IMPROVEMENT AND EVALUATION OF CLIGEN FOR STORM GENERATION

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ABSTRACT. *The program, CLIGEN, generates peak rainfall intensity and storm duration and other daily weather variables for WEPP to predict the rate of runoff and soil loss. Unrealistic peak rainfall intensity simulated by CLIGEN (version 4.2) led to a discovery of a software bug and subsequent modification of the method to estimate the monthly mean of the maximum 30-min rainfall depth for storm generation. To evaluate the modified CLIGEN, break-point rainfall data for 14 sites in the United States were used for periods varying from 4 to 19 years. The modified CLIGEN was then used to generate weather data for a period of 100 years for the 14 sites. WEPP (version 99.5) was run for the 14 sites, using three soil types for each site, so that the simulated mean annual runoff and soil loss can be compared with those using the observed break-point data. For most (> 96%) of the 42 site-soil combinations tested, there is no significant difference in WEPP-simulated mean annual runoff and soil loss at the 0.05 level between the break-point rainfall data and CLIGEN-generated rainfall data. The bias in the mean is less than 2 to 3% for runoff and soil loss when all sites are considered. The minimum bias in the mean annual runoff and soil loss lends support for the modified CLIGEN to generate input for WEPP for the purpose of runoff and soil loss predictions.*
Keywords. *WEPP, Weather generator, Runoff, Soil erosion, Simulation.*

WEPP represents a new generation of physically based soil erosion prediction technologies (Laflen et al., 1991, 1997; Flanagan and Nearing, 1995), and CLIGEN provides the simulated long-term weather data to determine the rate of runoff and soil loss across the landscape (Nicks et al., 1995). In particular, CLIGEN simulates peak rainfall intensity, an important variable needed by WEPP to calculate the peak runoff rate (Stone et al., 1995; Foster et al., 1995). Peak rainfall intensity profoundly influences the predicted soil loss in WEPP because peak rainfall intensity directly affects interrill erosion, and indirectly affects rill erosion through its effects on peak runoff rate, storm runoff amount and the shear stress. Therefore, adequate reproduction of the intensity characteristics by weather generators such as CLIGEN is crucial to successful soil loss predictions.

Two groups of weather variables are generated by CLIGEN. The first group includes all the daily weather variables such as occurrence and non-occurrence of rainfall, rainfall amount on rain days, daily temperatures and solar radiation. The second group is related to storm patterns on rain days. Other weather generators such as WGEN, WXGEN, and USCLIMATE also simulate daily variables (Richardson and Wright, 1984; Richardson and Nicks, 1990; Hanson et al., 1994). A number of studies have attempted to compare and evaluate these models for weather generation in terms of the quality of the simulated daily variables (Johnson et al., 1996; Wallis, 1993; Wallis and Griffith, 1995; Wilks, 1999). Although there are subtle differences among the various weather generators, CLIGEN is on par with other generators in terms of preserving the low-order statistics of rainfall, temperature, and solar radiation on daily, monthly, and annual bases. Unique to CLIGEN is the capacity to simulate the three additional weather variables to characterize the storm pattern, namely storm duration, time to peak, and peak intensity.

Rainfall amount and these three additional variables are of particular importance for WEPP. In fact, these three variables to define storm patterns were generated especially for WEPP (Nicks and Lane, 1989; Nicks et al., 1995). Nicks and Gander (1994) calculated the R-factor for the USLE for the eastern United States (east of the 105th meridian) and found that, "While there is not exact agreement between the contour lines constructed using CLIGEN and those given in the USLE handbook, the pattern is quite similar. . .". Baffaut et al. (1996) undertook a sensitivity analysis of CLIGEN parameters and concluded that, "The half hour largest intensity and. . . were not found significant for average annual soil loss calculation purposes". Headrick and Wilson (1997) found that CLIGEN was acceptable for five sites in Minnesota in terms of rainfall depth and non-precipitation variables. For rainfall intensity at intervals less than 24 h, the simulated rates were higher than those observed. Because of the uniqueness of the storm generation component of CLIGEN, there have been no comparative studies and little systematic evaluation of CLIGEN in terms of the generated storm pattern and the simulated runoff and soil loss using WEPP.

The objective of this study was to evaluate CLIGEN in terms of simulated runoff and soil loss using break-point rainfall data for 14 sites in the United States. The work reported in this article was prompted by the unrealistic peak intensities simulated by CLIGEN (ver. 4.2). An error in the

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source code was subsequently uncovered, which led to a modification of the method to estimate the monthly mean of the maximum 30-min rainfall depth for storm generation.

Background

CLIGEN input parameters have been prepared for 1,078 sites in the United States and are widely available to allow weather generation for input to WEPP. Spatial interpolation of the input parameter values can be used to produce the input file for CLIGEN at other sites if needed. For many other parts of the world, however, raw weather data, including break-point rainfall data, have to be statistically analyzed to prepare the necessary input file to use CLIGEN and subsequently WEPP for soil erosion predictions.

A case in point involves a site in the subtropical region of Australia (lat. 26°04′S, long. 153°48′E). To prepare the input file for this site to run CLIGEN, parameter values for Everglade, Florida (lat. 26°51′N, long. 81°23′W) were monitored to ensure that the calculated model parameter values for the Australian site are of comparable magnitude. One of the required parameters for storm generation in CLIGEN was the average monthly peak 30-min rainfall depth in inches (http://hydrolab.arsusda.gov/nicks/parameters.htm). Baffaut et al. (1996), however, seemed to indicate that it was actually the peak 30-min intensity in inches per hour. In the same article, the authors noted that the predicted rate of soil erosion is insensitive to this intensity parameter, a trend that does not seem to fit comfortably with our established understanding of the soil erosion processes. This conflict in definition of one of the CLIGEN input parameters and the unusual finding of parameter insensitivity led to a close examination of the peak rainfall intensity simulated by CLIGEN. (Subsequent re-analysis of the original 15-min rainfall data for West Lafayette, Station No. 129430, for the period from 1971 to 1996, has shown that the parameter in the CLIGEN input file was in fact the average of the highest monthly maximum 30-min rainfall intensity in inches per hour, although the maximum 30-min rainfall depth should have been used.)

To test the sensitivity of this intensity parameter, the latest version of CLIGEN (ver. 4.2) was run to generate weather data for a period of 10 years. For the Australian site, the average and maximum peak intensity for the 10-year period was 38 mm/h and 250 mm/h, respectively. It was found that the average and maximum peak intensity remained unchanged when the original parameter values were doubled, or when the corresponding values for Everglade, Florida, were used. These strange results led to an examination of the CLIGEN source code for storm generation. A coding error was uncovered that explained why CLIGEN generated the peak intensity independent of the intensity parameter. As for many other bugs in computer software, the cause was actually a simple one. CLIGEN computed a ratio $w = R_{0.5}/R$, where both $R_{0.5}$ and R were rainfall depth (originally in inches). $R_{0.5}$ had been converted from inches into millimeters (mm), while R was not. The resulting w is thus 25.4 times larger than it should be. For most, if not all, sites, the computed w is out of bounds set internally in CLIGEN. The variable, w, thus assumed a constant value of 0.95 for nearly all months and for all sites. The net result of this bug is that for nearly all sites, the peak intensity (in mm/h) is about 3.1 times larger than daily rainfall (mm) on average, and the storm duration is nearly always 3.0 h on average irrespective of the climatic environment for which CLIGEN is used. This bug explains why Baffaut et al. (1996) found that the intensity parameter was unimportant for soil loss prediction and why Headrick and Wilson (1997) noted the considerable overprediction of the rainfall intensity for sites in Minnesota. However, when this simple coding error is corrected, storm duration generated by CLIGEN became excessively long, and the predicted runoff and soil loss using WEPP became unacceptably low. It was therefore decided to modify part of the code for storm generation in CLIGEN, and evaluate the performance of the modified CLIGEN (ver. 5.0) using measured break-point rainfall data.

Materials and Methods

WEPP climate input files were prepared using break-point data for 14 sites in the United States (Risse et al., 1995; Zhang et al., 1995a,b; Liu et al., 1997). Break-point data consist of time intervals and the cumulative rain amount for each interval. Rainfall intensity is assumed to be constant within each interval, and there are a series of "breaks" to separate distinct rainfall intensity between adjacent time intervals. Break-point data for these 14 sites were used for this article because they were benchmark sites for other WEPP validation studies and because the climate and other WEPP input files are readily available at http://topsoil.nserl.purdue.edu/. Runoff and soil loss data for these sites were used for either parameter estimation (Risse et al., 1995; Zhang et al., 1995a,b) or WEPP hillslope and watershed validation studies (Zhang et al., 1996; Liu et al., 1997) or both (table 1).

For each storm event, rainfall amount, storm duration, the ratio of time to peak to storm duration, and the ratio of peak intensity to the average intensity were calculated using break-point rainfall data (Risse et al., 1995; Zhang et al., 1995a,b; Liu et al., 1997). The observed maximum and minimum temperatures were used for some sites (Risse et al., 1995; Zhang et al., 1995a,b) and generated using CLIGEN for others (Liu et al., 1997). Other daily weather variables (i.e., solar radiation, wind speed and direction, and dew-point temperature) were all generated using CLIGEN (Risse et al., 1995; Zhang et al., 1995a,b; Liu et al., 1997). Parameter values in the CLIGEN database for the on-site or a nearby weather station were used to generate these other weather variables. The latitude and longitude recorded in the header information of the WEPP climate files were used to determine the weather station that must have been used to provide the additional weather data so that the same set of parameter values were used for this article. Site location, the corresponding weather station, period of record, and long-term mean annual rainfall are summarized in table 1. The long-term mean annual rainfall was calculated as the sum of the long-term mean monthly rainfall. The mean monthly rainfall for month j, R_j, is given by:

$$R_j = \frac{P(W|D)\, N_d\, R}{1 - P(W|W) + P(W|D)} \qquad (1)$$

Table 1. Site location, period of record, long-term mean annual rainfall (MAR) and the extent to which the break-point rainfall data were used previously*

Site	Weather Station	Lat. (°N)	Long (°W)	Elev. (m)	Period	MAR (mm)	Ke	H	W
Bethany, Mo.	Bethany, Mo.	40.25	94.03	277	1931-40	851	KRP	✓	
Castana, Iowa	Castana 4E, Iowa	42.07	95.82	438	1960-71	748	K		
Chickasha, Okla.	Norman, Okla.	35.23	97.43	362	1971-74	535			✓
Coshocton, Ohio	New Philadelphia, Ohio	40.50	81.45	274	1979-89	972			✓
Geneva, N.Y.	Geneva SCS, N.Y.	42.88	77.02	18	1937-46	811	KRP	✓	
Guthrie, Okla.	Okla City WB AP, Okla.	35.40	97.60	390	1942-56	836	KRP	✓	
Holly Springs, Miss.	Holly Springs EX ST, Miss.	34.82	89.43	146	1961-80†	1428	KRP	✓	✓
Madison, S.Dak.	Madison Rsrch Farm, S.Dak.	44.03	97.17	533	1962-70	597	KRP	✓	
Morris, Minn.	Morris WC School, Minn.	45.58	95.92	344	1962-71	594	KRP	✓	
Pendleton, Oreg.	Hood River Exp Sta, Oreg.	45.68	121.52	152	1979-89	750	K		
Presque Isle, Maine	Presque Isle, Maine	46.65	68.00	185	1961-65	880	KR	✓	
Riesel, Texas	Temple, Texas	31.05	97.35	210	1987-92	830			✓
Tifton, Ga.	Tifton 2 N, Ga.	31.47	83.53	112	1959-66	1206	K		✓
Watkinsville, Ga.	Siloam, Ga.	33.53	83.10	210	1972-82	1200	KRP	✓	✓

* Ke = effective hydraulic conductivity; K = baseline (Risse et al., 1995); R = row crops (Zhang et al., 1995a); P = perennial crops (Zhang et al., 1995b); H = hillslope validation study (Zhang et al., 1996); W = watershed validation study (Liu et al., 1997).

† Excluding 1969.

where P(W|D) is the probability of a wet day following a dry day, P(W|W) the probability of a wet day following a wet day, N_d, number of days in the month, and R the average rainfall amount per rain day. Monthly values for P(W|D), P(W|W), and R are available in the CLIGEN input files.

To evaluate the modified CLIGEN, WEPP was used to calculate the mean annual runoff and soil loss, first with the original break-point rainfall data for the period of record, and then with the CLIGEN-generated weather data for a period of 100 years. Three soils, namely Caribou, Providence and Tifton, were used for each site to simulate a range of model responses, resulting in a total of 42 site-soil combinations. The three soils were chosen because they have the highest (Tifton), the lowest (Providence), and the median (Caribou) baseline hydraulic conductivity (Risse et al., 1995). A standard USLE slope profile (length = 22 m, and steepness = 9%), fallow treatment and WEPP (ver. 99.5) were used for all simulation runs.

Note that we launch the modified CLIGEN only once to generate climate files for all 14 sites. This is important because CLIGEN uses identical seeds for random number generation. If we started CLIGEN separately for each site, the same sequence of random numbers would be used for all sites and the resulting weather data would be highly correlated.

The record lengths of the break-point rainfall data for the 14 sites are short with an average of 9.8 years (table 1). To take into account the natural climatic variability, the mean annual runoff and soil loss were multiplied by a factor equal to the ratio of the long-term mean annual rainfall to the mean annual rainfall for the simulation period. Other indicators, such as the gross runoff coefficient and the average sediment concentration, which are not sensitive to the mean annual rainfall for the simulation period, were also considered.

In addition, 95% confidence intervals for the mean annual runoff and soil loss simulated using the limited break-point rainfall data will be presented to quantify the uncertainty in the mean. The 95% confidence interval for the mean was calculated as follows:

$$\mu = \overline{X} \pm t_{0.025} \frac{s}{\sqrt{N}} \qquad (2)$$

where $t_{0.025}$ is the critical t-value at 0.05 level, N the sample size, and s the standard deviation. The confidence intervals are shown as error bars for comparing simulated mean annual runoff and soil loss for each of 42 site-soil combinations.

The CLIGEN code was modified to incorporate two main changes. First, a new algorithm to determine the monthly mean of the maximum 30-min rainfall depth was implemented. Secondly, the parameter values for storm duration and the coefficient of variation for the ratio of the maximum 30-min rainfall depth to daily rainfall required in CLIGEN were estimated using the break-point rainfall data.

To illustrate how peak rainfall intensity is simulated in CLIGEN, it is informative to define two important statistics. For each rain day, we have one observation of the maximum 30-min rainfall depth. We define $R_{0.5}$ as the average of these maximum 30-min rainfall depths. Numerically, $R_{0.5}$ equals half of the average I_{30} commonly used in relation to the R-factor for the USLE/RUSLE (Renard et al., 1997). We define $R_{0.5max}$ as the average of the highest of the maximum 30-min rainfall depth for each month. If there are n rain days in a month and n corresponding maximum 30-min rainfall depths, and let Z be the largest of the n observations, then $R_{0.5max}$ would be the average Z for the month. The parameter database for CLIGEN contains monthly values for $2R_{0.5max}$ (the factor of 2 occurs because 30-min intensity in mm/h is twice the rainfall depth in mm). The theory (Arnold and Williams, 1989), however, requires an average ratio of the maximum 30-min rainfall to the daily rainfall. The best estimate of this average ratio would be $R_{0.5}/R$, where R is the average rainfall per rain day. A relationship is therefore needed to determine $R_{0.5}$ from $R_{0.5max}$. From Williams et al. (1984) and Arnold and Williams (1989), $R_{0.5}$ is related to $R_{0.5max}$ by:

$$R_{0.5} = \frac{R_{0.5\,max}}{\ln F} \qquad (3)$$

where F is the exceedance probability for $R_{0.5max}$. If there are n rain days for the month, since $R_{0.5max}$ is related to the maximum of the n observations, F can then be approximated by:

$$F = \frac{2}{2n + 1} \quad (4)$$

In the modified CLIGEN, equations 3 and 4 are used to calculate $R_{0.5}$. When $n < 2.218$, $R_{0.5}$ is set to equal $R_{0.5max}$. In Arnold and Williams (1989), the Hazen frequency was used with $F = 1/(2n)$. The Hazen and a few other frequencies were defined elsewhere in relation to plotting positions for flood frequency analysis (Maidment, 1993). Another popular frequency estimator is Weibull's with $F = 1/(n + 1)$. In figure 1, the ratio $R_{0.5}/R_{0.5max} = -1/\ln(F)$, which can be regarded as an adjustment factor to convert $R_{0.5max}$ into $R_{0.5}$, is graphed as a function of the number of rain days. It can be seen that the adjustment factor for $R_{0.5}$ used in this article is similar to Weibull's when the number of rain days is large. The factor is higher when the number of rain day is small and it is not allowed to exceed unity.

In CLIGEN (Nicks et al., 1995), the instantaneous peak intensity, r_p in mm/h, was determined as:

$$r_p = -2\,P\ln(1 - A) \quad (5)$$

and storm duration, D in h, as:

$$D = -\frac{\Delta}{2\ln(1 - A)} \quad (6)$$

where P is the simulated rainfall amount (in mm), Δ is a dimensionless parameter, and A is a random number drawn from a gamma distribution described by Williams et al. (1984). The parameter A represents the ratio of the maximum 30-min rainfall to total rainfall for individual events. Arnold and Williams (1989) developed a theory for the instantaneous peak intensity (eq. 5). The factor of 2 in equations 5 and 6 came about because the basic time interval is 30 min, and 30 min = 1/2 h. The parameter Δ can be interpreted as the mean of the ratio of the peak intensity to the average intensity, and its value was set internally in CLIGEN. Sometime in the early 1990s, the value of Δ was changed from 4.607 to 9.210 (cf. Nicks and Lane, 1989; Nicks and Gander, 1994; Nicks et al., 1995). Internally, the coefficient of variation (CV) of A was set to 0.30 in CLIGEN.

Rearranging equations 5 and 6 leads to:

$$r_p = \Delta \frac{P}{D} \quad (7)$$

and

$$A = 1 - \exp\left(-\frac{r_p}{2\,p}\right) \quad (8)$$

For measured break-point data, P, D, and r_p are known. The parameters Δ and the CV of A, therefore, can be estimated using statistical methods.

Results

There are site-to-site variations in the two parameters Δ and CV of A, and the site-averaged monthly distribution of Δ and CV of A is shown in figure 2. The average Δ varies in the range from 3.7 to 4.5 for the period from March to November, and may be regarded as essentially constant for this period. If we exclude the three months from December to February when soil erosion is comparatively low, the average Δ for the remaining nine months was 3.99. The average CV of A for the corresponding period was 0.37. It is interesting to note that the estimated average Δ is close to 4.607 used in CLIGEN in the early 1990s. The newly estimated values for Δ and CV of A are implemented in the modified CLIGEN.

The long-term mean annual rainfall using the average rainfall per rain day and the expected number of rain days (see eq. 1) is compared with the simulated mean annual rainfall using CLIGEN-generated rainfall data for a period of 100 years for all 14 sites (fig. 3). A comparison between the long-term mean annual rainfall and the actual mean

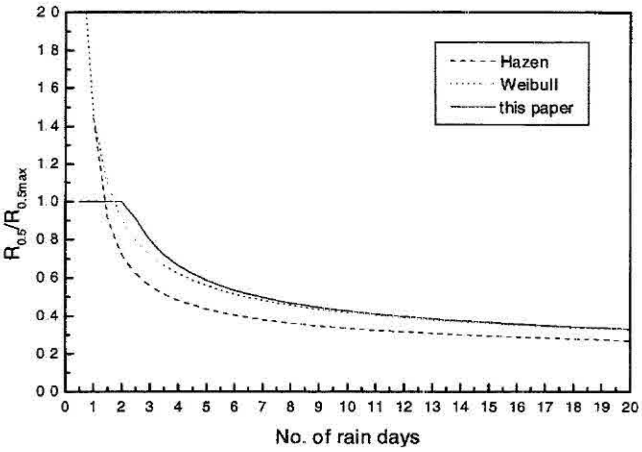

Figure 1–The adjustment factor for the mean 30-min rainfall depth as a function of the number of rain days.

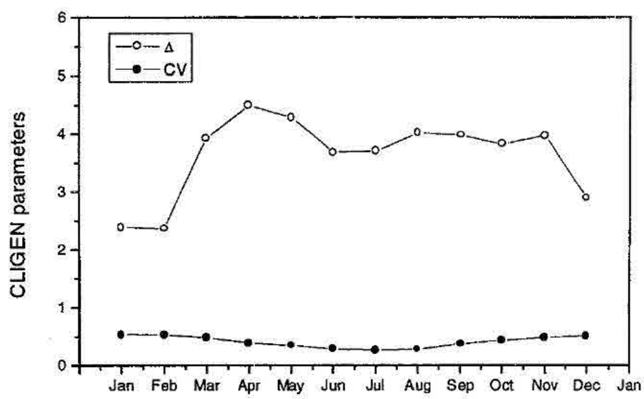

Figure 2–Site-averaged monthly distribution of the CLIGEN parameter for storm duration (Δ) and the coefficient of variation (CV) of the ratio of the maximum 30-min rainfall to daily rainfall.

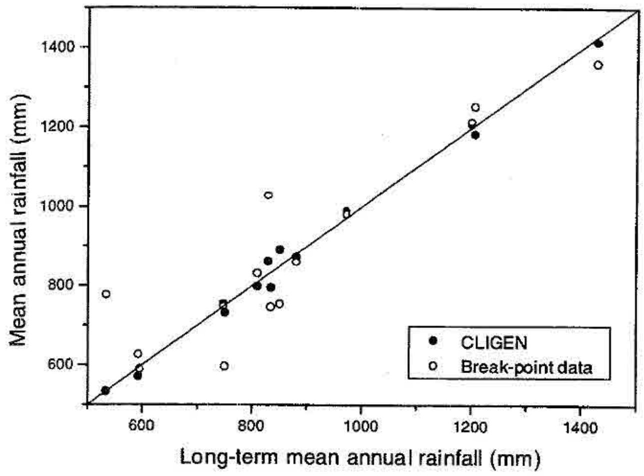

Figure 3–A comparison of the long-term mean annual rainfall with CLIGEN-simulated rainfall and measured break-point rainfall. The long-term mean annual rainfall was determined using average rainfall on rain days and the expected number of rain days.

annual rainfall using break-point data for the period of record for the 14 sites is also shown in figure 3. It can be seen that CLIGEN preserves the mean annual rainfall very well for a simulation period of 100 years. The break-point rainfall data for the 14 sites show some scatter because of the relatively short period of record. As discussed in the section above, because of the natural variability in rainfall, the mean annual runoff and soil loss for comparison purposes were adjusted using the long-term mean annual rainfall so that the true difference in the simulated runoff and soil loss can be detected.

Simulated mean annual runoff using the modified CLIGEN and WEPP and the reference runoff using the measured break-point data and WEPP are shown in figure 4. Runoff calculated using the break-point data and WEPP is called the reference runoff because it is not observed runoff, and only provides a reference against which the performance of the modified CLIGEN will be assessed. It can be seen that the modified CLIGEN performed favorably in generating the necessary rainfall data for WEPP to predict the mean annual runoff for the 42 site-soil combinations. The absolute difference in the mean annual runoff ranges from 1.0 to 82.6 mm with an average of 21.2 mm, or 8.7% of the mean reference runoff for the 42 site-soil combinations. By comparison, the average 95% confidence interval (i.e., the size of the error bar), for the reference mean annual runoff is 58.3 mm/y, or 24% of the mean. For the 42 site-soil combinations, the 1:1 line goes through 41 error bars (fig. 4), indicating that the simulated mean annual runoff using the break-point rainfall data and CLIGEN-generated rainfall data is not significantly different at 0.05 level for most sites. This is a conservative statement because the variance of the mean annual runoff using the 100-year generated rainfall data has not been considered. The variance of the simulated runoff would be about an order-of-magnitude smaller than that of the reference runoff. Had the variance of the simulated runoff been considered, the difference between the simulated and reference runoff would have been even less significantly different. The mean annual runoff for the 42 site-soil combinations is 242 mm using the break-point data and 243 mm using the modified CLIGEN. Linear regression of the simulated against the reference runoff showed that the ratio of the reference to simulated runoff was 0.983 for the 42 site-soil combinations with $r^2 = 0.97$. Therefore, on the whole, the bias in the mean annual runoff is less than 2%.

A comparison between the break-point data and CLIGEN-generated data is also made in terms of the simulated mean annual soil loss using WEPP (fig. 5). The error bars for soil loss appear to be greater than those for runoff (cf fig. 4 and fig. 5), indicating a greater natural variability in soil loss in comparison with runoff. The average 95% confidence interval for the mean annual soil loss is 27.3 t/ha, or 38% of the mean. It can be seen that modified CLIGEN and WEPP are able to reproduce the soil loss in the mean for the 42 site-soil combinations. The absolute difference in the mean annual soil loss ranges from 0.07 to 49.3 t/ha with an average of 10.8 t/ha, or 15% of the mean reference soil loss for the 42 site-soil

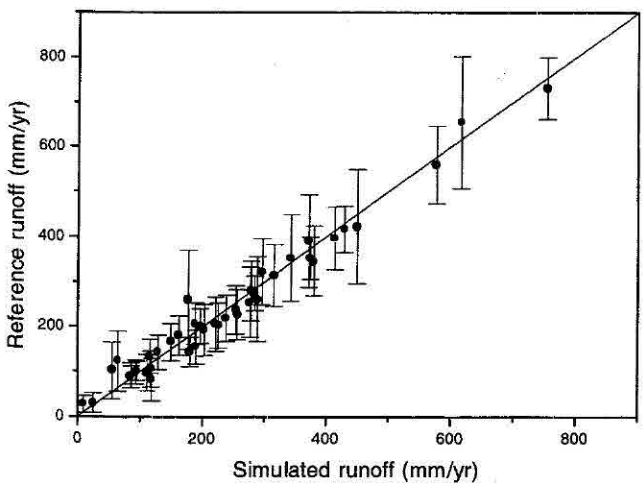

Figure 4–A comparison of the mean annual runoff using measured break-point data and rainfall data generated with CLIGEN (version 5.0). Error bars represent the 95% confidence intervals for the mean annual runoff.

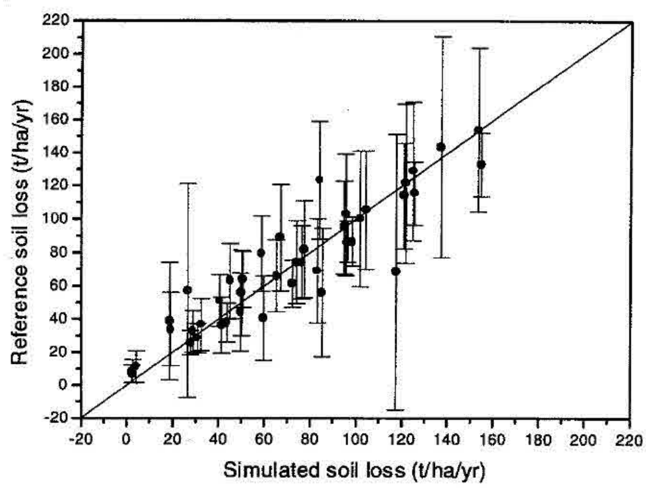

Figure 5–A comparison of the mean annual soil loss using measured break-point data and rainfall data generated with CLIGEN (version 5.0). Error bars represent the 95% confidence intervals for the mean annual soil loss.

combinations. The 1:1 line goes through 40 of 42 error bars (fig. 5), indicating once again that the simulated mean annual soil loss using break-point rainfall data and CLIGEN-generated rainfall data are not significantly different at the 0.05 level for most sites. The mean annual soil loss for the 42 site-soil combinations is 71.4 t/ha using the measured break-point data and 70.5 t/ha using rainfall data generated with the modified CLIGEN. Overall simulated mean annual soil loss using the rainfall data generated by the modified CLIGEN and the reference soil loss are also closed related. Regression analysis shows that the ratio of the reference to simulated soil loss is 0.973 for the 42 site-soil combinations with $r^2 = 0.97$. Therefore the overall bias in the mean annual soil loss is less than 3%, and the result is quite similar to that for runoff.

Results presented above were based on the adjusted runoff and soil loss to reduce the effect of the natural variability in the break-point and CLIGEN-generated rainfall data on simulated runoff and soil loss. If we define the gross runoff coefficient as the ratio of total runoff to total rainfall, and average sediment concentration as the total soil loss to total runoff, these ratios would be independent of the adjustment factor used. The gross runoff coefficient was 28.1% using the break-point data and 27.8% using the modified CLIGEN. The average sediment concentration was 29.5 kg/m^3 using the break-point data and 29.0 kg/m^3 using the modified CLIGEN. The difference in the mean between CLIGEN-generated and measured rainfall data with respect to the annual runoff and soil loss is small indeed.

Discussion

Runoff and soil loss have high natural variabilities. Event to event and year to year comparison would be fraught with difficulties. It is important for weather generators such as CLIGEN to preserve the mean because the mean is not only the most reliable of all parametric statistics, but the mean is also of great practical importance. Another important consideration about weather generators is the purpose for which the output shall be used. In the context of CLIGEN and WEPP, the objective has always been to predict the rate of runoff and soil loss. The results presented in this article on the minimum bias in the mean annual runoff and soil loss, therefore, lend strong support for the modified CLIGEN to generate input for WEPP for the purpose of runoff and soil loss predictions.

The theories of Williams et al. (1984) and Arnold and Williams (1989) require the mode in the frequency distribution of the ratio of the maximum 30-min rainfall to daily rainfall. In the modified CLIGEN, this mode was estimated as $R_{0.5}/R$ and $R_{0.5}$ was further estimated from $R_{0.5max}$. A case may be made for estimating the ratio or $R_{0.5}$ directly from the original data. This would involve re-processing a large amount of 15-min rainfall data and re-packaging the parameter files for the 1078 sites in the United States. It can, however, be argued that even if we recalculate the parameters, the results may not necessarily be better because of the inherent problem with parameter estimation when there are numerous small rainfall amounts in the original records. On most days, the rainfall amount is small and storm duration is short. The net result is that the ratio of the maximum 30-min rainfall to daily rainfall would be close to one for most days, and paradoxically, relatively small $R_{0.5}$ values would occur due to the preponderance of low intensity events. $R_{0.5max}$, on the other hand, is robust and insensitive to the presence of numerous small events. All things considered, $R_{0.5max}$ may be the best choice we have or even more meaningful than $R_{0.5}$ in the context of runoff and soil erosion processes.

Conclusion

Unrealistic peak rainfall intensity simulated by CLIGEN led to the discovery of a software bug in the program. The component of CLIGEN for storm generation was subsequently modified to better estimate the monthly mean of the maximum 30-min rainfall. Break-point rainfall data for 14 sites in the United States were used to evaluate the modified CLIGEN. Runoff and soil loss data for these 14 sites were used previously for parameter estimation and WEPP validation. Three soils for each site were used to test a range of model responses. For most (> 96%) of the 42 site-soil combinations tested, there is no significant difference between the break-point rainfall data and CLIGEN-generated rainfall data in terms of the mean annual runoff and soil loss simulated using WEPP. The bias in the mean is less than 2 to 3% for runoff and soil loss when all sites are considered, although the difference in the mean annual runoff and soil loss can be great for individual sites because of the large natural variability in runoff, and in soil loss especially. The minimum bias in the mean annual runoff and soil loss lend strong support for the modified CLIGEN to generate input for WEPP for the purpose of runoff and soil loss predictions.

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