# Predicting runoff for a RUSLE2 ephemeral gully calculator

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## 1. Abstract

RUSLE2 provides robust estimates of average annual sheet and rill erosion from a wide range of land use, soil, and climatic conditions, but it cannot calculate channel erosion, including ephemeral gully erosion. Estimation of ephemeral gully erosion within RUSLE2 has been identified as a priority need by user agencies. RUSLE2 currently uses runoff from the location-specific 10-yr 24-hr precipitation depth ($P_{10y,24h}$) estimated using aUSDA curve number (CN) method to calculate sediment transport capacity. Because this approach assumes a 10-yr transport event occurs every day, it gives a conservative estimate of sediment deposition along RUSLE2 hillslope profiles and in the channel at the bottom of the hillslope. However, applying the same approach to calculation of erosion in the channel could lead to excessive sensitivity of ephemeral gully erosion estimates to tillage frequency, since the storm simulated may be large enough to cause the channel to erode to its ultimate shape on the first day after each tillage event. We therefore sought a smaller suitable index storm for ephemeral gully erosion estimation. This paper describes steps toward the end of estimating index storm size and frequency using only information already contained within the RUSLE2 databases. We then outline a possible method of using the index storms to calculate ephemeral gully erosion within a RUSLE2 context as a scaled sum of a location-specific number and distribution of erosion events each year, whose sizes and durations are estimated from the existing RUSLE2 databases and whose total runoff volume approximates local average annual runoff.

## 2. Introduction

The Revised Universal Soil Loss Equation Version 2 (RUSLE2) estimates rill-interrill soil erosion caused by raindrop impact and Hortonian overland flow (Foster et al., 2003). The RUSLE2 climate databases include only monthly averages for precipitation, temperature, and erosivity density (erosivity per unit rainfall, MJ $ha^{-1}$ $h^{-1}$), plus the location's 10-yr 24-hr precipitation depth ($P_{10y,24h}$). However, RUSLE2 disaggregates the climate data to daily values and, combined with numerous daily soil and vegetation variable estimates, calculates long-term average sheet and rill erosion on a daily basis. RUSLE2 is a hybrid model in that it computes sheet and rill erosion on hillslopes based on regression equations driven by rainfall erosivity, but uses process-based equations to determine sediment transport and deposition using runoff from a design storm. RUSLE2 uses the $P_{10y,24h}$ precipitation depth with daily curve number estimates (a function of soil hydraulic class, soil biomass, soil consolidation, soil roughness, and soil residue cover) to compute the runoff, and uses the result to estimate sediment transport and deposition, contour failure, and backwater ponding upslope of barriers and buffer strips (Foster, 2005). Even after appropriate scaling, calculating erosion by routing a 10-yr event through a channel every day could lead to excessive sensitivity of ephemeral gully erosion estimates to tillage frequency, since the event might cause the channels to erode to its ultimate geometry on the first day after each tillage operation. Therefore, we sought to estimate a smaller more appropriate size for storms forming the ephemeral gully.

## 3. Methods

AnnAGNPS (version 3.5) was selected as a suitable model for runoff estimation because it uses the stochastic climatic generator GEM (Harmel et al. 2002) to estimate stochastic rainfall, it uses management descriptions based on RUSLE databases, and it estimates daily runoff using CN technology (Bingner and Theurer, 2001). Thirty-year AnnAGNPS runoff simulations were developed using climate data from 26 U.S. locations (annual precipitation from 191 to 1420 mm) for each factorial combination of four soils (soil hydrologic classes A, B, C, and D) and four managements (tilled fallow, tilled maize, no-till maize, and pasture) even though some combinations were not physically possible (e.g. maize production with only 191 mm of precipitation). All the locations were in the continental U.S. between 30 and 48 degrees N latitude and 74 and 123 degrees W longitude. Official RUSLE2 climate databases (NRCS, 2008) for the same counties as the AnnAGNPS locations and were screened so that average annual precipitation in the selected RUSLE2 climate file for each location differed by no more than 15% from that in the AnnAGNPS input dataset.

AnnAGNPS requires users to choose a base CN (NRCS, 2004) and daily adjusts that CN based on a water balance and planting and harvesting events. RUSLE does not compute a water balance, but internally calculates a time varying CN that reflects daily changes in biomass, residue, consolidation, and roughness. Because decay of soil biomass, surface residue, and surface roughness depend on climate data, for a given soil and management (tillage operations and biomass inputs), a location's average annual RUSLE2 CN is lower in cool and dry climates than in warmer and wetter climates. The CN is a non-linear transform of the underlying parameter, S, the "potential maximum retention," which has the same dimensions as the precipitation, P. When the "initial abstraction" is taken as 0.2S, and S and P are in mm, daily runoff, Q (mm), is calculated as:

$$Q = \frac{(P - 0.2S)^2}{P + 0.8S} \quad [1]$$

S = (25400 - 254 CN) / CN

Our analysis focused on prediction of S. Daily AnnAGNPS outputs were aggregated into monthly means of rainfall, snowfall, snowmelt, effective rainfall (sum of rainfall and snowmelt), and runoff. We followed steps 1 to 4 (below) to predict monthly runoff and corresponding storm sizes from RUSLE2 databases.

(1) Create an adjusted RUSLE2 precipitation file based on RUSLE2 monthly temperature and rainfall to capture the main effects of snow accumulation in early winter and melting in late winter.
(2) Calculate $S_i/S_a$, the ratio of monthly to annual average S from AnnAGNPS runoff predictions for each climate, soil, and management contribution; and use regression tools to predict this ratio from parameters derived from the RUSLE2 climate database after adjusting for snow accumulation and melting (step 1). This ratio reflects seasonal trends caused by the AnnAGNPS water balance adjustments to the CN.
(3) Calculate average monthly runoff from RUSLE2 databases using regression to estimate AnnAGNPS average monthly runoff for each location, soil, and management combination from the 30-year daily AnnAGNPS runoff predictions for 4992 combinations (26 locations, 4 soils, 4 managements, 12 months).
(4) Predict the scale and shape parameters of a gamma distribution fitted to the series of 30-year daily AnnAGNPS runoff predictions for all 416 combinations (26 locations, 4 soils, 4 managements) from the RUSLE2 databases and use this to predict the return interval if monthly runoff occurred in a single storm.

## 4. Results

**(1) Snowpack accumulation and melting.** Adjusted RUSLE2 monthly precipitation amounts, ARrain (mm), were calculated by subtracting the change in snowpack (mm) from the average monthly precipitation, Rrain (mm), from the RUSLE2 database for a location (precipitation was reduced when the snowpack increased and increased when the snowpack decreased):

DeltaSnowPack = Rrain * TempFunc [2]

TempFunc = -0.0735 + 0.00851*RTemp + DeltaTemp*(-0.04386+0.0061*RTemp), RTemp≤8
TempFunc = 0, RTemp >8

where: RTemp is the mean monthly temperature (°C) in the RUSLE2 climate database for a location, and DeltaTemp is the change in RTemp from the previous month. DeltaSnowPack (mm) is positive (the snowpack is increasing) if TempFunc is positive, which occurs when DeltaTemp is less than about -2 °C. If DeltaTemp is positive, the snowpack melts and ARrain is larger than Rrain. If the absolute magnitude of DeltaTemp is small, there is little gain or loss of snow pack. The main effect of Rtemp is to amplify the impact of DeltaTemp. The TempFunc effect is multiplied by the monthly precipitation (Rrain, mm), so effects are larger in wetter climates. This four parameter model estimates ($R^2$ = 0.65, n=104) the monthly average of changes in snowpack predicted by 30 years of AnnAGNPS climate simulations at the 26 locations. Over the range of the database, with 104 location months with RTemp ≤ 8 °C, this relationship predicts DeltaSnowPack to range from -31 to +43 mm, while the AnnAGNPS results ranged from about -69 to +51mm, with two observations less than -30, and two above +30. This adjustment shifts precipitation in the correct direction to capture important winter effects, but does not capture the entire effect for the highest snow locations (e.g., March in Portland, ME).

**(2) Monthly water balance adjustment to S (and CN).** AnnAGNPS adjusts the daily CN based on a soil water balance. We calculated the ratio of the average monthly S, $S_i$, to that of its annual average, $S_a$, as predicted by the AnnAGNPS model for a particular climate, soil, and management. We then fitted the resulting monthly "S-ratio" to RUSLE2 climate parameters. A 60 degree of freedom (12 monthly intercepts plus the interactions of 12 months with 4 parameters) regression model was highly significant ($R^2$ = 0.99, n=4992). Table 1 gives the parameter estimates for estimating the "S-ratio" from RUSLE2 climate databases. This ratio reflects the seasonal variation in "maximum detention" and can be used to adjust the RUSLE2 S, $S_R$, corresponding to the daily CN estimated by RUSLE2, thus approximating water balance effects. The monthly intercept estimate (mon) was the most important predictive factor (had the highest F in the ANOVA) in the model. As seen in Table 1, the water balance adjustment increases S during the summer (triple in August), thus decreasing runoff between June and October. In contrast, S is close to half its annual average value from November to March, thus increasing runoff for a given daily rainfall. The main effect of mon is significantly modified by interactions with the other four parameters in the model: RTemp and ARrain and the deviations of these monthly values from their annual averages for each location. The monthly $S_i$ can be disaggregated into daily values as is done with all the other RUSLE2 climate variables. It should be noted that the coefficients in Table 1 are only appropriate for adjusting S (and CN) in northern temperate climates.

**(3) Calculate average monthly runoff from RUSLE2 databases.** A parameter, q , was calculated as:

$$q = (ARrain - 0.2\ S_R S_i/S_a)^2 / (ARrain + 0.8\ S_R S_i/S_a) \quad [3]$$

where $S_i/S_a$ is the monthly "S-Ratio" predicted in step (2) using the coefficients in Table 1. The parameter q is the predicted depth of runoff (mm) that would occur if the entire monthly precipitation fell as one storm. Thus q reflects a combination of soil, management, and climatic effects on runoff. AnnAGNPS average monthly runoff (4922 observations) was fitted to a 23 parameter regression model based on information available in the RUSLE2 climate, soil, and management databases. The model predicted average annual runoff ($R^2$ = 0.95, n=416) and average monthly runoff ($R^2$ = 0.89, n=4992) well. Space does not allow presentation of the model and parameter estimates, but the variables involved were: q as defined through equation [3], soil hydrologic class (A, B, C, or D), RTemp, ARrain, $S_R$, $P_{10y,24h}$, the ratio $S_i/S_a$, the average monthly erosivity density, the monthly rainfall erosivity (MJ mm $ha^{-1}$ $h^{-1}$), the range between the minimum and maximum monthly q, the range between the minimum and maximum monthly temperatures, the range between the minimum and monthly erosivity densities, and total annual rainfall erosivity for the location.

**(4) Determine the gamma function scale and shape parameters daily runoff amounts.** Preliminary analysis indicated that the shape factor for the gamma distribution of runoff events was approximately 0.5 at all locations. Under this assumption, and using only location, soil, management combinations that had more than 6 runoff events within the 30-year simulation, the scale factor was estimated with a 22 parameter model from ($R^2$ = 0.99, n=377) involving various combinations and interactions of the following variables calculated from RUSLE2 databases: ARrain, $S_R$, soil hydrologic class, $P_{10y,24h}$, average monthly erosivity density, the range between the location's minimum and maximum monthly temperatures, the range between the minimum and monthly adjusted rainfall, the range between the minimum and monthly erosivity density, and total annual rainfall erosivity.

**5. Discussion - A possible way forward**

Below, we outline a possible procedure to use the results obtained above to estimate monthly and annual ephemeral gully erosion within RUSEL2 as the sum of a location-specific number of runoff events with whose sum approximates local monthly and annual average runoff.

(1) Use an inverse gamma function to determine the return period of a postulated single storm making up the total monthly rainfall calculated in step (3) for the predominant soil and management of the hillslope with a shape parameter of 0.5 and a scale parameter determined in step (4). If the return period is less than 0.5 yr, then the monthly runoff will be used as the "index" storm to determine sediment transport and ephemeral gully erosion. If the return period is greater than 0.5 year, then the monthly runoff will be distributed into two or more equal storms of size $Q_{ev}$, with a return period less than 0.5 year.

(2) Determine precipitation depth of each event, $P_{ev}$, from event $Q_{ev}$ using equation [1] with $S_i$ chosen to represent the predominant soil and management of the cropped portion of the hillslope. The event rainfall erosivity, $R_{ev}$, will be determined by multiplying $P_{ev}$ by the location erosivity density for the day of the event. This $R_{ev}$ will be used in RUSLE2 to calculate event sediment yield from the hillslope to the ephemeral gully.

(3) Assuming a base runoff duration of 1 hour, vary event durations inversely as some function of the ratio of daily erosivity density, $ED_i$, to the location's annual average erosivity density, $ED_a$, thereby reflecting the effect of rainfall intensity on peak runoff rates.

(4) Calculate index event ephemeral gully erosion for the channel using the CREAMS (Knisel, 1980) equations (for which the user must specify the channel steepness, length, and initial channel width, depth, and soil depth to a non-erodible layer), or with another physics-based ephemeral gully prediction equation.

(5) Determine the long term average precipitation, $P_{ei}$, for the month (or fraction of a month) represented by the runoff event from of the location's climate database.

(6) Use the ratio $P_{ei}$ / $P_{ev}$ to scale or calibrate the ephemeral gully erosion estimate. Since the erosivity density will be common, the ratio $P_{ei}$ / $P_{ev}$ will be the appropriate scaling factor to calibrate ephemeral gully erosion under the assumptions that the RUSLE2 sheet and rill erosion estimate is acceptable, and that the ratio of sheet and rill to ephemeral gully erosion in the simulated event sequence will be the same as that for the location's ambient climate.

The above procedures remain untested. Further work is needed to determine the reliability of the several regression equations and parameter sets through their application to independent datasets and observations.

There are clearly many limitations to the above procedures. One example is that the assumption underlying the calibrating of the ephemeral gully erosion in (6) with $P_{ei}$ / $P_{ev}$ will not be valid in areas where erosion is caused mainly be low intensity winter rains and/or snowmelt (e.g. western regions of the U.S. where $R_{eq}$ rather than R is used in RUSLE1). In these situations, erosion predictions based on index event ephemeral gully erosion procedures may better capture actual seasonal variation in erosion rates than would variation in rainfall erosivity. However, some other sort of calibration would be needed before the estimates could be applied since the sequence of storms used in the simulations would have a return period considerably greater than one year. This is particularly true since the monthly runoff amounts will be over-predicted in dry areas since the predicted value distribution was truncated when negative runoff values predicted by regression equations were set to zero.

Nevertheless, we suggest that the methods outlined above are worth pursuing because they represent a possibility of producing "calibrated" long term average ephemeral gully erosion estimates, at least for croplands in the eastern U.S., using existing procedures and databases. The only additional information that the user would need to provide would be the initial channel dimensions and soil properties of the potential ephemeral gully area.

**Table 1 Coefficient estimates for predicting the ratio of $S_i$/S, monthly to annual average "maximum storage," a transform of the CN through equation [1], from RUSLE2 climate file parameters.**

| Effect† | Jan | Feb | Mar | Apr | May | Jun | Jul | Aug | Sep | Oct | Nov | Dec |
|---|---|---|---|---|---|---|---|---|---|---|---|---|
| mon | 0.46 | 0.43 | 0.51 | 0.91 | 0.90 | 1.66 | 2.26 | 3.02 | 1.80 | 1.33 | 0.40 | 0.54 |
| DevTemp*mon | -0.039 | -0.051 | 0.064 | -0.005 | -0.037 | -0.034 | -0.069 | -0.037 | -0.035 | -0.10 | -0.080 | -0.034 |
| DevARrain*mon | 0.000 | -0.001 | -0.004 | -0.001 | -0.004 | -0.005 | -0.007 | -0.007 | -0.010 | -0.002 | -0.000 | -0.000 |
| RTemp*mon | 0.012 | 0.017 | 0.017 | 0.013 | 0.011 | -0.013 | -0.033 | -0.048 | -0.025 | -0.016 | 0.009 | 0.013 |
| ARrain*mon | -0.004 | -0.004 | -0.002 | -0.002 | 0.001 | 0.003 | 0.004 | 0.003 | 0.003 | 0.002 | 0.001 | -0.002 |

† mon is month, RTemp is the average monthly RUSLE2 temperature (°C), ARrain is the average monthly precipitation after adjusting for snowpack changes (mm), DevTemp is the deviation of monthly RUSLE2 average temperature from annual mean temperature, DevARain is the deviation in monthly adjusted RUSLE2 precipitation from the location's average monthly precipitation.

## 5. References


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