGEN database. Other required parameters for interpolation in the CLIGEN database including solar radiation, time to peak, maximum 30-minute peak intensity, and dew point temperatures have been updated, and are also based on weather data within the desired period of records. Therefore, the use of weather generated from CLIGEN using the updated database should provide more realistic runoff and soil loss estimates from WEPP for conservation planning and management.

We examined the spatial patterns in trends of changes in precipitation, maximum and minimum temperature, and WEPP-predicted runoff and soil loss, from the use of the original to the updated database across the United States. Although the spatial patterns of mean annual precipitation and maximum and minimum temperature in the original and updated database across the United States showed similarities, there were variations in terms of percentage changes both annually and seasonally. Some of the

Table 2

Extreme outlier stations for precipitation and minimum temperature (T_{min}) in the original (corrected) and updated CLIGEN databases.

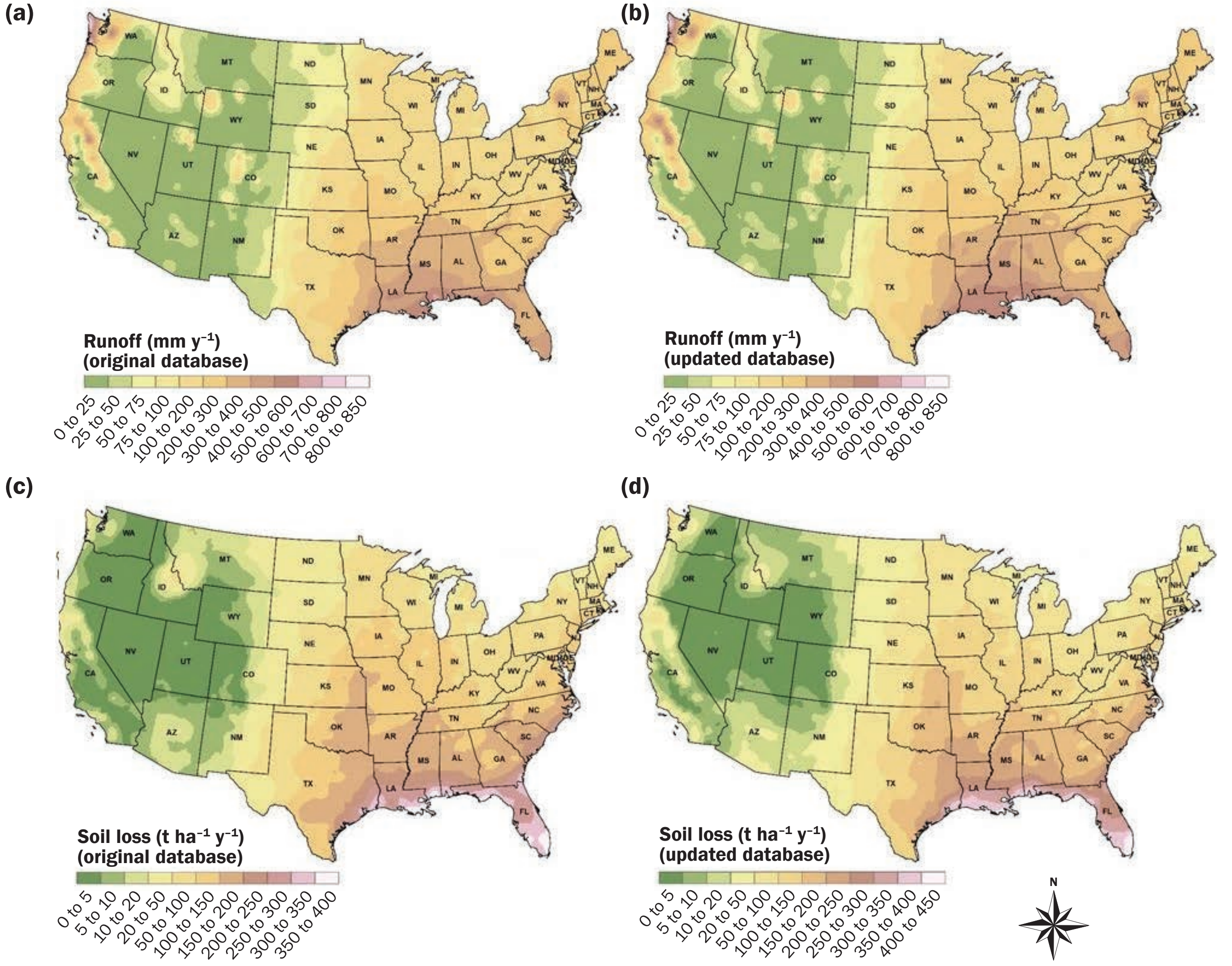
			1995	2015†	Annual	Winter	Spring	Summer	Fall
No.	Station ID	Station name	Average annual precipitation (mm)		Precipitation change (%)				
1	IA134389	KEOSAUQUA ST PARK, IA	646 (1894 to 1992)*	981	52	63	57	55	37
2	IA130364	ATLANTIC 1E, IA	580 (1894 to 1992)	863	49	51	56	53	33
3	IA136327	OSKALOOSA, IA	638 (1894 to 1992)	919	44	56	39	53	32
4	CA043855	HAYFIELD RESERVOIR, CA	93 (1948 to 1992)	131	41	60	23	43	22
5	HI512751	KAINALIU 732 AP, HI	1388 (1949 to 1992)	819	−41	−50	−42	−40	−35
			Monthly mean daily T_{min}		T_{min} change (°C)				
6	VA441614	CHATHAM 4N, VA	6.7 (1930 to 1992)	5.1	−1.7	−1.8	−1.9	−1.1	−1.8
7	CA046635	PALM SPRINGS, CA	13.4 (1927 to 1992)	15.5	2.1	1.8	2.2	2.1	2.1
8	AZ026481	PHOENIX WB AP, AZ	14.8 (1948 to 1992)	17.1	2.3	2.1	2.6	2.1	2.3
9	NV266779	RENO WSFO AP, NV	0.5 (1938 to 1992)	2.9	2.4	1.6	2.3	3.3	2.5
10	CA046136	NEVADA CITY, CA	3.8 (1931 to 1992)	6.5	2.7	2.1	1.8	3.5	3.4

*In parentheses, period of time series used to compile the original (corrected) 1995 CLIGEN database.

†For the 2015 CLIGEN database, period of record for all stations was 40 years from 1974 to 2013.

Figure 9

(a and b) Water Erosion Prediction Project (WEPP)-predicted mean annual runoff (mm y^{-1}), (c and d) WEPP-predicted mean annual soil loss (t ha^{-1} y^{-1}), resulting from the (a and c) original (corrected) and the (b and d) updated CLIGEN database. Simulations were conducted for Universal Soil Loss Equation (USLE) unit plot (22.1 m length and 9% slope gradient) with silt loam texture soil and tilled fallow conditions.



most notable trends when comparing the updated database to the original database are the following: (1) increases in annual precipitation and minimum temperature across the United States; (2) increases in annual maximum temperature in the western half of United States, and decreases in the eastern half of the United States; (3) increases in precipitation evident in the Midwest in spring, fall, and winter, the Northwest in spring, and the Southeast in fall; and (4) increases in maximum daily temperature in the western half of United States and parts of the Northeast in the winter, fall, and spring, whereas minimum daily temperature has increased in all seasons across the United States.

Table 3

Possible combinations of increasing and decreasing trends of average annual precipitation, runoff, and soil loss from original (corrected) to updated CLIGEN database.

	Variables			
Group	Precipitation	Runoff	Soil loss	Number of stations
1	↑	↑	↑	827
2	↑	↑	↓	145
3	↑	↓	↑	41
4	↑	↓	↓	122
5	↓	↓	↓	178
6	↓	↓	↑	69
7	↓	↑	↓	30
8	↓	↑	↑	186

Notes: ↑ = increasing trend. ↓ = decreasing trend.

Figure 10

Water Erosion Prediction Project (WEPP)-predicted (a) mean annual runoff change and (b) mean annual soil loss change, from the original (corrected) to the updated CLIGEN database for the eastern United States.

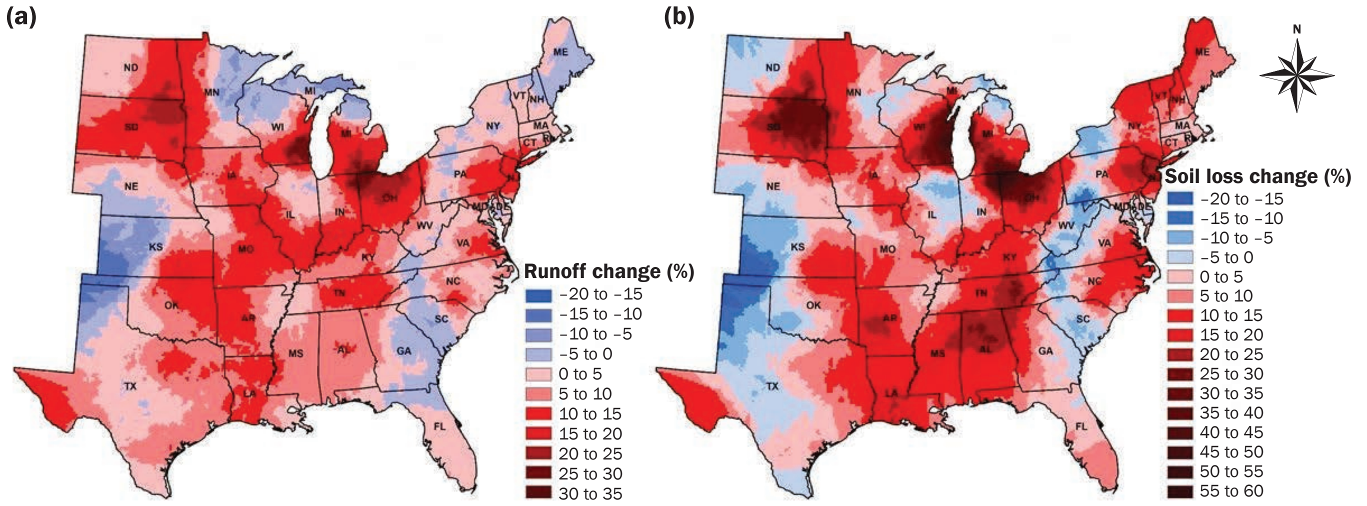
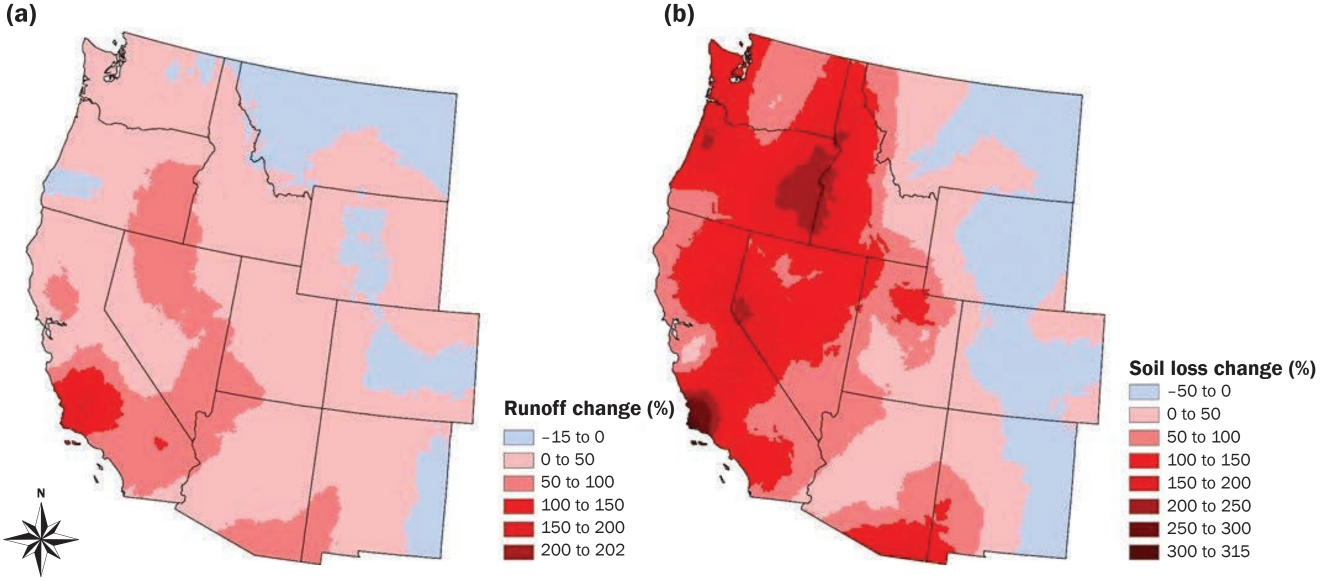


Figure 11

Water Erosion Prediction Project (WEPP)-predicted (a) mean annual runoff change and (b) mean annual soil loss change, from the original (corrected) to the updated CLIGEN database for the western United States.

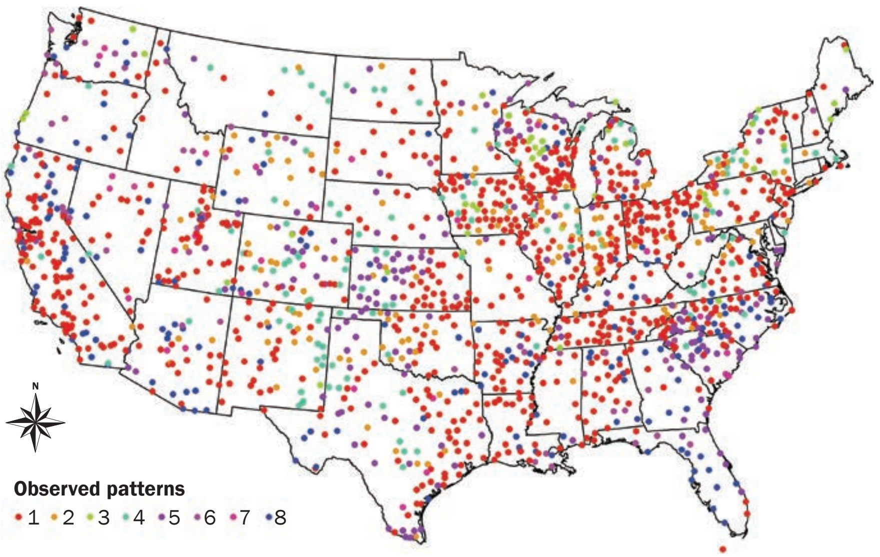


The spatial trends of changes in WEPP-simulated mean annual runoff and soil loss with the updated CLIGEN database, as compared to those when using the original CLIGEN database, showed increases in runoff and soil loss in most parts of the United States. There were stations that showed either increasing or decreasing trends in runoff and/or soil loss with the updated database. These variations were essentially because of differences in monthly precipitation and intensity values in the two databases. Stations that experienced both increased precipitation and intensities showed increased runoff and soil loss for the updated database and vice versa. At other stations, increasing or decreasing trends in runoff and soil loss were variable as a result of complex interactions of monthly precipitation and intensity.

This study characterized the expected changes in runoff and soil loss for tilled fallow conditions in response to changes in the CLIGEN database via the mechanisms of the direct effects of precipitation amount and intensity values. Future study is recommended to investigate the impacts of the use of the updated CLIGEN database for crop management systems on runoff and soil loss predictions. While a substantial decrease in

Figure 12

Observed patterns of increasing and decreasing trends of average annual precipitation, runoff, and soil loss from original (corrected) to updated CLIGEN database for 1,598 common CLIGEN stations. The eight groups of observed patterns are shown in table 3.



the absolute values of runoff and soil loss under crop management systems is expected compared to tilled fallow conditions, the potential impacts of varying precipitation and higher temperatures in the updated database on crop growth, crop yields, and residue mass production should be evaluated. This will help stakeholders and policy makers make better informed decisions for soil conservation planning and land management when utilizing the WEPP erosion model.

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Figure 13

Comparisons of mean monthly precipitation and mean maximum daily 30-minute precipitation intensity (*MX 0.5 P*) between original and updated database for selected stations ([a and b] Group 1, WI476678, [c and d] Group 2, IL116910, [e and f] Group 4, KS143554, [g and h] OK344298, and [i and j] Group 8, CA041018).

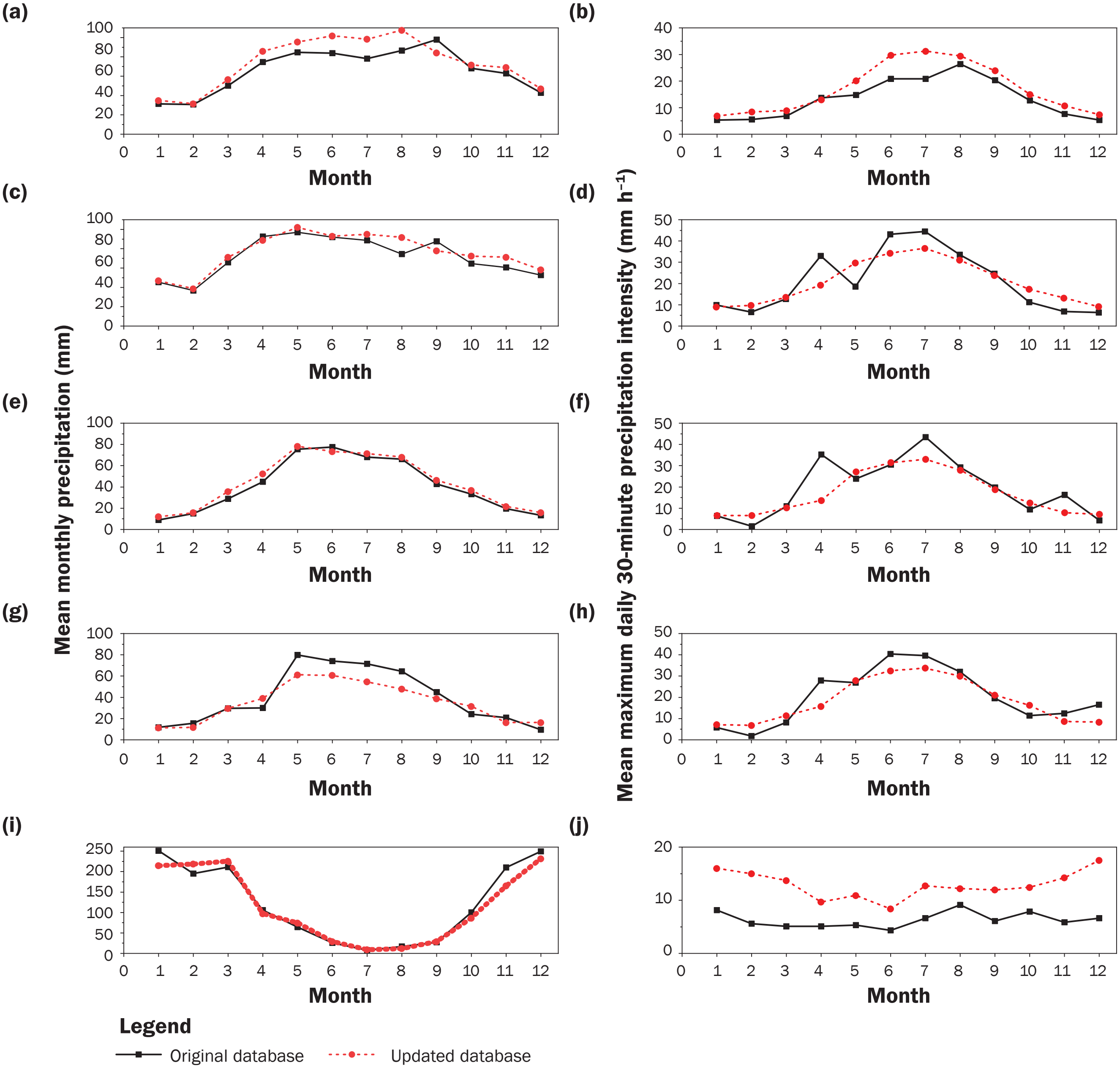
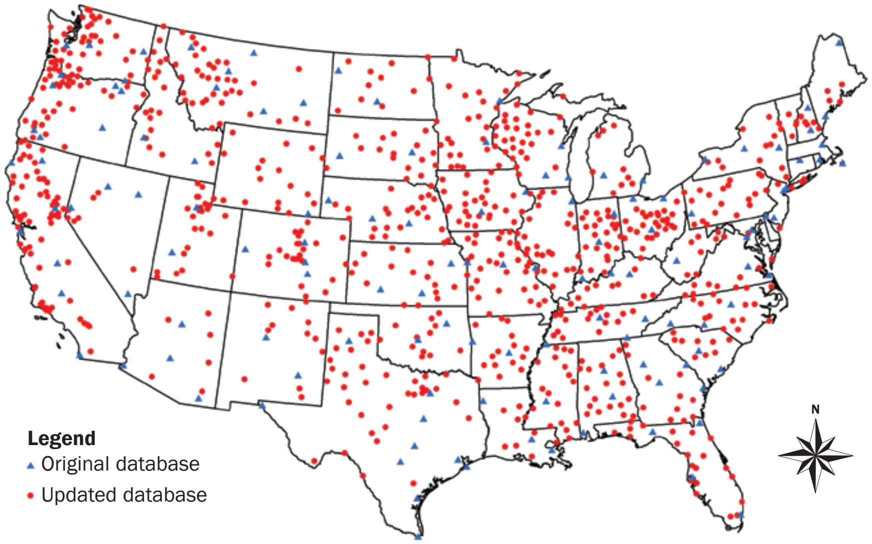


Figure 14

Distribution of stations for mean maximum daily 30-minute peak precipitation intensity (*MX 0.5 P*) in the original and updated climate databases. The original database contains 133 stations and the updated database has 796 stations.



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