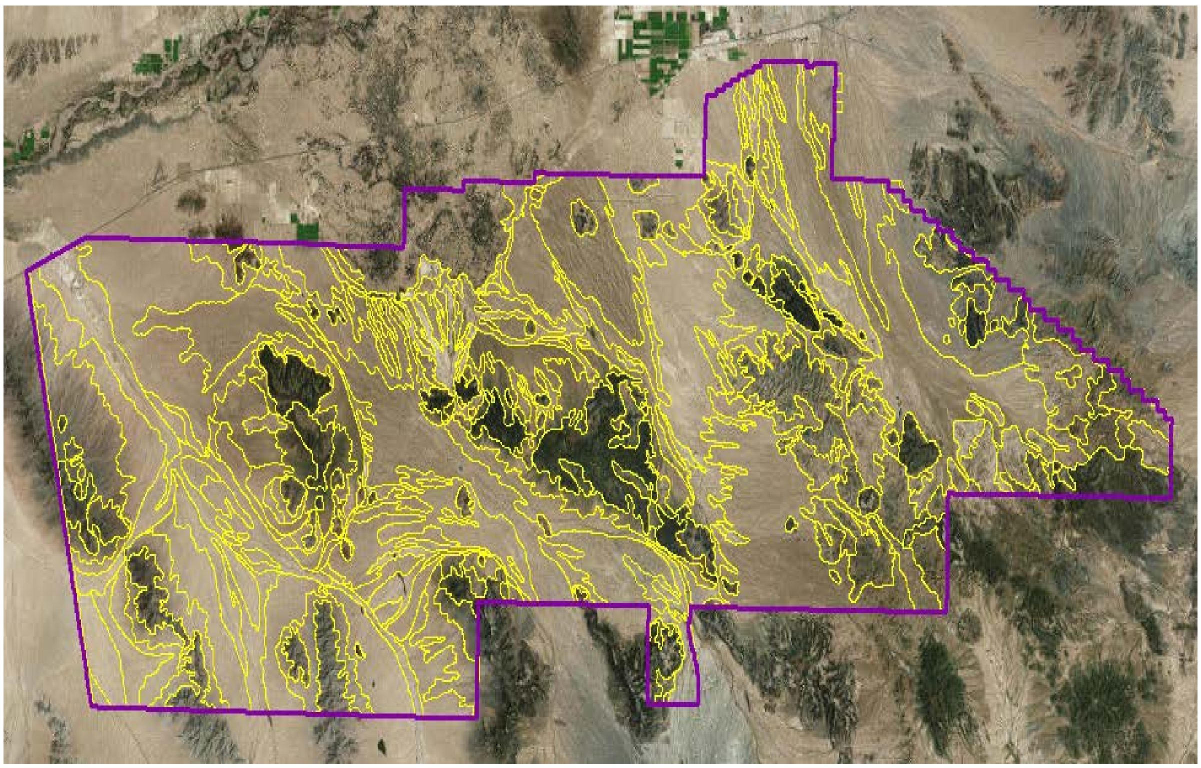
Erosion Mapping of the Barry M. Goldwater Range (BMGR) East using the Revised Universal Soil Loss Equation (RUSLE)



Prepared for the
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1. Introduction

This study focuses on upland erosion at the Barry M. Goldwater Range (BMGR) East located within portions of Maricopa, Pima, and Yuma counties, Arizona. The Revised Universal Soil Loss Equation (RUSLE) is used to estimate the mean annual soil erosion.

Wischmeier and Smith (1965, 1978) used annual data from 10,000 test plots from agricultural areas in the U.S. with a standard 22m flow length. The original Universal Soil Loss Equation has been widely used worldwide to estimate annual soil erosion from hill slopes for sediment yield.

$$A = RKLSCP \tag{1}$$

where A is the average annual soil loss

R is the rainfall erosivity factor

K is the soil erodibility factor

L is the field length factor

S is the field slope factor

C is the cropping management factor

P is the conservation practice factor

The Revised Universal Soil Loss Equation (RUSLE) upgraded the USLE by focusing on better parameter estimation (Renard et al., 1997). In summary, the RUSLE revised soil erodibility factor depending on seasonal weather changes, the slope gradient and length, and a new procedure to calculate the vegetation factor. Both USLE and RUSLE are possible to estimate the average annual soil loss with a simple equation, but there are a number of limitations for both empirical models. For instance, the models are not event-based, so that mean annual soil losses are considered. Also, the models only consider upland erosion in terms of sheet and rill erosion.

It means that the gully erosion and deposition of sediment are not considered in the models. In the case of applications of USLE outside the U.S., the parameters occasionally need adaptation (Julien, 2010). The sedimentation rates in U.S. reservoirs have been computed by Kane and Julien (2007). The RUSLE model has been used extensively around the world by Dr. Julien's research team. For instance it was applied on large watershed in Congo (Goy, 2015), Malaysia (Teh, 2011), Afghanistan (Sahaar, 2013), and South Korea (Kim, 2006; Kang, 2019)

2. Factors for RUSLE

Each factor of the RUSLE is reviewed in this section. Since a farming and cropping land is unusual in the BMGR East, the conservation-practice factor is assumed constant (P factor =1). Additionally, the cropping management factor (C-factor) was compiled by CEMML. The unit conversion factors from U.S. units to SI units are listed in Appendix I.

2.1. R-Factors

The rainfall erosivity factor describes rainstorm properties. Generally, the rainfall erosivity (R-factor) was calculated with Eq 2.

$$R = \sum E \cdot I_{30}\,, \qquad E = \sum e \cdot \Delta P = 916 + 331\, log_{10} I \qquad (2)$$

where R is rainfall erosivity factor (foot-tons▪ inch/ha▪hr▪yr)

I_{30} is the maximum 30-minute rainfall intensity (in/hr)

E is the total amount of storm kinetic energy (foot-tonf/acre)

ΔP is the rainfall amount for each interval (in)

e is the estimated unit kinetic energy of rainfall (foot-tons/ acre▪in)

I is the rainfall intensity (in/hr)

Several approaches are used to estimate R-factor values for areas without data and/or resources required to calculate R. They are summarized as follows four-step process (Renard et al., 1997):

1) R-factor values are calculated by the prescribed method (Wischmeier and Smith, 1978; Renard et al., 1994) for stations with recording rain gages;
2) **A relation is established between the calculated R-values and more readily available types of precipitation data (i.e. monthly or annual totals);**
3) The relation is extrapolated and R-values estimated for stations with the associated precipitation data;
4) Isolines are drawn between stations—R-values for sites between iso-erodent lines are estimated by linear interpolation.

In this project, the relationship between R-value and available types of precipitation data (approach 2) is used for estimating the R-factor.

2.1.1. Data description

There are 172 rain gauging stations (in AZ) and they have monthly precipitation from Oct 2011 to Jun 2018 (Figure 1). To avoid distortion, a year not including at least one monthly precipitation (MP) is discarded. The number of years including all monthly precipitation data for 172 gauging stations is delineated in Figure 2. There are 15 stations including complete MP data from 2012 to 2017, and 48 stations are including complete datasets from 2012 to 2015. Because 17 gauging stations are small to estimate R-factor value for ungauged regions, the 45 results are used to estimate R-factor values. In Figure 3 several parameters are compared at 45 gauging station: (1) mean annual precipitation; (2) averaged monthly precipitation on rainy season (Jul~Sep); and (3) maximum monthly precipitation from 2012~ to 2015 are compared.

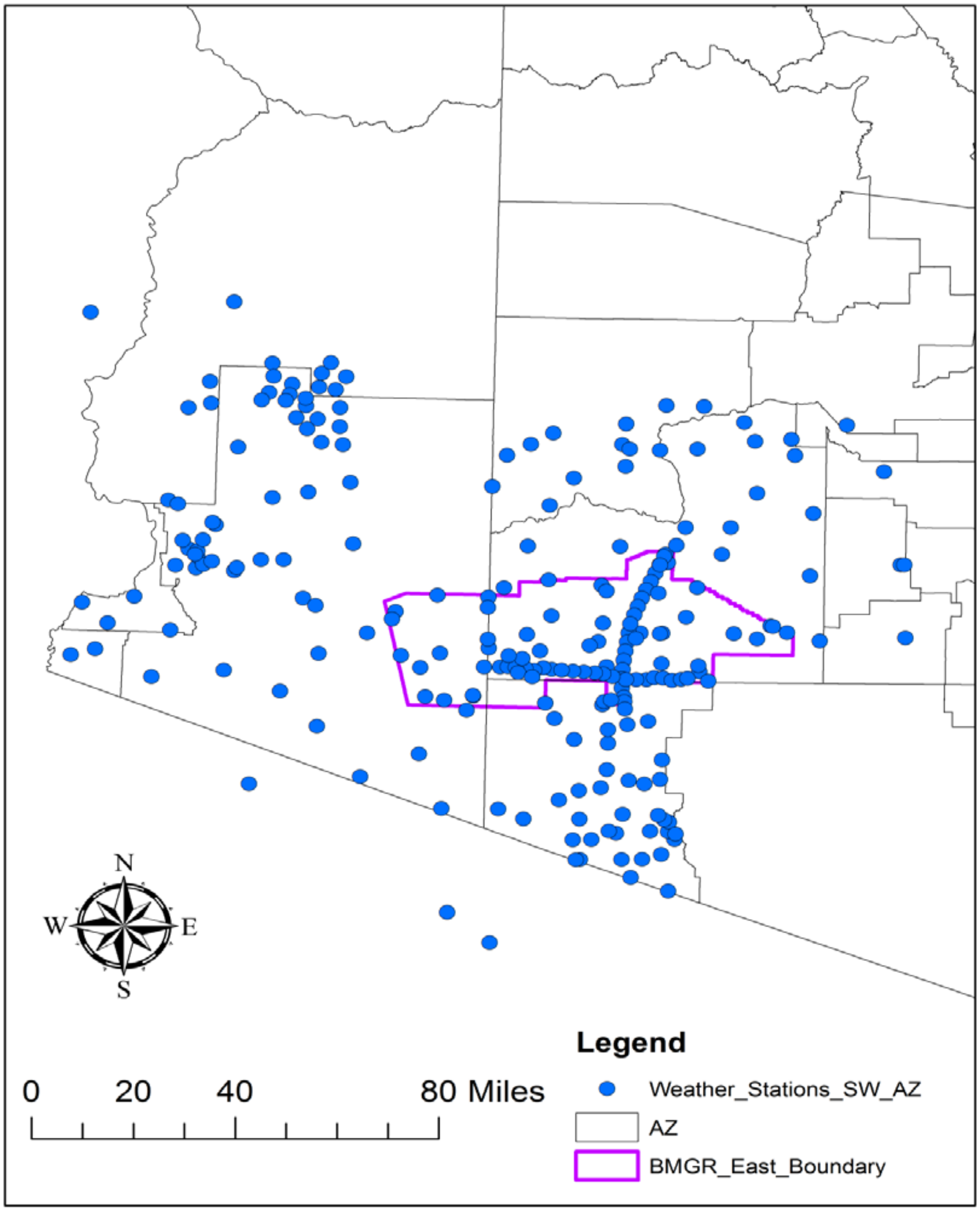


Figure 1. Precipitation data at 172 gauging stations in AZ (near BMGR)

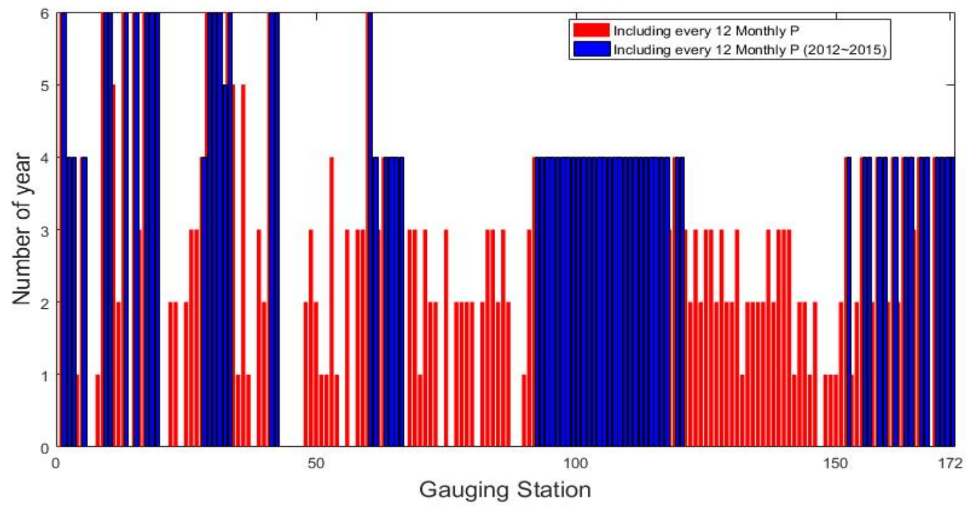


Figure 2. The number of year (full data) for all gauging stations

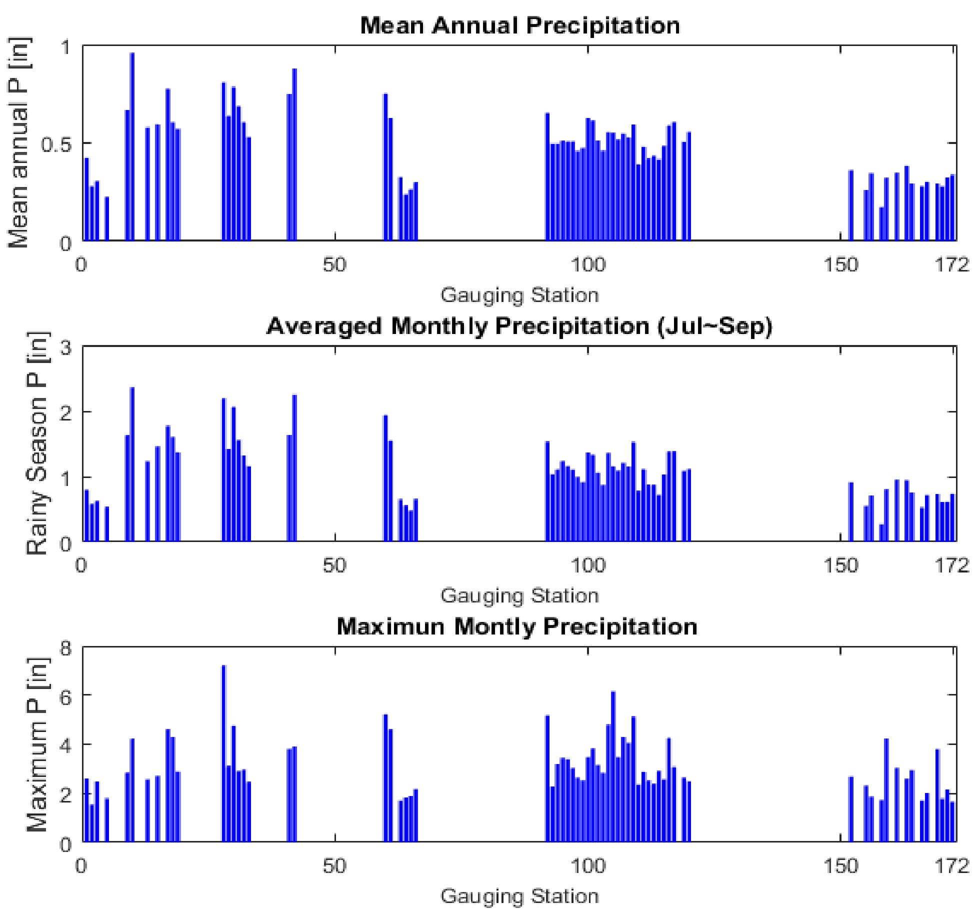


Figure 3. Analyzed precipitation for all gauging stations

2.1.2. Estimating the R-Factor

There are several methods to estimate the R-factor value from monthly or annual precipitation. In this study, 4 different methods are considered and compared to estimate the R-factor value.

a) Modified Fournier Method (after Renard and Freimund)

Fournier (1960) developed an index using monthly and yearly precipitations to estimate rainfall aggressiveness, later research showed that the index was correlated to other climatic variables, which are also contributing factors in the triggering or reactivation of erosive phenomena. The Fournier index (*F*) is calculated as:

$$F = P_{max}^2 / P \quad (3)$$

P_{max} is the monthly average amount of precipitation of the rainiest month (mm) and P is the average annual quantity of precipitation (mm). Arnoldus (1980) suggested the modified original index

$$F_M = \sum_{i=1}^{12} P_i^2 / P \quad (4)$$

P_i is the monthly average amount of precipitation for month *i* (mm) and *P* is the average annual quantity of precipitation (mm). Renard and Freimund (1994) suggested the relationship between the Modified Fournier Index (MFI) and R-factor (MJ mm ha^{-1} h^{-1} yr^{-1}) based on 132 stations for the US.

$$R = 0.07397 F^{1.847} \quad (5a)$$

$$R = 98.77 - 6.081 F + 0.4770 F^2 \quad (5b)$$

It is suggested to use the first equation is used for locations with the Modified Fournier Index less than 55 and second equation is used for locations with the Modified Fournier Index greater than 55. Since the estimated Modified Fournier Index (MFI) is higher than 55, the second equation is used to calculate the R-factor values at 45 stations. Cooper (2011)

The relationship between rainfall erosivity (R, hundred ft▪tonf▪in▪acre^{-1}▪h^{-1}▪yr^{-1}) and mean annual precipitation (P, in) in Western United States was suggested

$$R = 9.17P^{0.2} \tag{6}$$

It showed extreme low R^2 value (0.0176).

b) Renard and Freimund (1994)

Renard and Freimund also suggested the relationship between R-factor (MJ mm ha^{-1} h^{-1} yr^{-1}) and mean annual precipitation (mm) from 132 mean annual precipitation values (mm) in the US.

$$R = 0.04830P^{1.610} \tag{7a}$$

$$R = 587.8 - 1.219P + 0.004105P^2 \tag{7b}$$

It is suggested to use the first equation be used for location with the mean annual precipitation is less than 850 mm and vice versa.

c) Teh (2011)

The relationship between the R-factor (MJ mm ha^{-1} h^{-1} yr^{-1}) and the mean annual precipitation (mm) from Bols (1978) was applied

$$R = \frac{2.5P^2}{100(0.073P + 0.73)} \tag{8}$$

The R-factor values (MJ mm ha^{-1} h^{-1} yr^{-1}) from the above methods are compared in Figure 4. The R-factor in U.S. customary units (hundred ft▪tonf▪in▪acre^{-1}▪h^{-1}▪yr^{-1}) could be change as SI units (MJ mm ha^{-1} h^{-1} yr^{-1}) when multiplied by 17.02. Due to the extreme low precipitation at the BMGR, some relationships shows extreme low result of R-factor value. Other references suggest R-factor values for BMGR from 40 to 800 MJ mm ha^{-1} h^{-1} yr^{-1} (Figure 5).

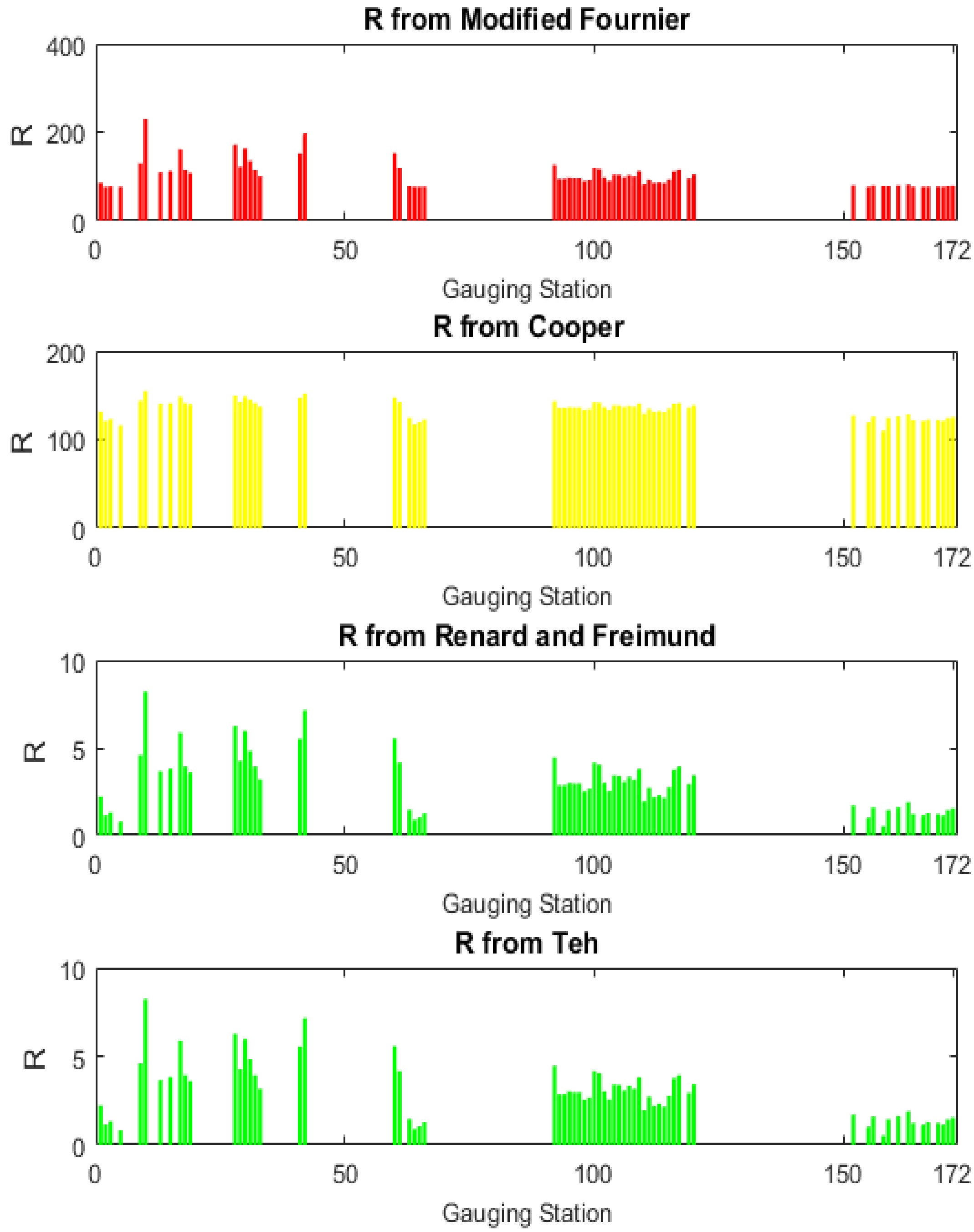
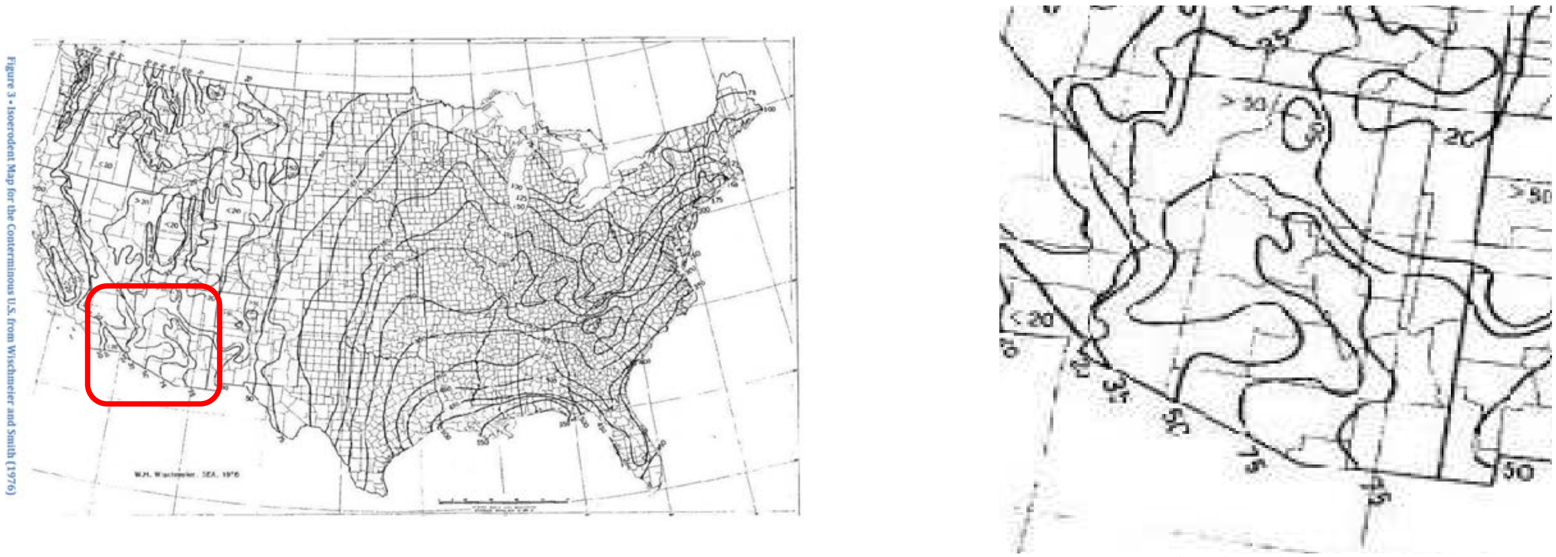
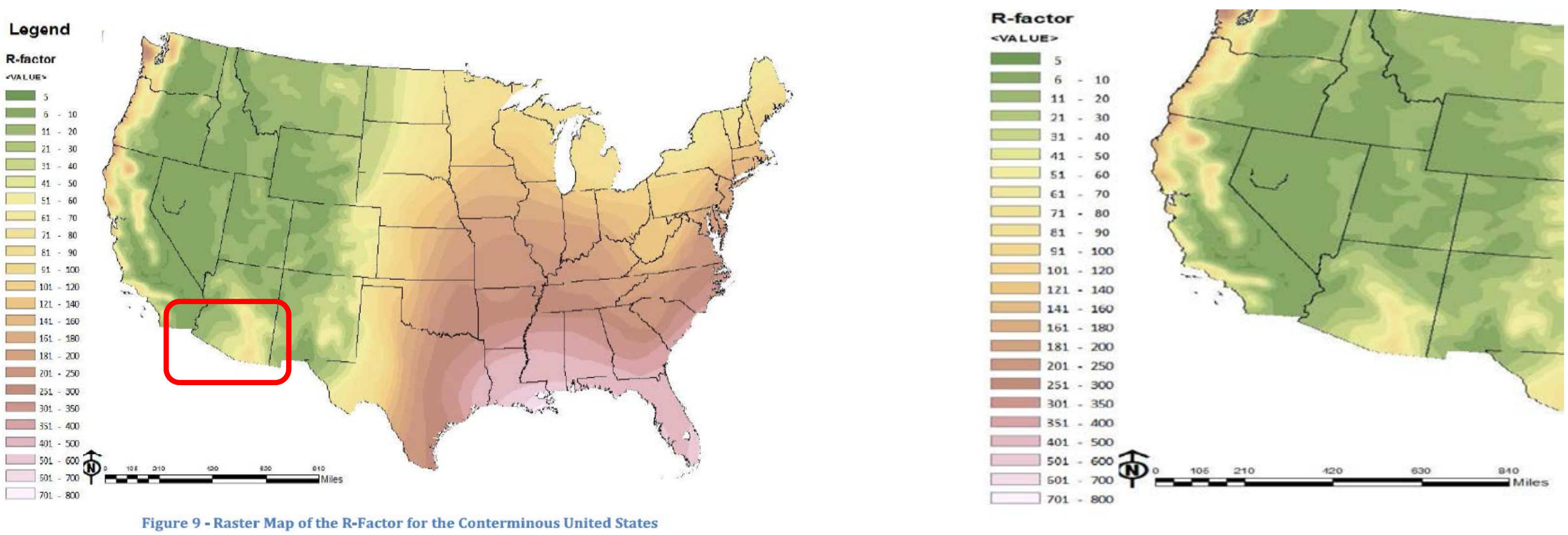


Figure 4. Estimated R-factor for each gauging stations (unit: MJ mm ha^{-1} h^{-1} yr^{-1})



(a) Wischmeier and Smith 1976 (unit: hundred ft▪tonf▪in▪acre^{-1}▪h^{-1}▪yr^{-1})



(b) Cooper 2011 (unit: hundred ft▪tonf▪in▪acre^{-1}▪h^{-1}▪yr^{-1})

Figure 5. R-factor value from other references

The relationships from two methods: (1) Modified Fournier; and (2) Renard and Freimund provide the best results. Finally, the original kriging is applied to the 48 point R-factor values to estimate R-factor for the entire region (Figure 6 and Figure 7).

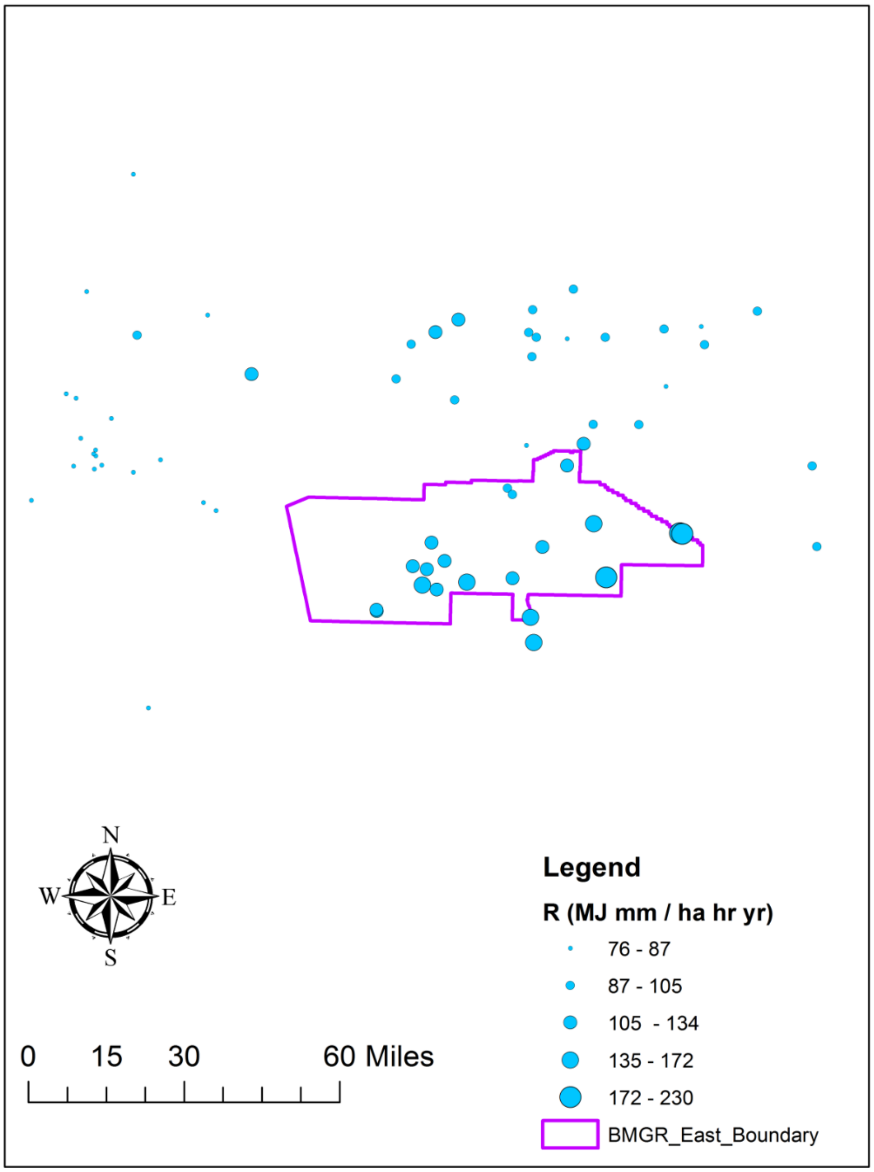


Figure 6. Estimated R-factors for 48 stations

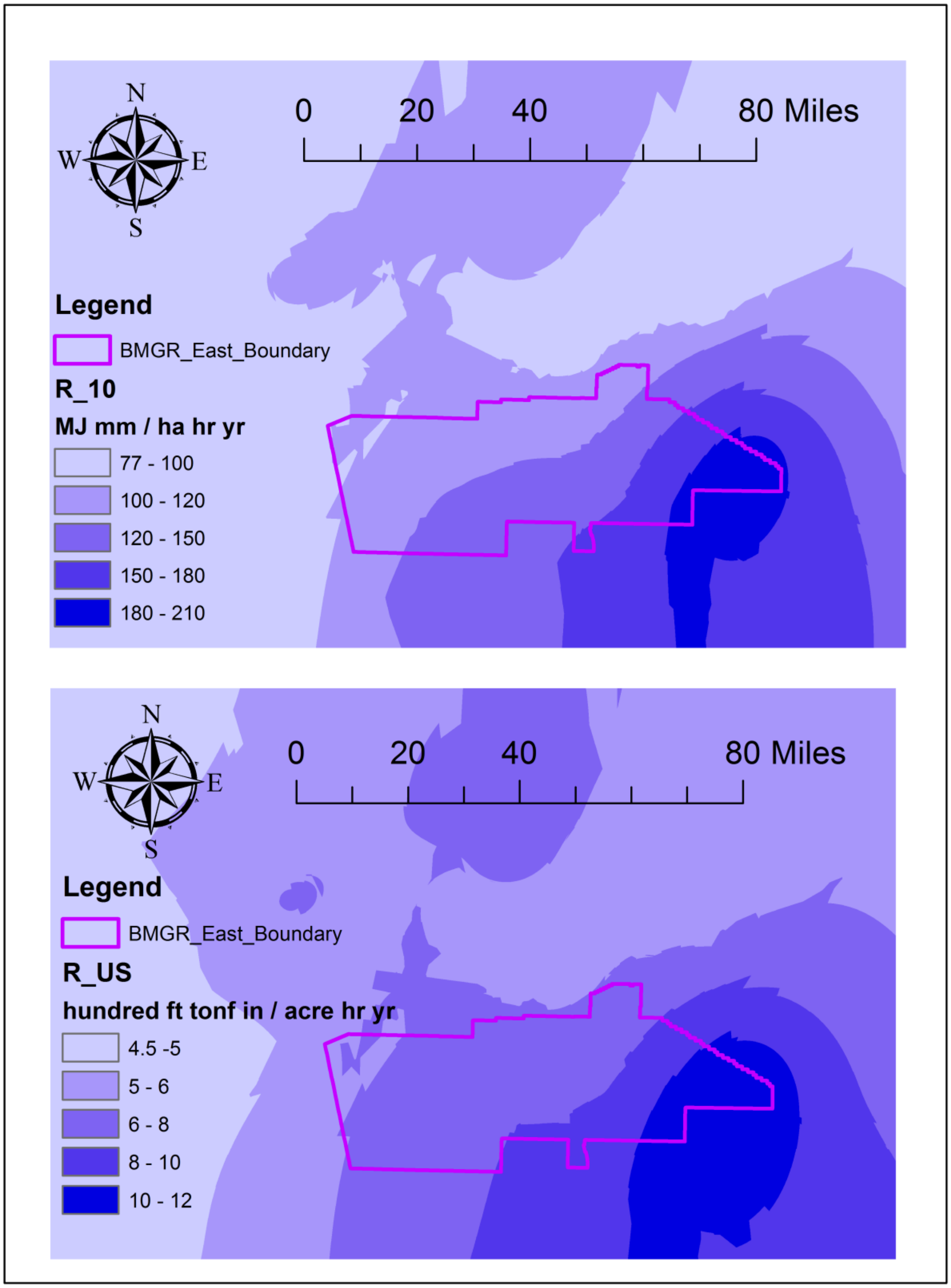


Figure 7. Kriging Result of R-factor

2.2. Length and Slope (LS) Factor

The "L-factor" is the slope length factor. It is the ratio of soil loss from the field slope length to that of a standard plot length of 72.6ft (= 22.13m) (Wischmeier and Smith, 1978).

$$L = (\frac{\lambda}{22.13})^m \tag{9}$$

where λ slope length (m)

m empirical coefficient (dimensionless).

The L factor is defined in Eq 9, and the empirical coefficient (m) could range from 0 to 0.975. Wischmeier and Smith (1978) recommended to use 0.2 < m < 0.5, and McCool (1989) suggested m = 0.5 from the studies with hundred data points. In this study, m = 0.5 was used for a slope length exponent. The slope steepness factor(S) is the ratio of soil loss from the field slope gradient to that from a 9% slope under otherwise identical condition (Wischmeier and Smith, 1978).

$$S = \left[\frac{\sin(\theta)}{0.0896}\right]^n \tag{10}$$

where θ angle of the slope (^{O})

n empirical coefficient (dimensionless).

Alternatively, the slope steepness S is calculated as follows:

$$S = \begin{cases} 10.8 \times sin(\theta) + 0.03, & \theta < 9\% \\ 16.9 \times sin(\theta) - 0.5, & \theta \geq 9\% \end{cases} \tag{11}$$

Most of existing methods for calculating L and S factors are based on the following equations (McCool et al., 1989).

$$LS = L \times S \tag{12}$$

Both factors are calculated from the slope length (λ) and the slope angle (θ).The slope length is defined as the distance from the point of origin of overland flow to: (a) the point where the slope gradient decreases enough that deposition begins; or (b) the point where runoff enters a well-defined channel that may be part of a drainage network or a constructed channel (Wischmeier and Smith, 1978). Field measurements are the best to estimate the slope length, however it is not practical. GIS-based method have been used to estimate slope length and a common method is using *flow accumulation (flowacc)* based on the DEM. By multiplying the DEM resolution, the distance is estimated. However, this method is not reasonable because the flow accumulation is added in every convergence (Mediavialla et al., 2017). In this study, the CALSITE model (Bolton et al., 1995) is applied to estimate the slope length. This model considers flow accumulation area (cells) as in a circle. And then, the drop of water has travelled in an equivalent radius

$$\lambda = \sqrt{flowacc \times (resolution)^2/\pi} \quad (13)$$

The value of 0.5 was used for a lower threshold value of flow accumulation (at ridges or high points) and it represents the erosion happening in half of this cell. It is based on the assumption that the slope length estimations are measured from the center of a cell. Taking this into account, the equation 13 changes into

$$\lambda = \sqrt{(flowacc + 0.5) \times (resolution)^2/\pi} \quad (14)$$

Renard (1997) suggested that runoff erosion is usually concentrated in lengths shorter than 400ft (121.92m), and sometime it could extend to 1,000ft (304.8m). At a 10m DEM resolution, the flow accumulation higher than 2,922 will have a fixed slope length (=305m).

$$L = \begin{cases} (\lambda/22.13)^{0.5}, & flowacc < 2{,}922 \\ (305/22.13)^{0.5}, & flowacc \geq 2{,}922 \end{cases} \quad (15)$$

Finally, L and S factors are multiplied and the result is shown in Figure 8. The detailed GIS algorithm is delineated in Appendix II.

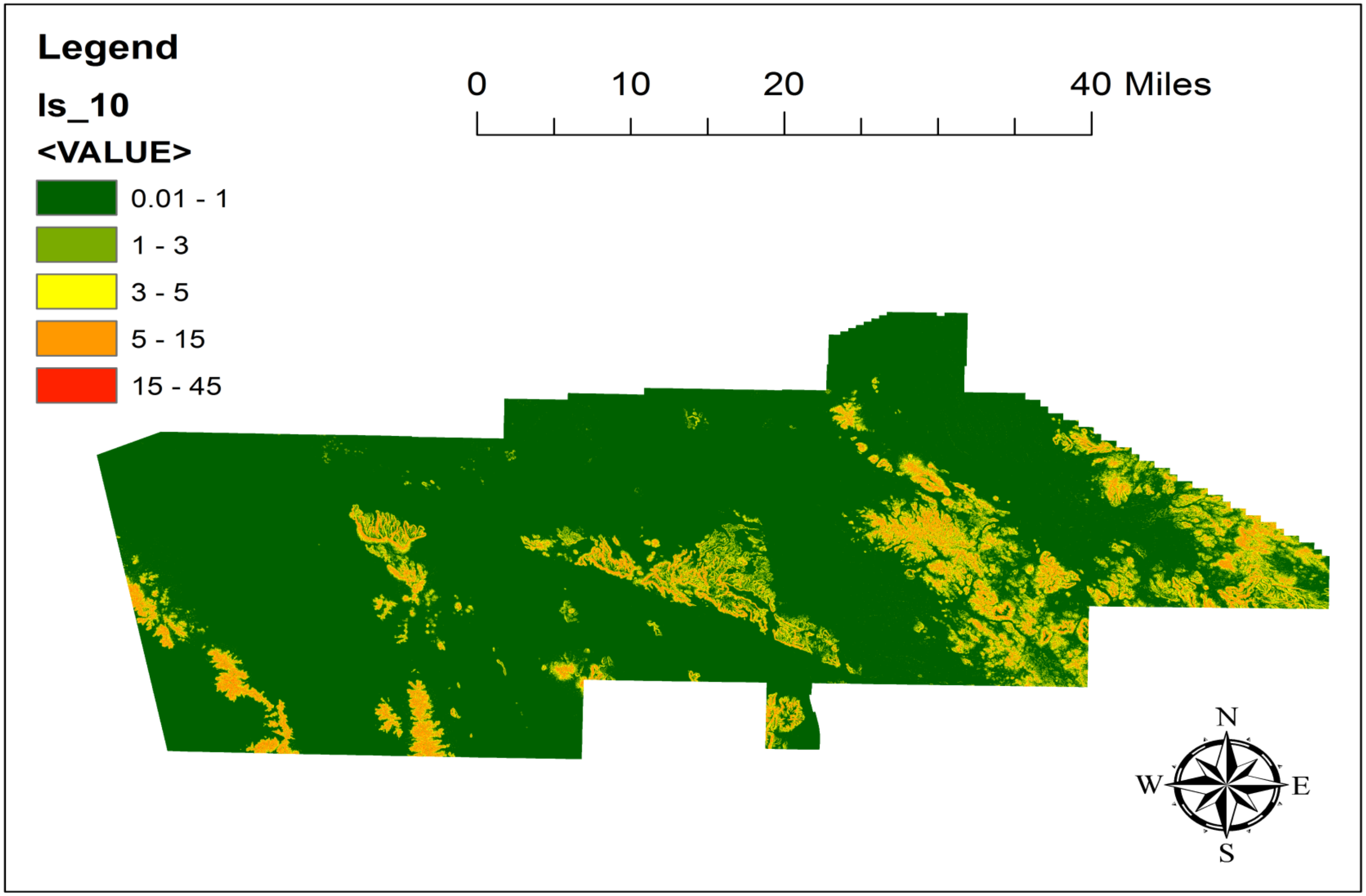


Figure 8. LS factor for BMGR East

2.3. Cropping Management (C) and Soil Erodibility (K) Factor

The cropping management factor (C-factor) has a reference value C = 1 for freshly tilled soils on farmlands. The C-factor values were estimated by CEMML as shown in Figure 9 - and these values are relatively low as shown in Figure 9.

The soil-erodibility factor (K factor) describes the inherent erodibility of the soils. The provided data for soil classification (Soil_class.shp), including 23 soil types at BMGR East. The Web Soil Survey (WSS) from United States Department of Agriculture (USDA) provided the K-factor value for each soil classification (Table 1), and the algorithm is defined in Appendix III. The K-factor value for three kinds of soils is not provided. Therefore, we used information from other reference (Miguel et al., 2016). The map for the K factor is shown in Figure 10.

Map unit symbol	Map unit name	K-factor
360	Carrizo-Riverwash complex, 0 to 2 percent slopes	0.02
345	Casa Grande-Kamato-Argigypsids complex, 0 to 2 percent slopes	0.28
350	Casa Grande complex, 0 to 2 percent slopes	0.24
335	Cheroni-Cooledge-Hyder complex, 2 to 15 percent slopes	0.1
20	Coolidge, Denure, and Rillito soils, 0 to 3 percent slopes	0.24
30	Denure-Pahaka complex, 1 to 3 percent slopes	0.24
325	Gilman silt loam	0.43
330	Glenbar silt loam	0.43
40	Growler-Mohall-Tucson complex, 0 to 3 percent slopes	0.28
60	Gunsight-Hyder-Riverwash complex, 1 to 45 percent slopes	0.1
50	Gunsight-Pinamt-Carrizo complex, 1 to 5 percent slopes	0.1
315	Gunsight, Momoli, and Chuckawalla soils, 1 to 8 percent slopes	0.24
300	Guvo-Rock outcrop complex, stony, 15 to 60 percent slopes	0.1
70	Hyder-Guvo-Rock outcrop complex, 15 to 65 percent slopes	0.05
355	Lajitas-Bosa-Rock outcrop complex, 15 to 50 percent slopes	0.05
80	Laposa-Schenco-Rock outcrop complex, 10 to 40 percent slopes	0.1
90	Lomitas-Rock outcrop-Quilotosa complex, 15 to 65 percent slopes	0.05
310	Mohall-Pahaka-Valencia complex, 0 to 3 percent slopes	0.28
100	Rillito-Growler-Why complex, 1 to 5 percent slopes	0.28
110	Rillito-Gunsight-Carrizo complex, 1 to 5 percent slopes	0.28
340	Supersition, Rositas, and Tucson soils, 0 to 8 percent slopes	0.17
320	Valencia-Mohall complex, occasionally flooded, 0 to 1 percent slopes	0.28

Table 1. K-factor value for missing soil classification

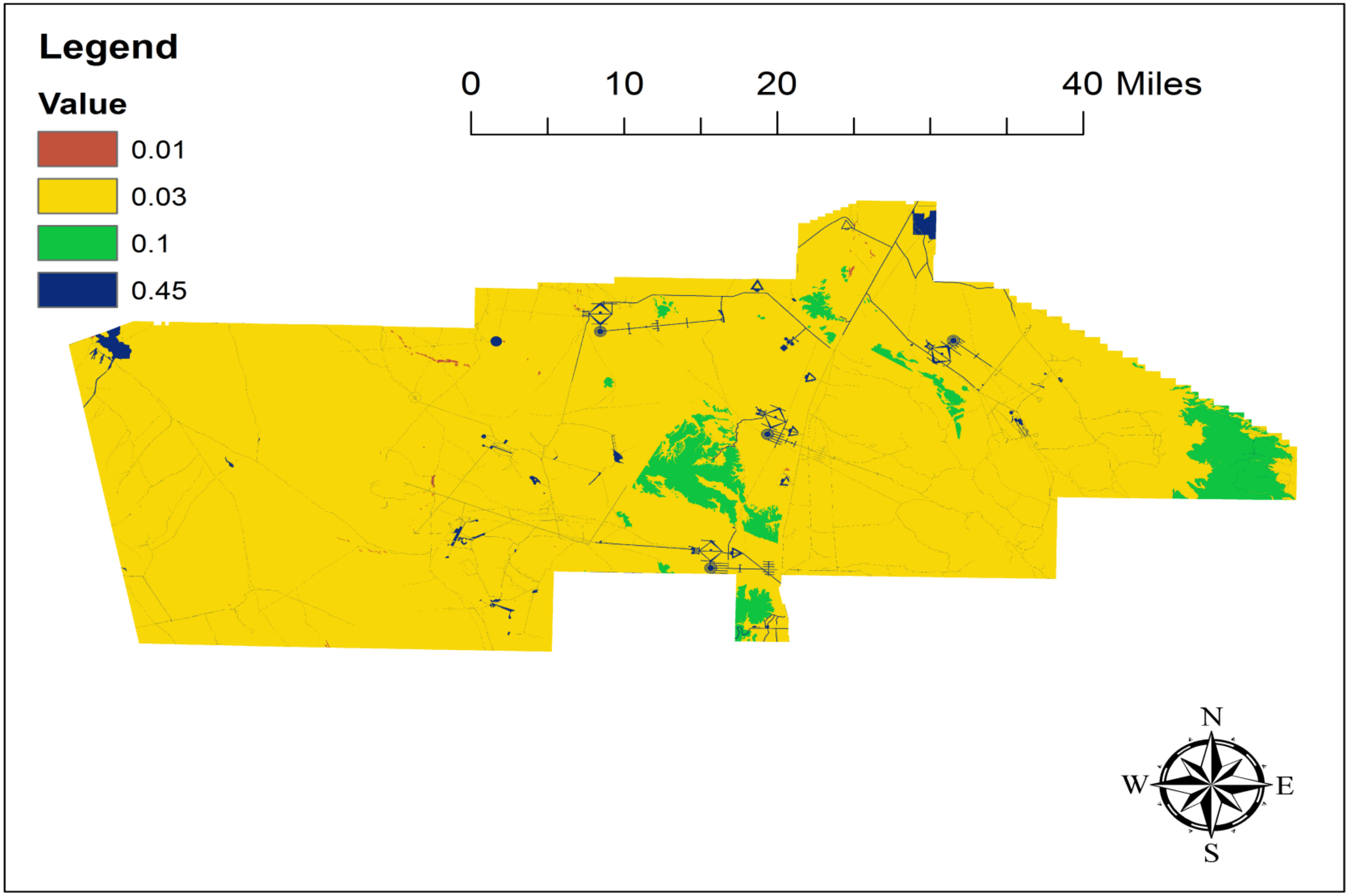


Figure 9. C-factor result for BMGR East

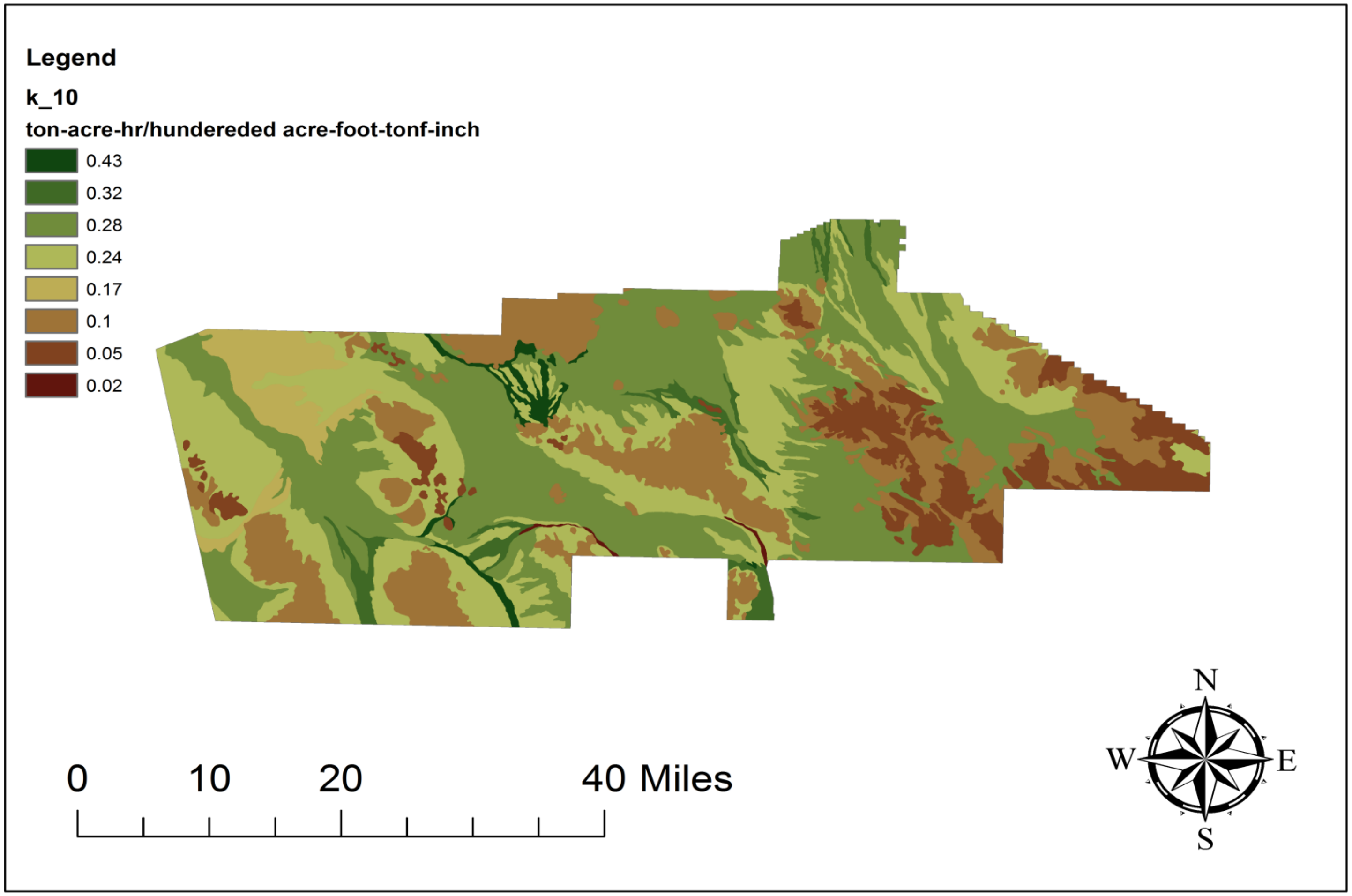


Figure 10. K-factor result for BMGR East

3. Erosion Mapping Result for BMGR East

The mean annual soil loss is calculated with Eq. 1 from the estimated factors (R, K, L, S, and C, assuming P = 1). Because the K factor was estimated in U.S customary units, the results are multiplied by 0.1317 for soil loss in metric tons per hectare per year (SI units). Final the mean annual soil erosion map is shown in Figure 11. Most regions within the BMGR East have low soil loss rates (< 0.5 tons/ha▪yr). However, some particular regions are expected to (mountains and unpaved roads on steep slope) have high soil loss rate (Figure 10). The erosion map for the BMGR East identifies a few vulnerable areas (up to 25 tons/ha▪yr) located in the mountains and around unpaved roads on steep slopes (Figure 12 and 13). A field investigation of these areas is suggested.

4. Conclusion

This research focused on demonstrating erosion mapping for the BMGR East using RUSLE. The averaged soil loss for BMGR East is relatively low (about 0.07 metric tons/ha▪yr on average) due to arid climatic conditions. These values (about 7 Mg/km^2▪yr) are low in comparison with soil erosion rates elsewhere around the world. The slope length steepness factor (LS) and the cropping-management factor (C) are the dominant components of soil erosion at BMGR East. A few vulnerable areas to soil erosion were identified on steep mountain slopes and around steeper unpaved roads. The erosion rates for roads in steep terrain could be as high as 25 metric tons per hectare per year. The remotely sensed images also matched the areas vulnerable to anthropogenic and natural soil erosion.

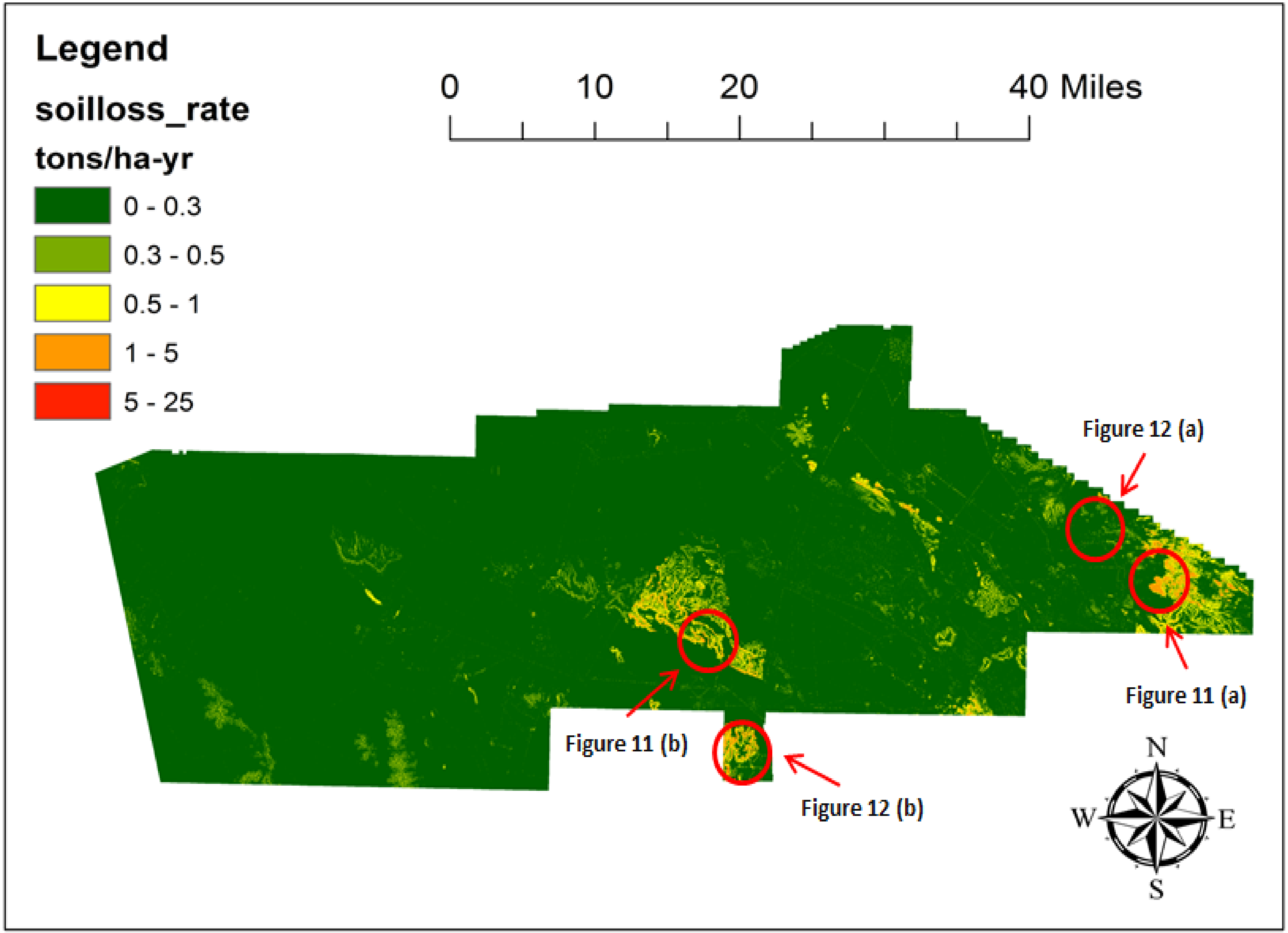
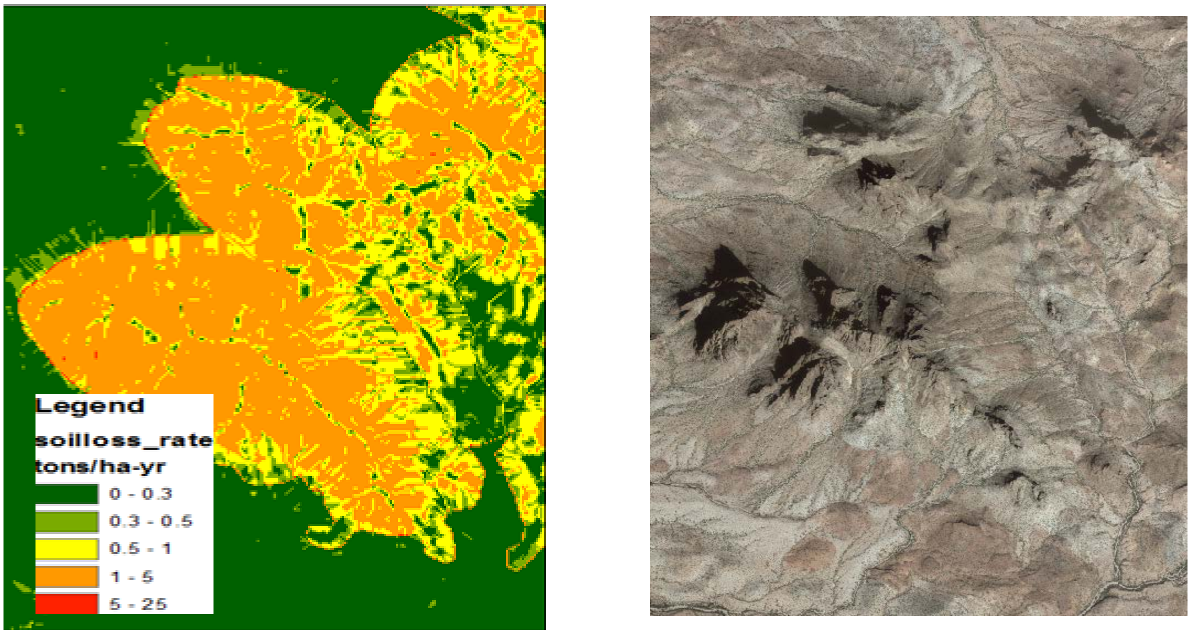
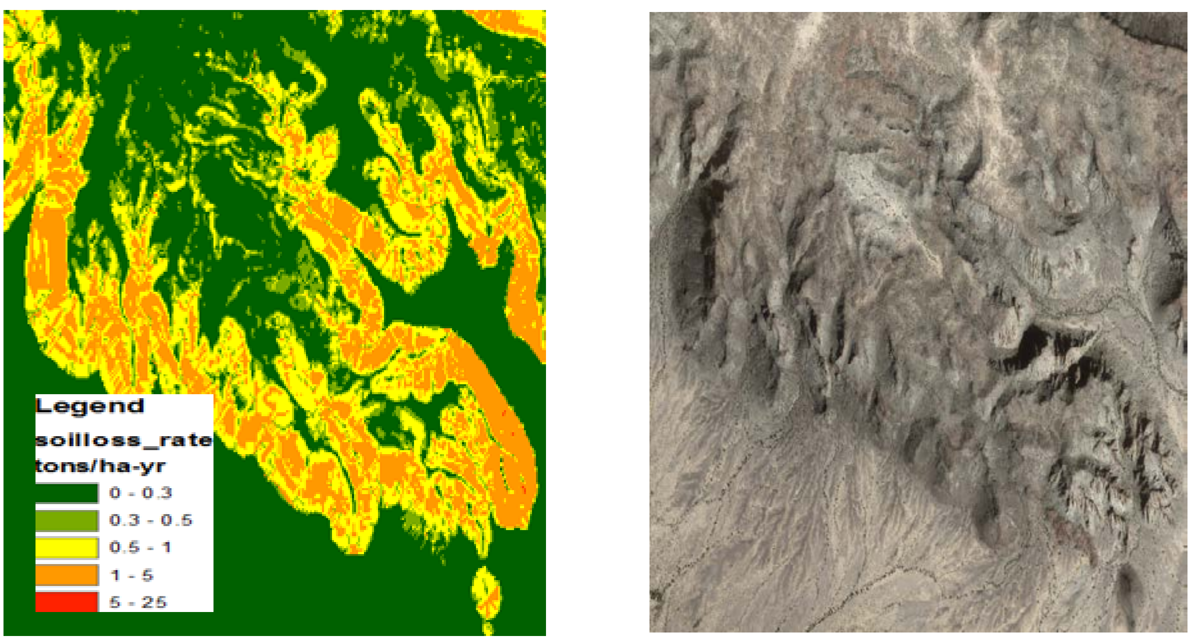


Figure 11. Erosion mapping for BMGR East



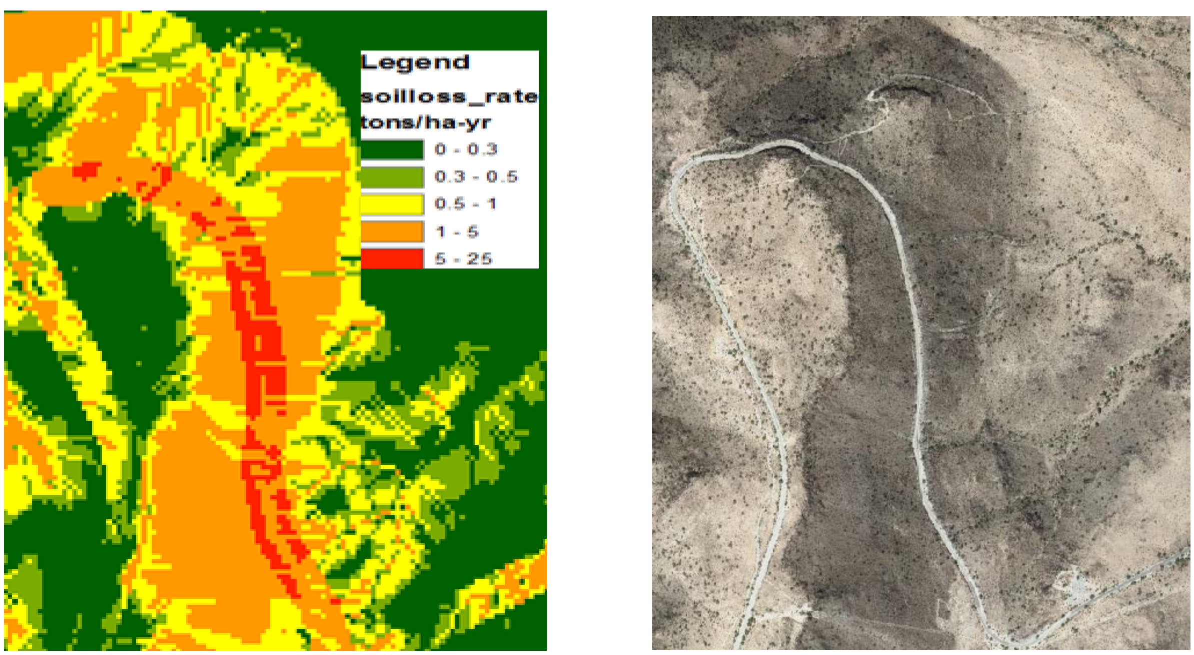
(a)



(b)

Figure 12. Erosion maps and LIDAR images for high soil loss rate in mountains

(a)



(b)

Figure 13. Erosion maps and LIDAR images for high soil loss rate on unpaved roads

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APPENDICES

I. Unit Conversion (Foster et al., 1981)

Table 2. Conversion factors for universal soil loss equation (USLE) factors.

To Convert From:	U.S. Customary Units	Multiply By:	To Obtain:	SI Units
Rainfall intensity, i or I	inch / hour	25.4	millimeter / hour	mm* / h
Rainfall energy per unit of rainfall, e	foot-tonf / acre-inch	2.638×10^{-4}	megajoule / hectare•millimeter	MJ† / ha•mm
Storm energy, E	foot-tonf / acre	0.006701	megajoule / hectare	MJ‡ / ha
Storm erosivity, EI	foot-tonf•inch / acre•hour	0.1702	megajoule•millimeter / hectare•hour	MJ•mm / ha•h
Storm erosivity, EI	hundreds of foot-tonf•inch§ / acre•hour	17.02	megajoule•millimeter / hectare•hour	MJ•mm / ha•h
Annual erosivity, R‖	hundreds of foot-tonf•inch / acre•hour•year	17.02	megajoule•millimeter / hectare•hour•year	MJ•mm / ha•h•y
Soil erodibility, K#	ton•acre•hour / hundreds of acre•foot-tonf•inch	0.1317	metric ton•hectare•hour / hectare•megajoule•millimeter	t•ha•h / ha•MJ•mm
Soil loss, A	ton / acre	2.242	metric ton / hectare	t / ha
Soil loss, A	ton / acre	0.2242	kilogram / meter²	kg / m²

*Hour and year are written in U.S. customary units as hr and yr and in SI units as h and y. The difference is helpful for distinguishing between U.S. customary and SI units.

†The prefix mega (M) has a multiplication factor of 1×10^6.

‡To convert ft-tonf to megajoule, multiply by 2.712×10^{-3}. To convert acre to hectare, multiply by 0.4071.

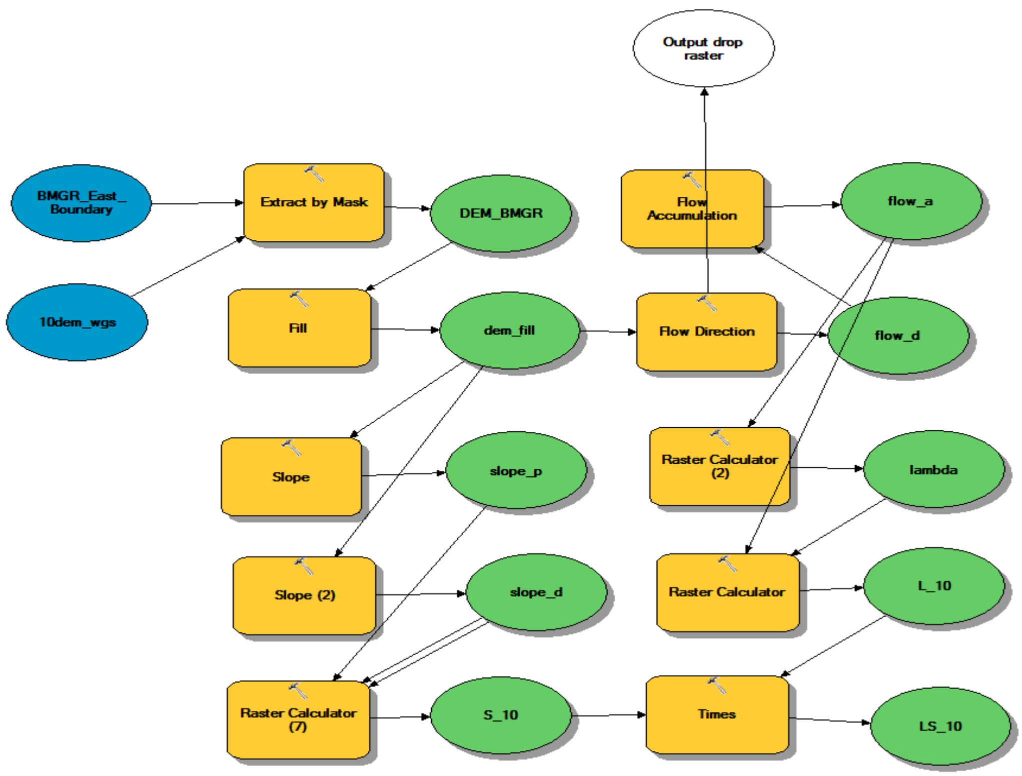
§This notation, "hundreds of," means numerical values should be multiplied by 100 to obtain true numerical values in given units. For example, R = 125 (hundreds of ft-ton•in/acre•hr) = 12,500 ft-tonf•in/acre•hr. The converse is true for "hundreds of" in the denominator of a fraction.

‖Erosivity, EI or R, can be converted from a value in U.S. customary units to a value in units of Newton/hour (N/h) by multiplying by 1.702.

#Soil erodibility, K, can be converted from a value in U.S. customary units to a value in units of metric ton•hectare/Newton•hour (t•h/ha•N) by multiplying by 1.317.

II. LS factor

From 10m dem (from USGS), various parameters for LS factor (slope in degree and percent, flow direction, flow accumulation) are estimated. The L and S factors are calculated with equation in Chapter 2.



Detail equation in the raster calculator

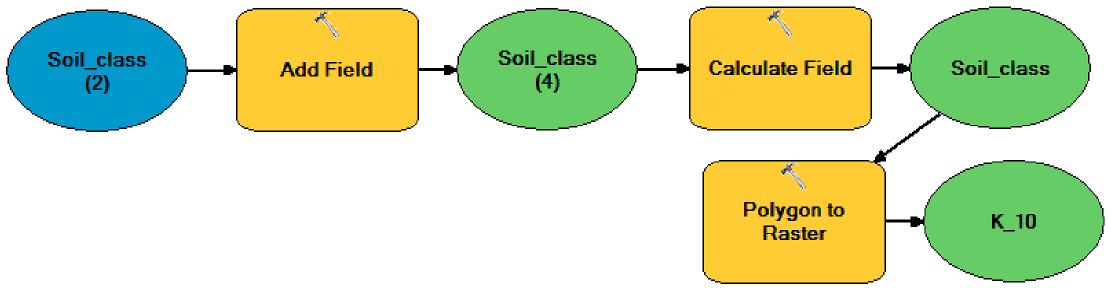
“lambda” = Power(("%flow_a%"+0.5)*100/3.14,0.5)

“S_10” = Con("%slope_p%"<9,10.8*Sin("%slope_d%"/57.296)+0.03,16.8*
Sin("%slope_d%"/57.296)-0.5)

“L_10” = Con("%flow_a%">= 2922,Power(305/22.13,0.5),
Power("%lambda%"/22.13,0.5))

III. K factor

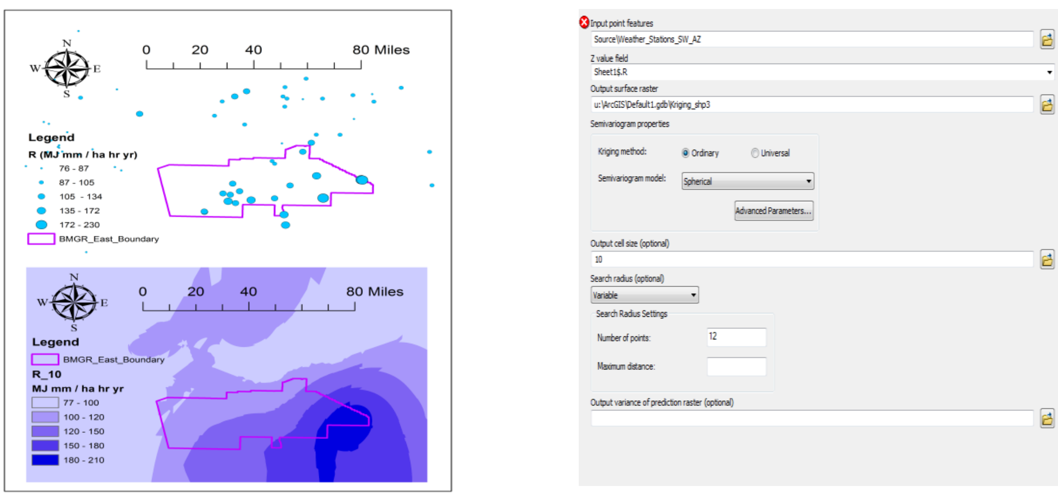
The provided data “Soil Class” includes the information about soil classification. The K factor value for each soil classification is assigned by below process.



GIS Process for RUSLE

1. R-Factor

The detail process of estimating R-factor [point value (R.xlsx)] is in the final report. The estimated R-factor from the Modified Fournier Index (MFI) is assigned to the plotted gauging stations (Weather_Stations_SW_AZ) by using join and related function (Figure A1 a). The kriging is applied to 48 point values and detail is in Figure A1 b. In the process, the point R-factor value is used as Z value field and cell size is set as 10m. Also, the ordinary method is applied to estimate R-factor value at ungauged region Figure A1 a.



(a) (b)

Figure A1. The process of ordinary kriging for R-factor

2. K-Factor

The provided data for soil classification (SoilsurveyArea_A.shp) is perfectly matched with the soil classification data from the United States Department of Agriculture (USDA).

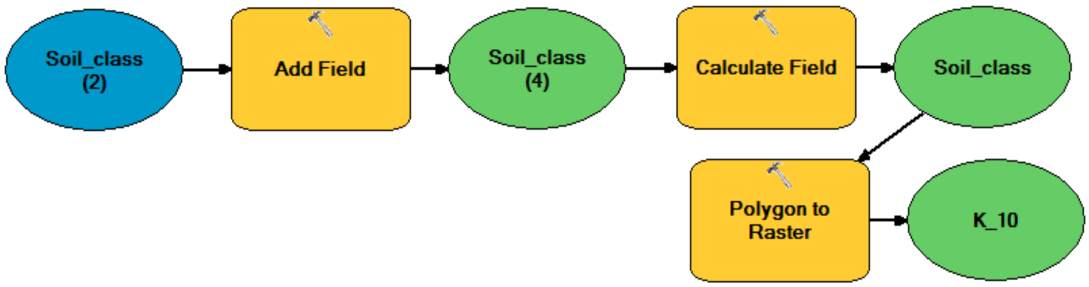
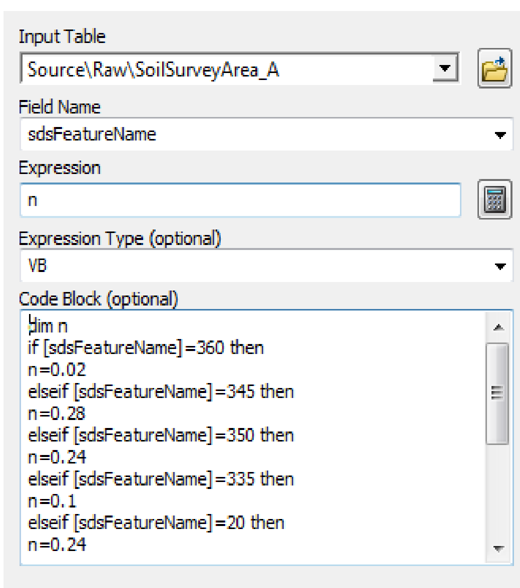


Figure A2. Process for K-factor

First, the attribute table is added to shape file and the K-factor value for each soil based on references is assigned by using calculate field function (Figure A3). Finally, raster for K-factor is created at 10m resolution.




```
dim n
if [sdsFeatureName]=360 then
n=0.02
elseif [sdsFeatureName]=345 then
n=0.28
elseif [sdsFeatureName]=350 then
n=0.24
elseif [sdsFeatureName]=335 then
n=0.1
elseif [sdsFeatureName]=20 then
n=0.24
.
.
.
elseif [sdsFeatureName]=340 then
n=0.17
else [sdsFeatureName]=320 then
n=0.28
end if
```

(a) (b)

Figure A3. The process of assigning K-factor value for each soil

3. L and S Factors

The DEM at 10m resolution is generated from the DEM from USGS and BMGR boundary.

First, the fill function should be conducted to remove small imperfections in the data. And then (1) Calculate Flow Direction (flow_d) from clipped Watershed DEM layer using Flow Direction tool, (2) Calculate Flow Accumulation (flow_a) with Flow Accumulation tool using flow direction data as the input raster, (3) Calculate slope of watershed in degrees (slope_d) and percent (slope_p) using Slope tool using clipped watershed DEM as the input layer.

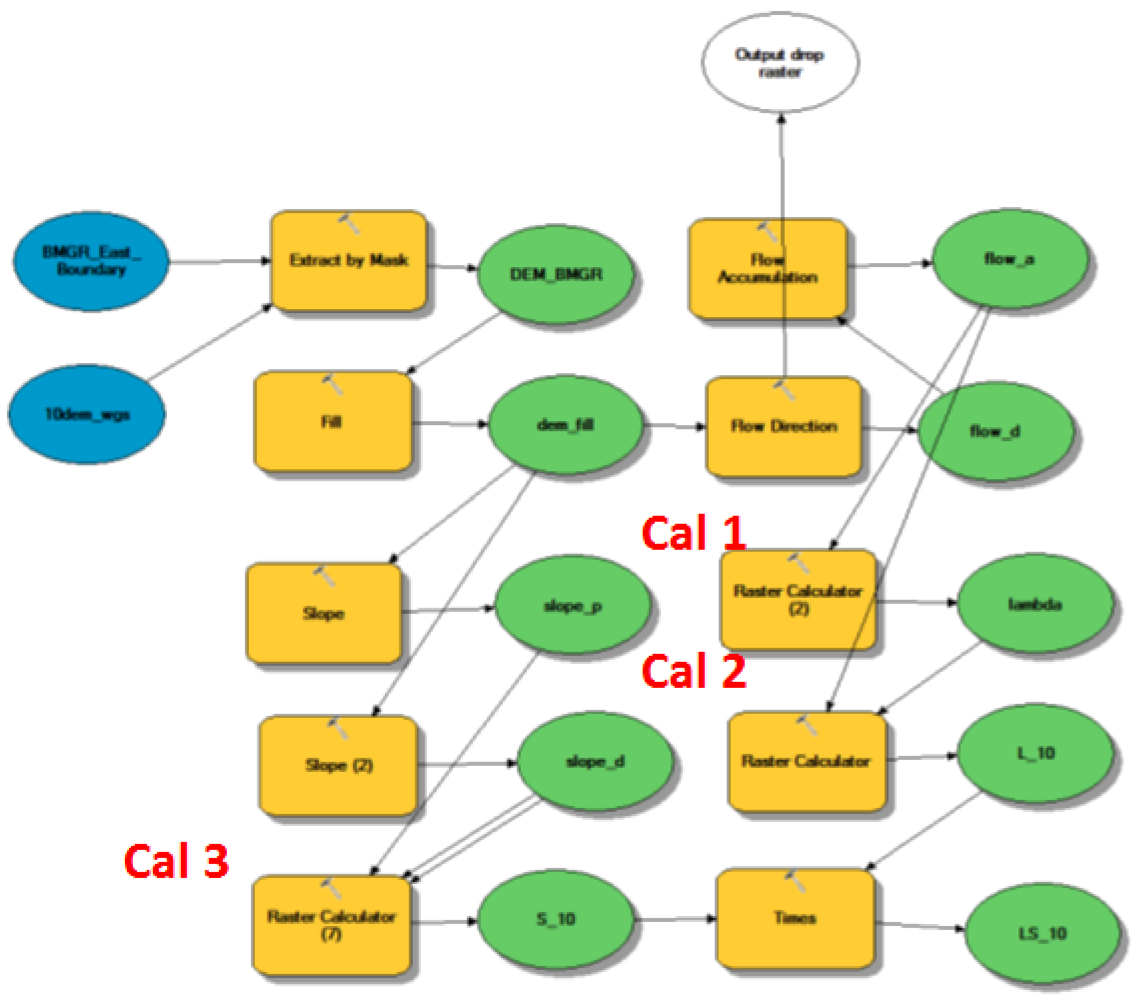


Figure A4. The process of estimating LS-factor

For each calculation, detail equation is below. Lambda is calculated to estimate L factor (Cal 1).

“lambda” = Power(("%flow_a%"+0.5)*100/3.14,0.5)

And then, the L factor is calculated (Cal 2).

“L_10” = Con("%flow_a%">= 2922,Power(305/22.13,0.5), Power("%lambda%"/22.13,0.5))

The S factor is estimated (Cal 3).

“S_10” = Con("%slope_p%"<9,10.8*Sin("%slope_d%"/57.296)+0.03,16.8*
Sin("%slope_d%"/57.296)-0.5)

In this equation, the degree of slope is changed as radian by dividing 57.296.

4. Annual Soil Loss (A)

Final annual soil loss is calculated by multiplying all estimated factors (Figure A5).

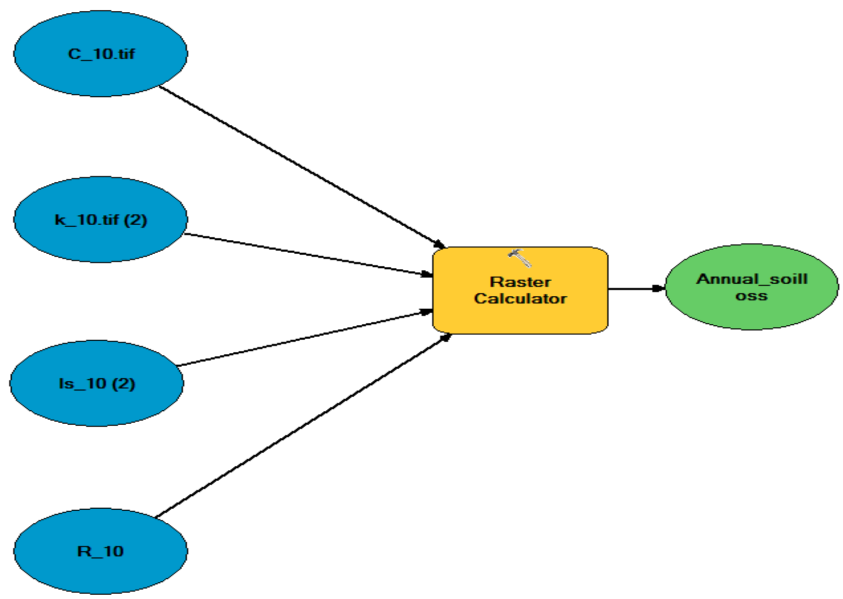


Figure A5. The process of estimating annual soil loss

The raster calculate function is used and the equation is

"%C_10.tif%" * "%k_10.tif (2)%" * "%ls_10 (2)%" * "%R_10%" * 0.1317