Rangeland Hydrology and Erosion Model:

Tutorial Guide

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Rangeland Hydrology and Erosion Model Tutorial Guide: Desert Southwest Grassland

1 Introduction

Soil erosion is a natural process and the erosion potential of a site is the result of complex interactions among soil, vegetation, topographic position, land use and management, and climate. Soil erosion occurs when climatic processes (wind, rainfall, and runoff) exceed the soils inherent resistance to these forces. Splash, sheet, and concentrated flow (i.e. rill) erosion are important erosion processes to measure and predict because they are the dominant types of soil erosion occurring on rangelands.

A new physically based model has been developed by the Agricultural Research Service (ARS) and Natural Resources Conservation Service (NRCS) NRCS for assessing soil loss rates on rangelands that specifically assesses the risk of soil loss at national, regional, and local scales. The Rangeland Hydrology and Erosion Model (RHEM) was developed exclusively from rangeland data from across the western United States (Figure 1). Measured field data from 49 Ecological Sites in 15 states addressing all major ecological regions was used to develop the RHEM erosion equations.

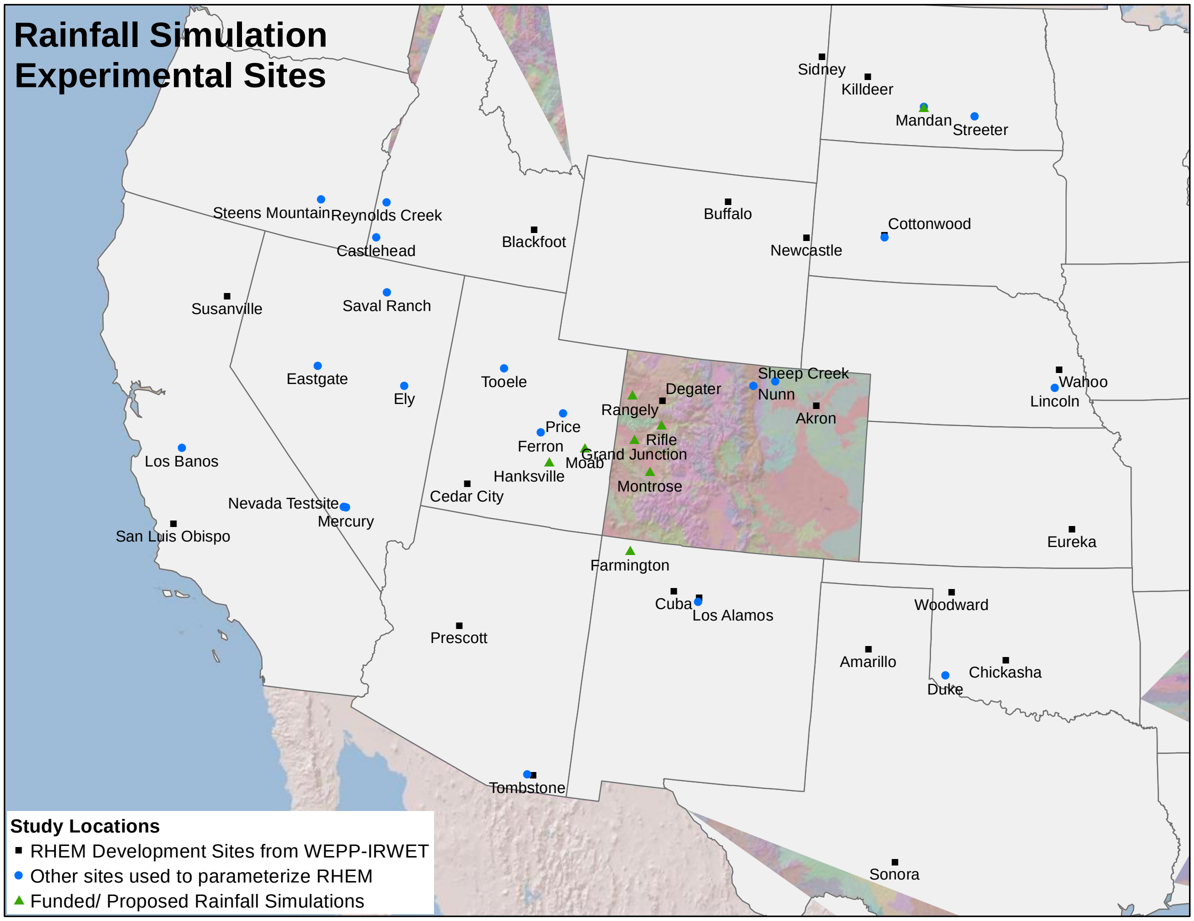


Figure 1: *Map of rainfall simulation experiments sites from which RHEM was developed shown on Omernik Level IV Ecoregions.*

The ecological site concept is the primary means of grouping landscape-level rangeland units in the US and provides a basis for evaluating ecosystem health, targeting conservation practices, and communicating regarding ecosystem responses to management (Williams *et al*. 2016). An ecological site unit is classified based on site-specific physical attributes (climate, soils, landscape position, and topography) that separate the respective unit from other units in its ability to produce characteristic vegetation and to respond to management and disturbances (USDA 2013). Plant community dynamics and ecosystem responses to management and disturbances are conceptualized within Ecological Site Descriptions (ESD) primarily using a State-and-Transition Model (STM).

Hydrologic function is well-recognized as an indicator of rangeland health, but hydrologic data and information on fundamental ecohydrologic feedbacks that govern state resilience are often missing in ESDs. Hydrologic vulnerability for a particular state is a function of climate (i.e., precipitation regime) and the susceptibility of the ground surface to runoff generation and erosion (Williams *et al*. 2016). Vegetation, litter, and ground cover dampen the erosive energy of rainfall and overland flow and delay and reduce runoff and erosion by trapping water input, stabilizing sediment, and promoting infiltration. Sparsely vegetated or bare patches (source areas) on sloping terrain exhibit high evaporative losses and low soil water storage, promote runoff and erosion, and facilitate transfer of water and soil resources to areas with ample surface protection (sink areas). Accumulation of soil water and nutrients in sink areas stimulates below ground biological activity, plant growth, and reproduction that further sustain the vegetative community and the overall source-sink structure. Alteration of a plant community structure that promotes water and soil retention can have major ramifications on hydrologic function and state resilience. Climate and its interactions with management provide the means of maintaining a state or in guiding change to a desired state through alteration of vegetation.

The current structure for ESDs includes a section for hydrologic function, but guidance is limited and actual information is often missing regarding the hydrology content. Upon completion of this tutorial you will be able to assess how plant community transitions in a STM affect hydrologic function of the site as a function of changes in plant lifeform and plant canopy, and ground cover. Additional information on rangeland hydrologic processes and the Rangeland Hydrology and Erosion Model (RHEM) tool can be found in the scientific publications listed in the Appendix.

1.1 Capabilities

RHEM estimates runoff, soil loss, and sediment delivery rates and volumes at the hillslope spatial scale and the temporal scale of a single rainfall event (Nearing *et al*. 2011).

1.2 Limitations

The RHEM model is a single event prediction tool and therefore does not predict daily and seasonal changes in plant growth and associated changes in standing biomass, foliar canopy cover, or ground cover. RHEM does not address channel, gulley, side-bank sloughing, head cutting, rain-on-snow, and/or seep induced soil erosion processes.

1.3 Objectives

- Use the RHEM model output for various ecological states to characterize how changes in foliar canopy cover percent and ground cover percent affect runoff and erosion and

- Use the Risk Assessment Tool (within RHEM) for illustrating how STM and probability of occurrence of yearly soil losses between ecological states can be used to define different soil erosion severity levels.

2 Description of the Ecological Site

Example 1: This exercise will illustrate the use of the RHEM Web-based interface at the Kendall Grassland site (109°56’28”W, 31°44’10”N), 1526 m asl), located in the Walnut Gulch Experimental Watershed (WGEW), *ca*. 11 km east of Tombstone, AZ (Fig. 2). The Soil Map Unit is a complex of 1) *Elgin and similar soils,* 50 percent; and *Stronghold and similar soils,* 40 percent. The area of interest is the Elgin soil, which is correlated with the Limy Slopes 12-16” PZ ecological site (Site ID: R041XC308AZ, Major land resource area (MLRA): 041-Southeastern Arizona Basin and Range).

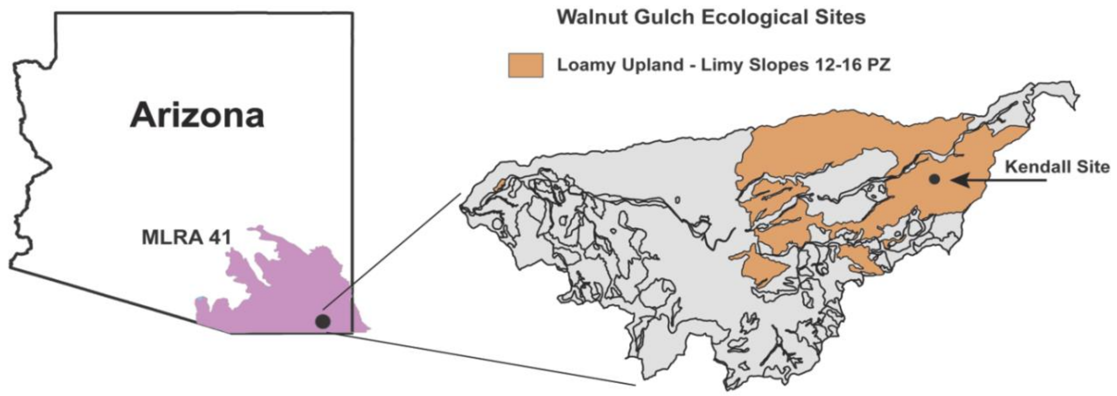


Figure 2. *Limy Slopes 12-16” PZ Ecological Site within the Walnut Gulch Experimental Watershed in Tombstone, Arizona.*

2.1 Climatic Features

The climate of the area is semiarid with annual precipitation of approximately 345 mm (13.6 in) and a highly spatially and temporally varying precipitation pattern dominated by the North American Monsoon. Summer rainfall occurs in July-September. The precipitation originates in the Gulf of Mexico or Pacific Ocean (from the southwest) and occurs as brief convective, intense thunderstorms. Cool season moisture tends to be frontal, originates in the Pacific or Gulf of California, and falls in widespread storms with long duration and low intensity. Snow rarely lasts more than one day. May and June are the driest months of the year. Humidity is generally very low. Mean annual temperature is 18^{o}C.

2.2 Soil Features

Using Web Soil Survey (http://websoilsurvey.sc.egov.usda.gov/App/HomePage.htm), the soil mapped in this example is an Elgin-Stronghold complex, 3 to 20 percent slopes, Chochise County, Arizona, Douglas-Tombstone Part (AZ671) (Fig. 3).

2.2.1 Map Unit Composition

- Elgin and similar soils, 50 percent; and Stronghold and similar soils, 40 percent

2.2.2 Description of Elgin Soil

Setting

- *Landform:* Fan terraces
- *Landform position (two-dimensional):* Summit
- *Landform position (three-dimensional):* Tread
- *Down-slope shape:* Convex
- *Across-slope shape:* Convex
- *Parent material:* Mixed fan alluvium

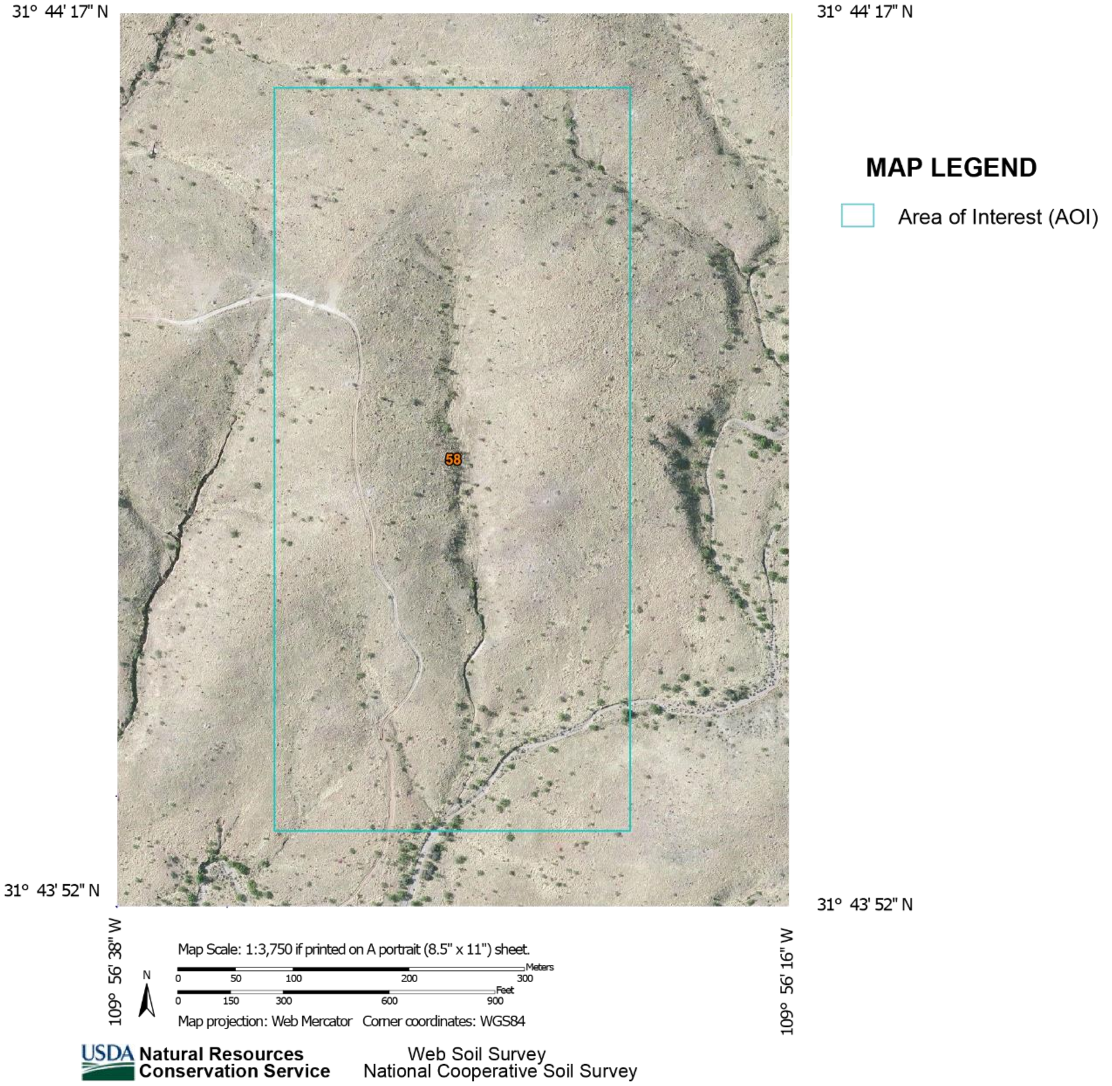
Typical profile

- *A – 0 to 2.54 cm (0 to 1 inches):* very gravelly fine sandy loam
- *Bt – 2.54 to 38.1 cm (1 to 15 inches):* clay
- *Btk – 38.1 to 53.3 cm (15 to 21 inches):* gravelly sandy clay loam
- *Bk1 – 53.3 to 68.6 cm (21 to 27 inches):* gravelly sandy loam
- *Bk2 – 68.6 to 152.4 cm (27 to 60 inches):* very gravelly sandy loam

Properties and qualities

- *Slope:* 3 to 20 percent
- *Depth to restrictive feature:* More than 2.03 *m* (80 *inches*)
- *Natural drainage class:* Well drained
- *Runoff class:* High
- *Capacity of the most limiting layer to transmit water (Ksat):* Moderately low to moderately high 1.52 to 5.08 *mm/hr* (0.06 to 0.20 *in/hr*)
- *Depth to water table:* More than 2.03 *m* (80 *inches*)
- *Frequency of flooding:* None
- *Frequency of ponding:* None
- *Calcium carbonate, maximum in profile:* 25 percent
- *Available water storage in profile:* Low (about 0.15 *m*) (5.7 *inches*)

Soil Map - Cochise County, Arizona, Douglas-Tombstone Part
(RHEM Tutorial Guide: Desert Southwest Grassland Limy Slopes 12-16” PZ Ecological Site)



Map Unit Legend

Cochise County, Arizona, Douglas-Tombstone Part (AZ671)			
Map Unit Symbol	**Map Unit Name**	**Acres in AOI**	**Percent of AOI**
58	Elgin-Stronghold complex, 3 to 20 percent slopes	48.8	100.0%
Totals for Area of Interest		**48.8**	**100.0%**

Figure 3. *Web Soil Survey area of interest with map unit legend*.

2.3 Plant Communities

Figure 4 shows the STM for the Limy Slopes 12-16” PZ ecological site. The model for this site includes 4 ecological states. The ecological states are outlined by bold black rectangles. Plant community phases are shown by light gray rectangles. Based on the ESD, within the

Historic Plant Community (HPC) or reference plant community state (concept established by the NRCS), fire and drought could cause temporary shifts between the two plant communities shown. According to STM, the Eroded to Limy Upland (hereinafter called Eroded) state is considered so degraded by soil erosion that it has crossed a threshold and, now has a different, less productive, potential plant community.

By 2006, seed sources for both shrub and Lehmann lovegrass (*Eragrostis lehmanniana*) (see Transition 1a in Table 1) had appeared in the upland areas around Kendall study area (Heilman *et al.*, 2010). The vegetation was beginning to transition from the HPC state toward the Lehmann state as small shrubs were getting established. Prolonged drought resulted in high perennial grass mortality prior to the 2006 summer monsoon (Robinett, 1992), and 2006 saw a significant shift toward the exotic grass and the shrub invaded states, which impacted the hydrological and sediment response of the system for a period of time (Polyakov *et al.*, 2010).

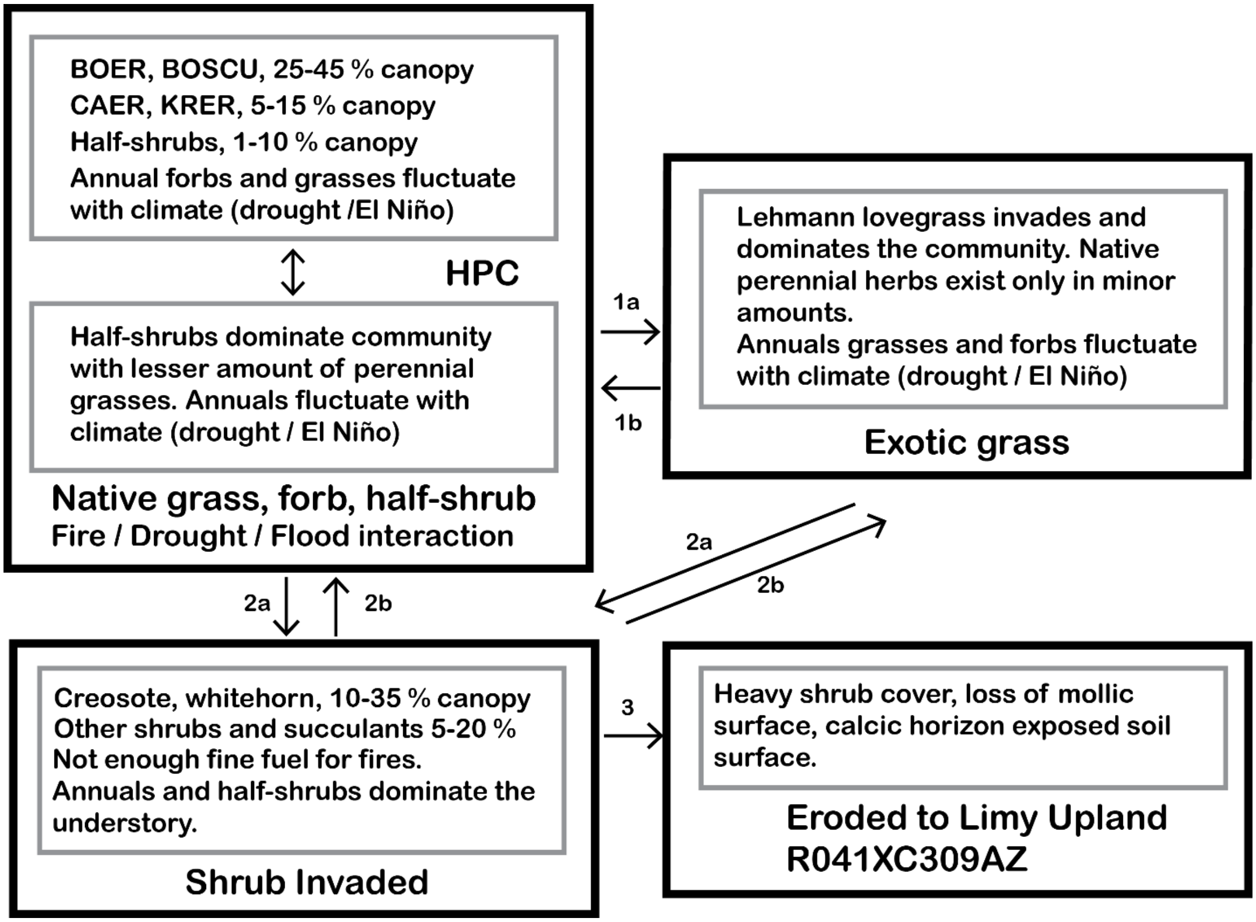


Figure 4. *The State and Transition Model diagram for the Limy Slopes 12-16" PZ Ecological Site; Site Type: Rangeland; Site Id: R041XC308AZ; Major Land Resource Area (MLRA): 041-Southern Arizona basin and Range. CAER=false mesquite (Calliandra conferta); KRER=ratany (Krameria erecta); BOER=black grama (Bouteloua eriopoda); BOSCU=sideoats grama (Bouteloua curtipendula).*

Table 1. Description of community transitions.

Transitions
1a. Continuous Heavy Grazing (CHG), introduction of a seed source, or direct seeding of Lehmann lovegrass.
1b. Unknown. Possible herbicide treatment of exotic species and seeding of native grasses.
2a. CHG with drought, fire interaction. Invasion by creosote bush and/or whitethorn acacia. Other shrubs and succulents can increase also. Lack of fine fuel for fire. Remnant perennial grasses cannot re-colonize areas with shrub competition.
2b. Prescribed Grazing/No Grazing (PG/NG) with herbicide shrub control. Possible seeding of native grasses, maintenance treatments for shrubs (fire, herbicide).
3. CHG, trailing and soil surface compaction, accelerated sheet and rill erosion. Over time (50-100 years); loss of dark colored (mollic)

Figure 5*. Historic Plant Community (HPC)*

The Historic Plant Community is dominated by warm season perennial grasses (Fig. 5). Perennial forbs are well represented on the site, as well as few species of half shrubs. Most of the major perennial grasses on the site are well dispersed throughout the plant community. Black gramma occurs in patches of various sizes and these patches appear to be well dispersed over large areas of the site. The aspect is open grassland.

With continuous heavy grazing, the potential dominant grasses are replaced by increases in species like red threeawn (*Aristida purpurea*). Low shrubs that can increase on the site include snakeweed (*Gutierrezia sarothrae*). Large shrubs such as creosote-bush (*Larrea tridenta*), whitethorn (*Aacia constricta*), paloverde (*Parkinsonia florida*) can invade this site from adjacent areas of Limy Upland. Natural fire may have been a factor in the development of the potential plant community. Gravel size cover may be inadequate on steep slopes in preventing water erosion. Lehmann lovegrass can invade and become dominant on areas of this site where perennial grass cover has been lost due to the interactions of drought, fire and continuous grazing.

Figure 6. *Exotic perennial grass*

When the native perennial grass cover is depleted due to the combination of continuous grazing and drought and /or fire, Lehmann lovegrass can invade areas of this site as long as seed source is present (Fig. 6). Over time Lehmann can dominate the grass and forb component of the plant community. The dominant half shrubs seem to be able to persist under these circumstances.

Figure 7. *Shrub Invaded State*

In the absence of fire for long periods and with the interaction of drought, fire and continuous grazing, shrubs like creosote-bush and whitethorn can invade and increase to dominate the site (Fig. 7). In some areas other shrubs like mesquite can also increase. As woody plants increase the herbaceous part of the plant community diminishes until there is no longer enough fine fuel produced to carry fire.

***Figure 8**. Eroded*

The interaction of continuous heavy grazing with drought and / or fire, over time (50-100 years) can lead to accelerated sheet and rill erosion and loss of the entire A (mollic) horizon (Fig.8). This state has heavy shrub cover and the calcic horizon is exposed at the soil surface. Its potential to grow perennial grasses is greatly reduced. Shrub control with herbicides will be short lived as the new site potential is shrubland. Shrubs like creosote dominate the plant community.

2.4 Data Available for Analysis

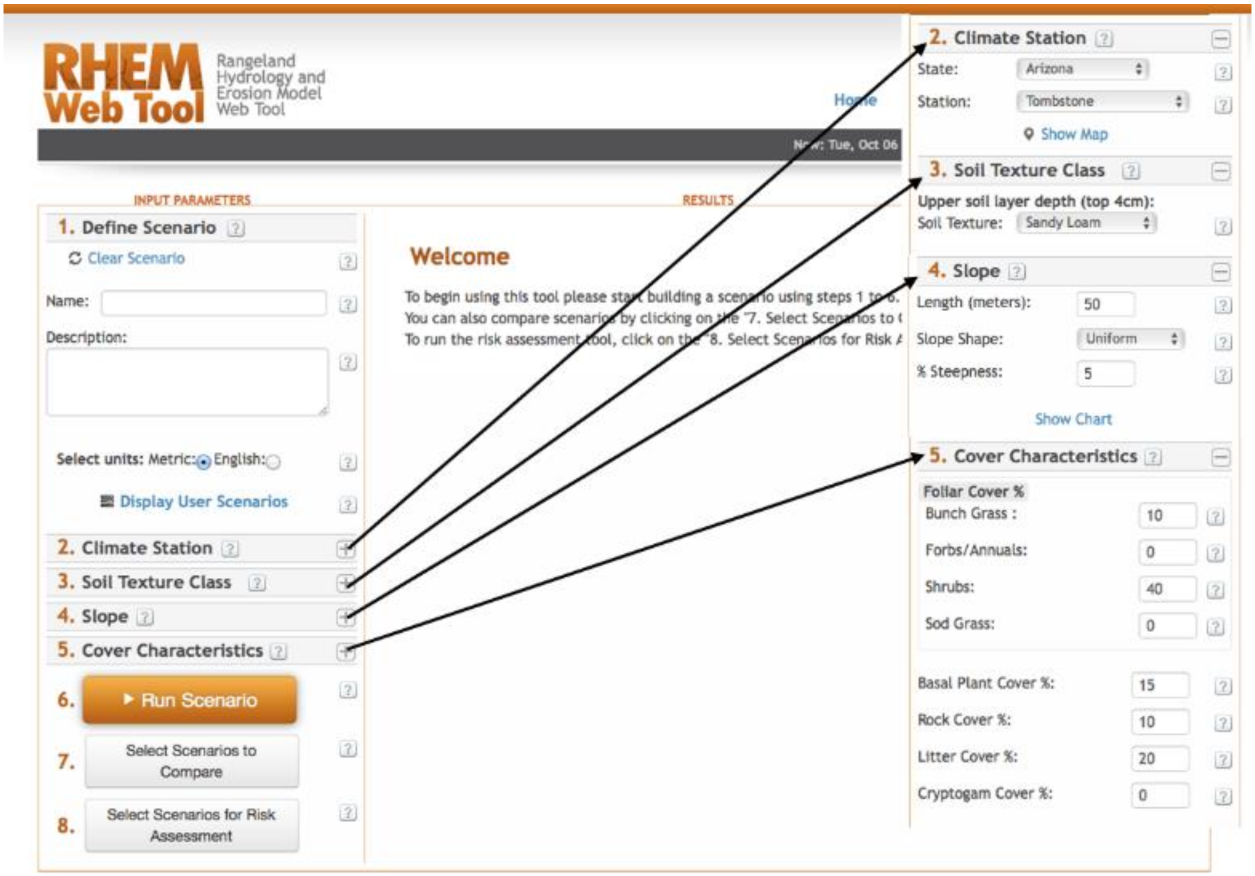
Table 2. Summary output of input parameters for various represented states.

Input Parameters	**Baseline Scenario HPC**	**Scenario 1 Eroded**	**Scenario 2 Shrub Invaded**	**Scenario 3 Exotic Grass**
State ID	AZ	AZ	AZ	AZ
Climate Station	Tombstone	Tombstone	Tombstone	Tombstone
Soil Texture	Sandy Loam	Sandy Loam	Sandy Loam	Sandy Loam
Soil Water Saturation (%)	25	25	25	25
Slope Length (m)	50	50	50	50
Slope Shape	S-Shaped	S-Shaped	S-Shaped	S-Shaped
Slope Steepness (%)	12.5	12.5	12.5	12.5
Bunch Grass Foliar Cover (%)	50	0	1	26
Forbs and/or Annual Grasses Foliar Cover (%)	1	0	2	2
Shrub Foliar Cover (%)	10	35	35	10
Sod Grass Foliar Cover (%)	0	0	0	0
Total Foliar Cover (%)	**61**	**35**	**38**	**38**
Basal Cover (%)	8	0	3	3
Rock Cover (%)	16	16	16	16
Litter Cover (%)	45	9	10	35
Cryptogam Cover (%)	1	0	0	0
Total Ground Cover (%)	**70**	**25**	**29**	**54**

3 Getting Started

3.1 Part I. Developing and Analyzing RHEM Scenarios

Figure 9 illustrates the sequence of steps performed within RHEM, and the numbers on the left of the input parameter window show the order in which they are performed. First the user accesses the application through an Internet browser interface (dss.tucson.ars.ag.gov/rhem/), and must register to use the application. The user is notified of any major updates, and provided disk space to save and edit scenarios that the user has created. The following steps describe the sequence of actions to run the model: 1) create a new scenario, 2) select units for input and output, 3) select a climate weather station, 4) select a soil texture class, 5) provide a description of slope and topography characteristics, 6) provide estimates of foliar canopy cover and ground cover characteristics, 7) run new scenario, 8) perform a comparison of scenarios, and 9) Risk assessment and analysis of soil loss.



Select units: Metric: ● English: ○

Welcome

To begin using this tool please start building a scenario using steps 1 to 6.
You can also compare scenarios by clicking on the "7. Select Scenarios to
To run the risk assessment tool, click on the "8. Select Scenarios for Risk

2. Climate Station
State: Arizona
Station: Tombstone

3. Soil Texture Class
Upper soil layer depth (top 4cm):
Soil Texture: Sandy Loam

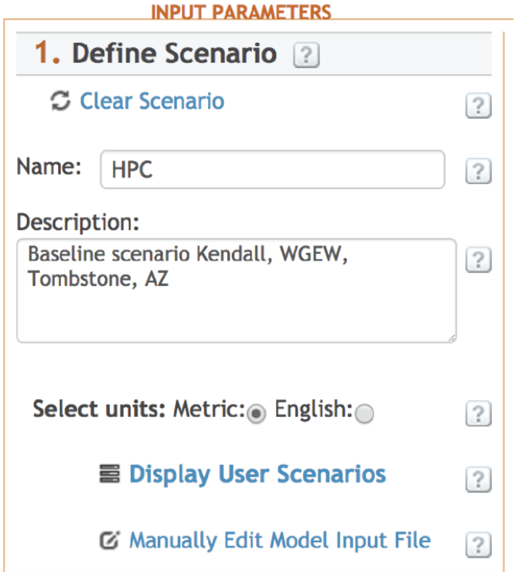
4. Slope
Length (meters): 50
Slope Shape: Uniform
% Steepness: 5

5. Cover Characteristics
Foliar Cover %
Bunch Grass : 10
Forbs/Annuals: 0
Shrubs: 40
Sod Grass: 0
Basal Plant Cover %: 15
Rock Cover %: 10
Litter Cover %: 20
Cryptogam Cover %: 0

Figure 9. RHEM Web-based system schematic

Step 1- Define scenario

Start RHEM with a new scenario by typing a name that identifies the new scenario and providing a short description of the project on the Name and Description dialog boxes, respectively.



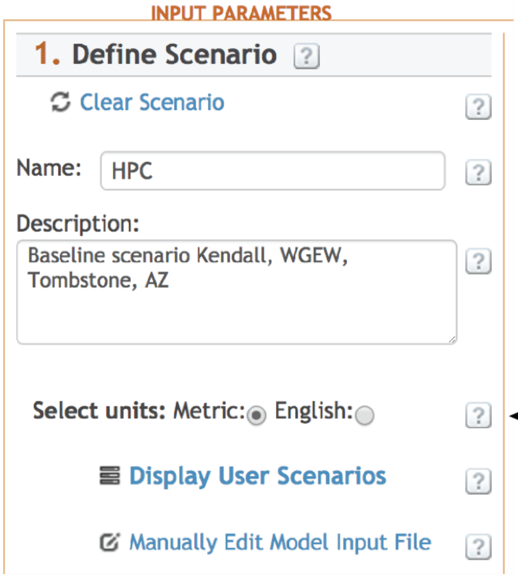
Name: HPC

Description: Baseline scenario Kendall, WGEW, Tombstone, AZ

Select units: Metric: ● English: ○

A scenario is defined as a unique set of input parameters needed to run RHEM. It can be saved to view results, compared with other scenarios, or modified to create a new scenario. The user can select the units to be used for the current scenario's input and output values.

Step 2- Select Metric or English Units



Name: HPC

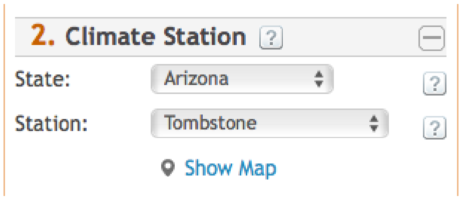
Description: Baseline scenario Kendall, WGEW, Tombstone, AZ

Select units: Metric: ● English: ○

Select units for input and output

Step 3- Climate station

The second step involves entering the climate data to parameterize the simulation model. In the Climate Station Panel two dialog boxes are available. In the State dialog box, select the state of the project location and in the Station dialog box select the name of the climate station that is close to the location being analyzed or a station with similar elevation to the study area.



2. Climate Station

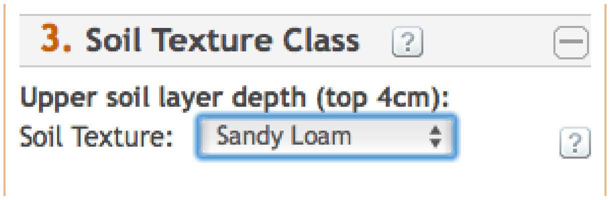
State: Arizona

Station: Tombstone

Climate data is obtained via the CLIGEN (Version 5.3) climate generator. RHEM uses the CLIGEN model to generate daily rainfall statistics for a 300-year weather sequence that is representative of a time-stationary climate and used by the rainfall disaggregation component of RHEM. The disaggregation component uses rainfall amount, duration, ratio of time of peak intensity to duration, and the ratio of peak intensity to average intensity to compute a time-intensity distribution of a rainfall event. The CLIGEN database consists of 2600 weather stations across the continental US.

Step 4- Soil texture class

In the Soil Texture Class panel, the user defines the soil texture of the upper 4 cm (1.57 in.) of the soil profile. It is input as a class name from the USDA soil textural triangle. The RHEM database contains a list of soil hydraulic properties to parameterize the Smith-Parlange infiltration equation and look-up tables with percent of sand, silt and clay to estimate the Darcy-Weisbach friction factor, and the maximum initial concentrated flow erodibility coefficient.



3. Soil Texture Class

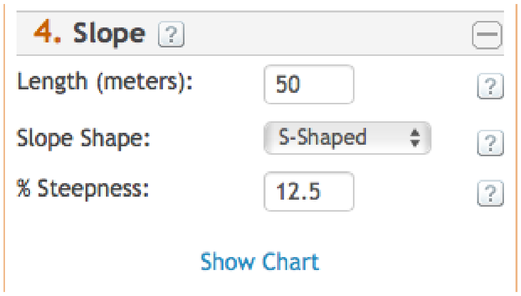
Upper soil layer depth (top 4cm):

Soil Texture: Sandy Loam

Step 5- Slope

To characterize the topography of the hillslope profile, the slope profile panel presents three dialog boxes to enter the slope length, slope shape, and slope steepness. In regard with the estimation of the slope length in RHEM, we define slope length as the length of the path that water flows down a slope as sheet and rill flow until it reaches an area where flow begins to concentrate in a channel, or to the point where the slope flattens out causing deposition of the sediment load. Slope lengths up to 120 m (394 ft.) are supported. A distance greater than 120 m

(394 ft.) is considered to be a very long slope length. We suggest using a slope length of 50 m for consistency and comparability. In addition, RHEM provides four hillslope shapes for different topographic scenarios as follows: uniform, convex, concave, and S-shaped. In order to assess sediment delivery from a hillslope to a channel, the user must designate the shape of the hillslope either as a concave or S-shaped. These are the slope shapes that will experience toe-slope deposition. The slope steepness is the slope of the hillslope area rather than the average land slope.


4. Slope

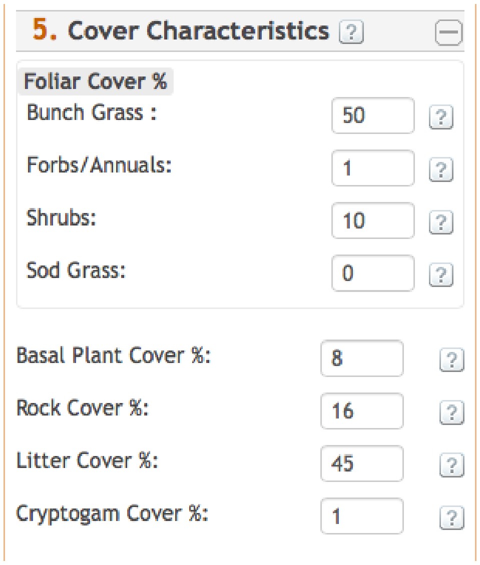
Length (meters): 50

Slope Shape: S-Shaped

% Steepness: 12.5

Step 6- Cover characteristics

The Cover Characteristics panel presents eight Dialog Boxes to enter information on vegetative foliar canopy cover and surface ground cover. RHEM's system of parameter estimation equations and procedure reflects the concept that hydrology and erosion processes are affected by plant growth forms and surface ground cover. Thus, the user can enter percent foliar canopy for four rangeland plant community groups: bunchgrass, shrub, sodgrass, and annual grass /forbs. In regard with surface ground cover input parameters, RHEM was designed to require minimal inputs that are readily available for most rangeland ecological sites. Percent ground cover by component is defined as follows: rocks, plant litter, plant basal area, and biological soil crust.


5. Cover Characteristics

Foliar Cover %

Bunch Grass : 50

Forbs/Annuals: 1

Shrubs: 10

Sod Grass: 0

Basal Plant Cover %: 8

Rock Cover %: 16

Litter Cover %: 45

Cryptogam Cover %: 1

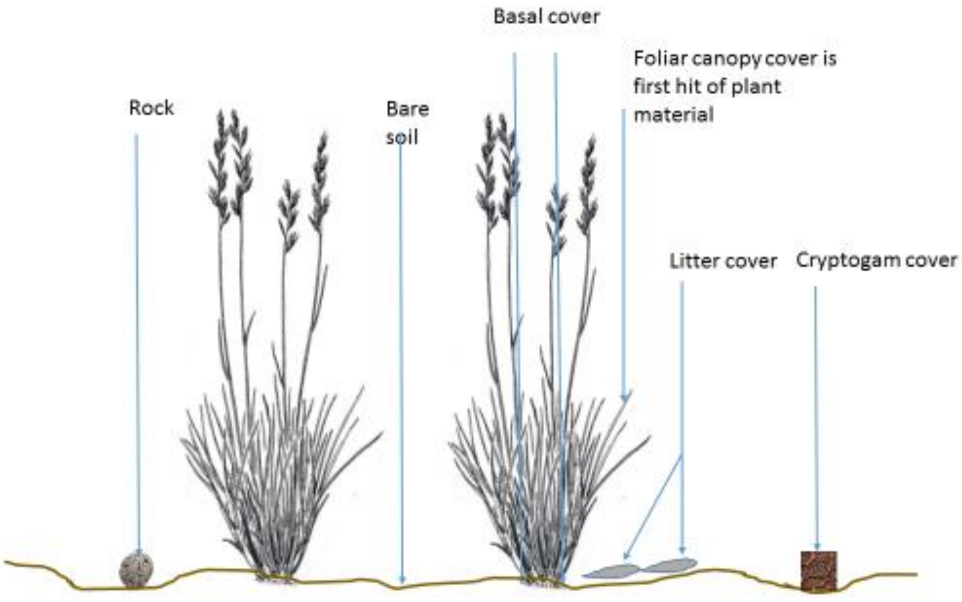
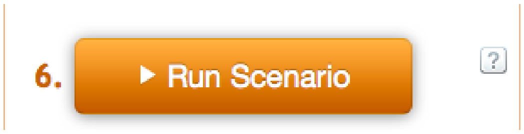


Figure 10. *Diagram of ground surface cover classes as used by RHEM.*

Step 7- Run scenario

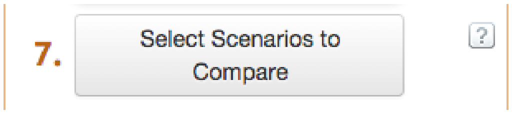
The Run Scenario panel is used to generate output from: a new scenario, an edited scenario, and re-named scenario. The web-based interface generates a summary report, input parameter file, and the storm file.



Repeat Step 1 through Step 6 for Exotic Grass, Shrub Invaded and Eroded states

Step 8- Select scenarios to compare

The Select Scenario to compare panel allows the user to compare up to five existing scenarios.



3.1.1 Modeling Results

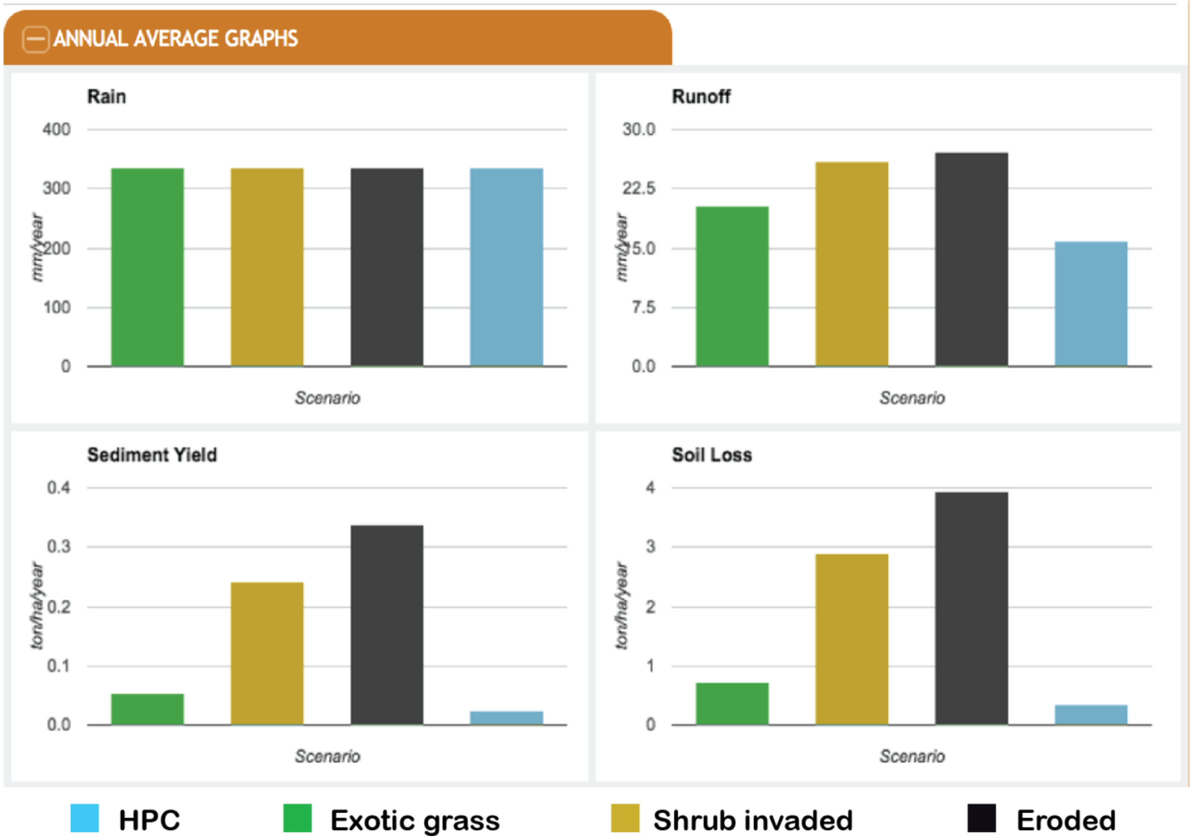
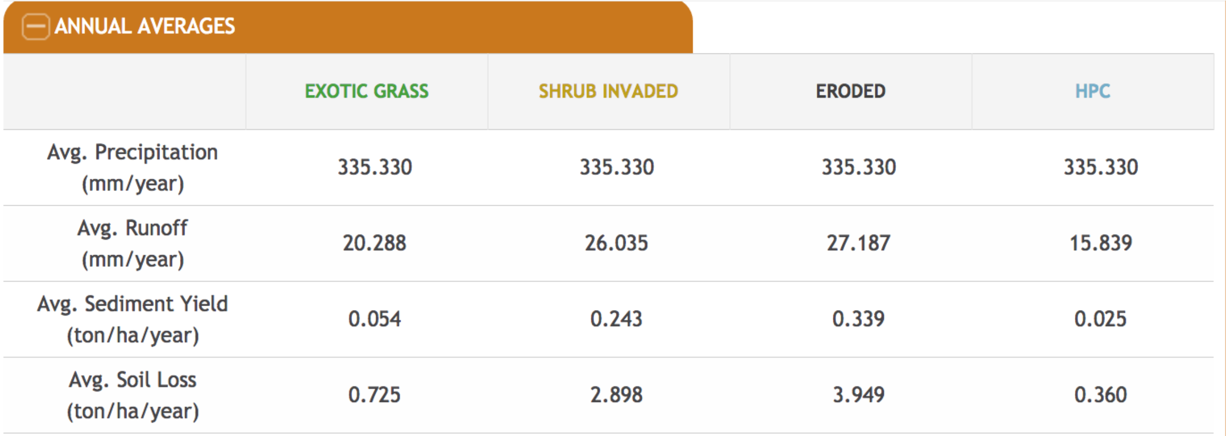


Figure 11. *Average Annual for rain, runoff, sediment yield, and soil loss.*

Table 3. Annual averages for precipitation, runoff, sediment yield, and soil loss for scenarios.



ANNUAL AVERAGES

	EXOTIC GRASS	SHRUB INVADED	ERODED	HPC
Avg. Precipitation (mm/year)	335.330	335.330	335.330	335.330
Avg. Runoff (mm/year)	20.288	26.035	27.187	15.839
Avg. Sediment Yield (ton/ha/year)	0.054	0.243	0.339	0.025
Avg. Soil Loss (ton/ha/year)	0.725	2.898	3.949	0.360

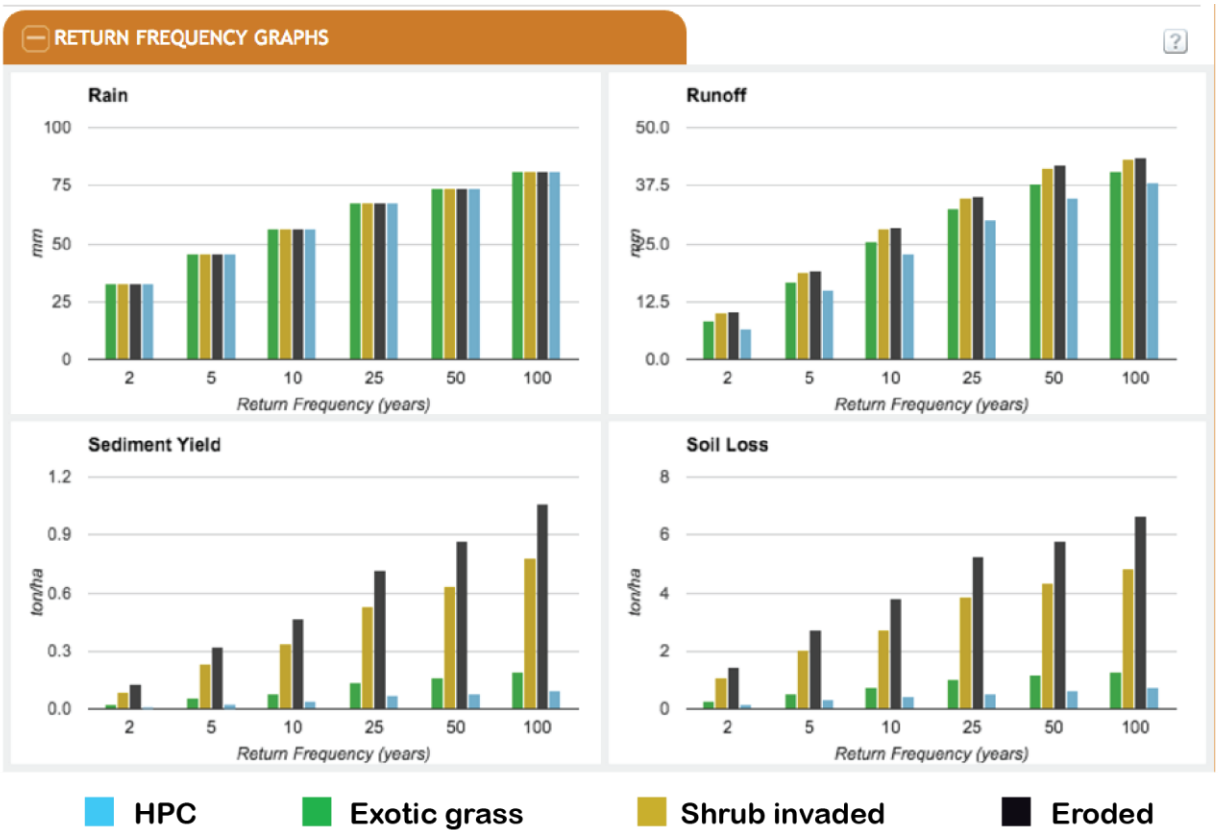
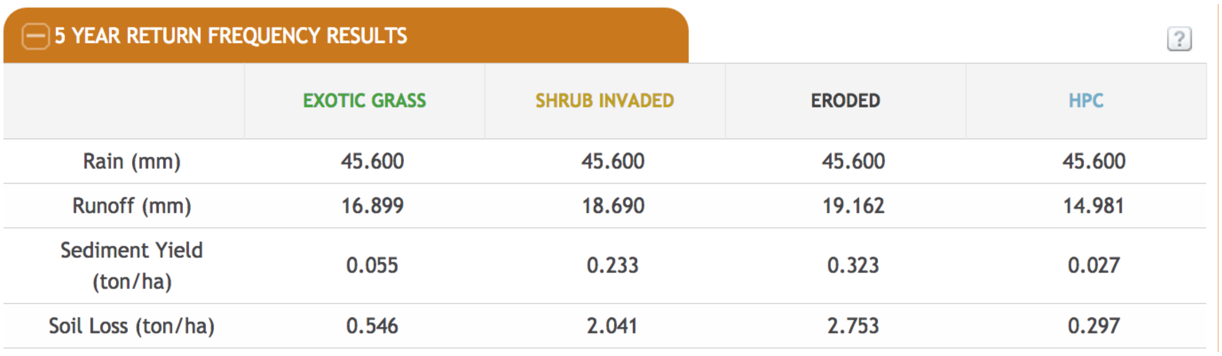


Figure 12. *Return frequency graphs for rain, runoff, sediment yield, and soil loss based on yearly summation values.*

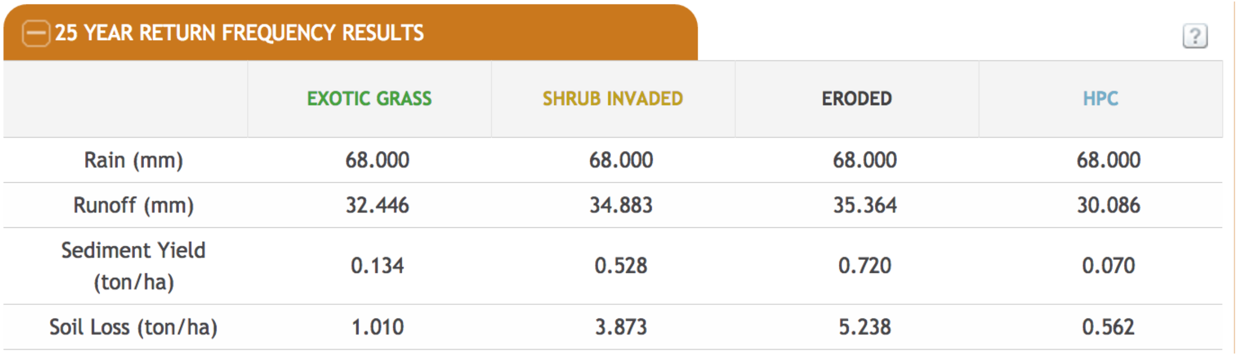
Table 4. Estimated rain, runoff, sediment yield, and soil loss for the 5-year return frequency year.



5 YEAR RETURN FREQUENCY RESULTS

	EXOTIC GRASS	SHRUB INVADED	ERODED	HPC
Rain (mm)	45.600	45.600	45.600	45.600
Runoff (mm)	16.899	18.690	19.162	14.981
Sediment Yield (ton/ha)	0.055	0.233	0.323	0.027
Soil Loss (ton/ha)	0.546	2.041	2.753	0.297

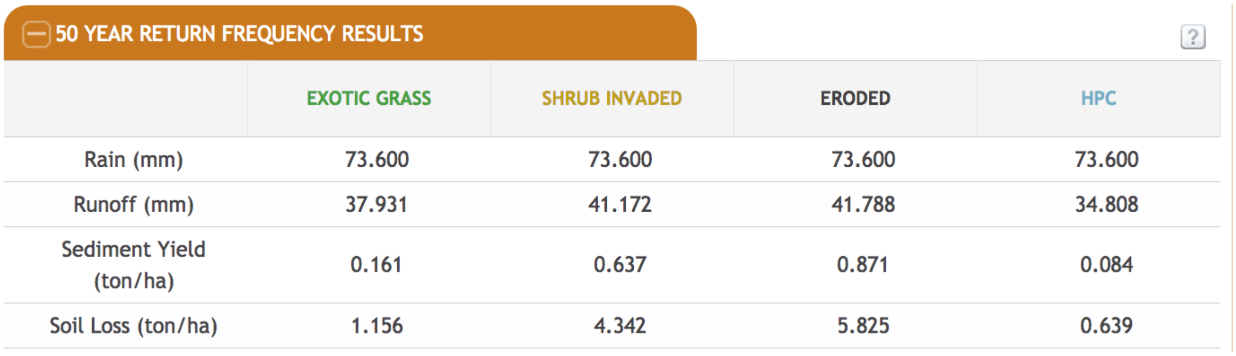
Table 5. Estimated rain, runoff, sediment yield, and soil loss for the 25-year return frequency year.



25 YEAR RETURN FREQUENCY RESULTS

	EXOTIC GRASS	SHRUB INVADED	ERODED	HPC
Rain (mm)	68.000	68.000	68.000	68.000
Runoff (mm)	32.446	34.883	35.364	30.086
Sediment Yield (ton/ha)	0.134	0.528	0.720	0.070
Soil Loss (ton/ha)	1.010	3.873	5.238	0.562

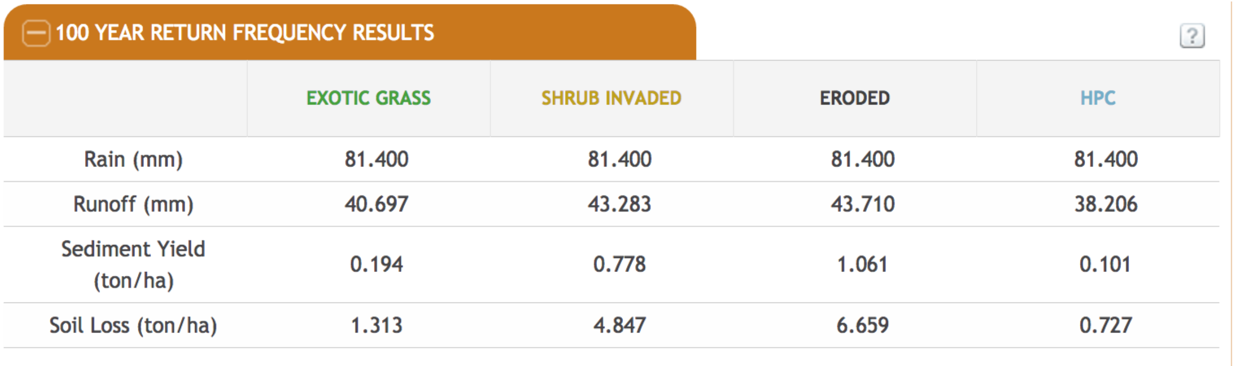
Table 6. Estimated rain, runoff, sediment yield, and soil loss for the 50-year return frequency year.



50 YEAR RETURN FREQUENCY RESULTS

	EXOTIC GRASS	SHRUB INVADED	ERODED	HPC
Rain (mm)	73.600	73.600	73.600	73.600
Runoff (mm)	37.931	41.172	41.788	34.808
Sediment Yield (ton/ha)	0.161	0.637	0.871	0.084
Soil Loss (ton/ha)	1.156	4.342	5.825	0.639

Table 7. Estimated rain, runoff, sediment yield, and soil loss for the 100-year return frequency year.



100 YEAR RETURN FREQUENCY RESULTS

	EXOTIC GRASS	SHRUB INVADED	ERODED	HPC
Rain (mm)	81.400	81.400	81.400	81.400
Runoff (mm)	40.697	43.283	43.710	38.206
Sediment Yield (ton/ha)	0.194	0.778	1.061	0.101
Soil Loss (ton/ha)	1.313	4.847	6.659	0.727

3.1.2 Discussion

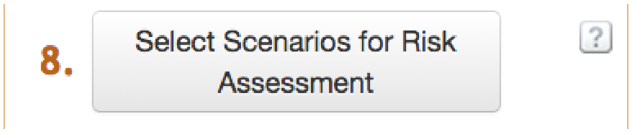
Soil loss on many rangelands is not uniformly distributed, spatially or temporally across the landscape. Average annual soil loss rates cannot explain all soil loss in arid and semiarid rangelands because most soil loss occurs during high-intensity rainfall events that generate large amounts of runoff and that may occur only a few times in a decade. The RHEM return frequency output is based on yearly summations of runoff and erosion, which will take into account the occurrence of years that have these large events.

For many arid and semiarid western rangelands soils, the sustainable soil loss rate is estimated to be ≤ 2.2 ton ha^{-1} $year^{-1}$ due to their shallow depth, low organic matter content, and the slow rate of soil formation in erratic and dry climates (DeBano and Wood, 1990). Weltz *et al*. 2014 proposed that soil loss rates of 2.2 to 4.5 ton ha^{-1} $year^{-1}$ put the long-term sustainability of these rangelands at risk and that soil loss rates > 4.5 ton ha^{-1} $year^{-1}$ be considered unsustainable. The output screens shown in Tables 4-7 provide a summary of soil loss rates for the 5, 25, 50, and 100- year recurrence interval. Based on the soil loss thresholds proposed by Weltz *et al*. 2014, the Eroded state becomes unsustainable for soil loss years with 25, 50, and 100-year return intervals.

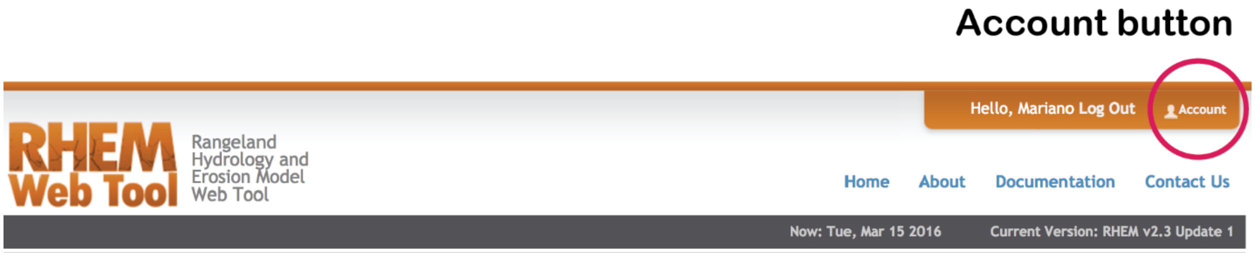
3.2 Part II. Developing and Analyzing a Risk Assessment Example

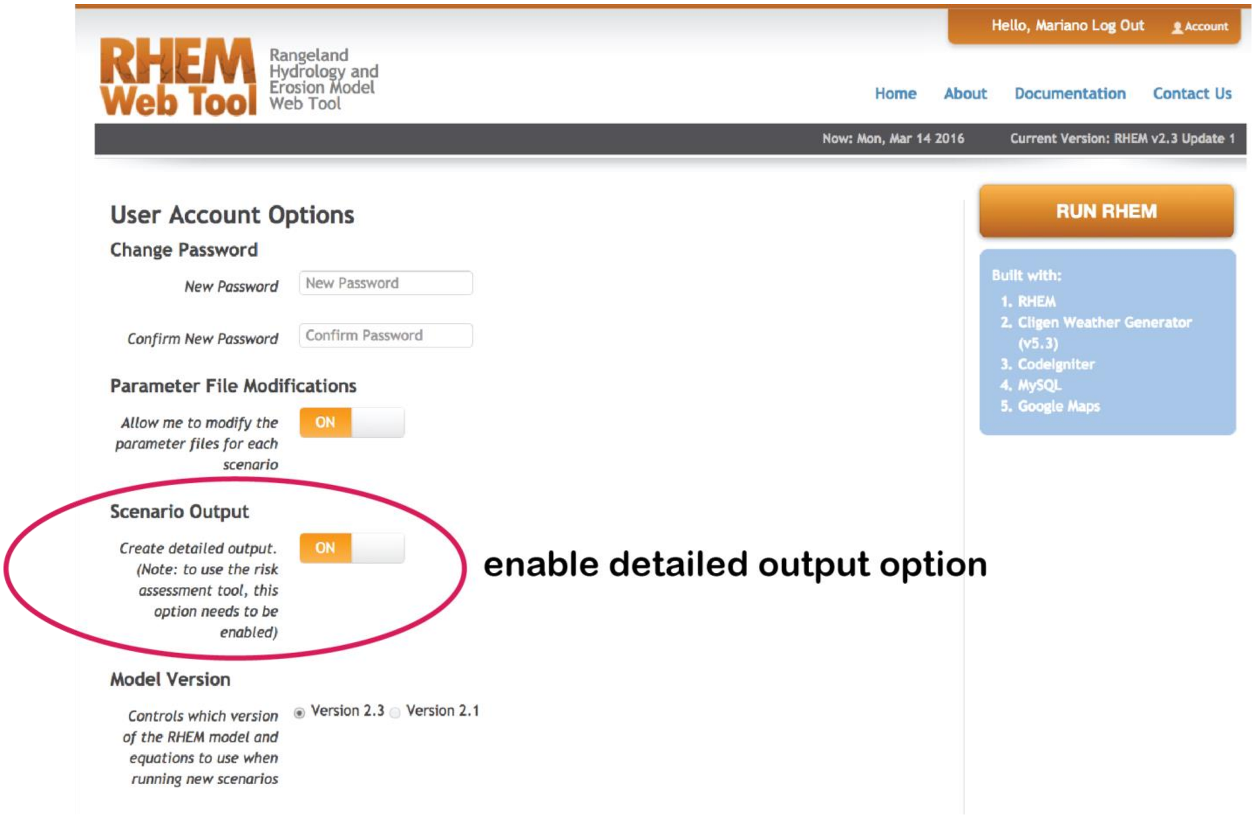
In this section you will use the Risk Assessment Tool for exploring how STM and probability of occurrence of yearly soil losses between ecological states can be used to define different soil erosion severity levels. The Risk Assessment Tool estimates probability of occurrence of yearly soil losses using the output generated from simulation runs discussed earlier.

Step 9- Select Scenarios for Risk Assessment



Only scenarios with detailed output and ran with version 2.3 of RHEM will be available for running the risk assessment analysis. To run scenarios with detailed output, please be sure to enable this in your “Account” section (top right corner). Figure 11 shows how to enable this option.





User Account Options

Change Password

New Password: New Password

Confirm New Password: Confirm Password

Parameter File Modifications

Allow me to modify the parameter files for each scenario: ON

Scenario Output

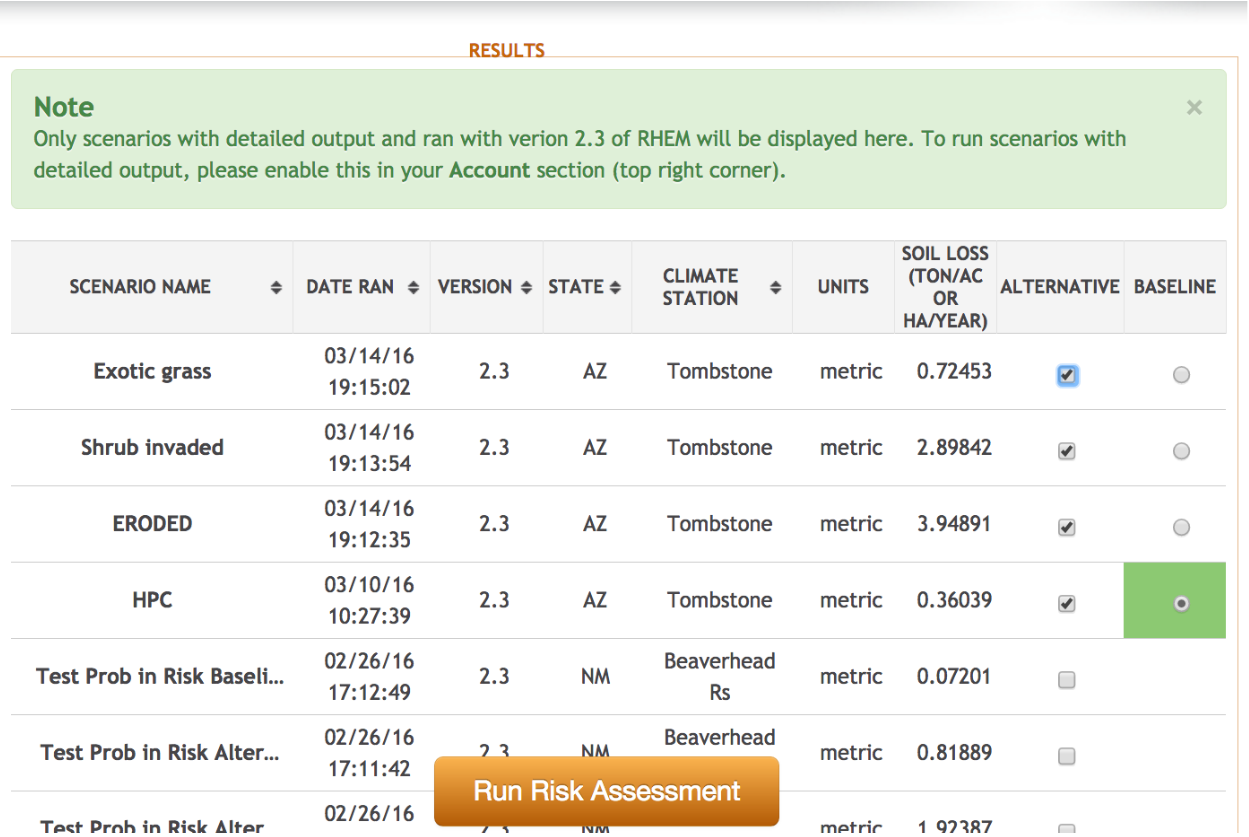
Create detailed output. (Note: to use the risk assessment tool, this option needs to be enabled): ON

Model Version

Controls which version of the RHEM model and equations to use when running new scenarios: ● Version 2.3 ○ Version 2.1

Figure 13. *Screenshot illustrating how to enable the detailed output option.*

To run the Risk Assessment Tool, check off on the list of scenarios displayed on the dialog window the four scenarios generated from simulation runs discussed earlier in Part I (Figure 14). By default, the Risk Assessment Tool assigns the first scenario checked off as the reference or baseline state.



Note
Only scenarios with detailed output and ran with verion 2.3 of RHEM will be displayed here. To run scenarios with detailed output, please enable this in your **Account** section (top right corner).

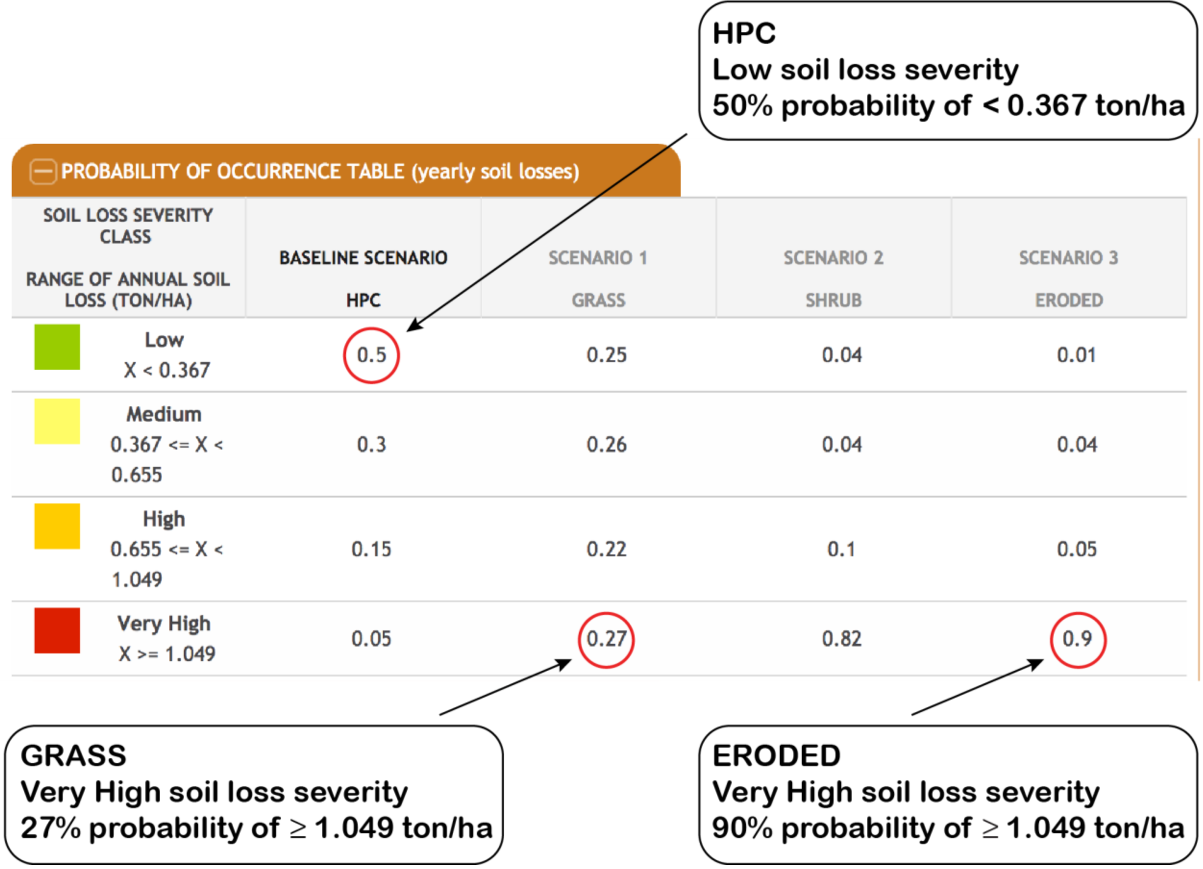
SCENARIO NAME	DATE RAN	VERSION	STATE	CLIMATE STATION	UNITS	SOIL LOSS (TON/AC OR HA/YEAR)	ALTERNATIVE	BASELINE
Exotic grass	03/14/16 19:15:02	2.3	AZ	Tombstone	metric	0.72453	☑	○
Shrub invaded	03/14/16 19:13:54	2.3	AZ	Tombstone	metric	2.89842	☑	○
ERODED	03/14/16 19:12:35	2.3	AZ	Tombstone	metric	3.94891	☑	○
HPC	03/10/16 10:27:39	2.3	AZ	Tombstone	metric	0.36039	☑	●
Test Prob in Risk Baseli...	02/26/16 17:12:49	2.3	NM	Beaverhead Rs	metric	0.07201	☐	
Test Prob in Risk Alter...	02/26/16 17:11:42	2.3	NM	Beaverhead	metric	0.81889	☐	
Test Prob in Risk Alter	02/26/16				metric	1.92387	☐	

Figure 14. *Screenshot illustrating scenarios with detailed output previously generated in Part I. The green button indicates the baseline scenario.*

For this exercise, the HPC state, which is described in the STM (Fig. 4), is used as a reference state. The assumption is that partitioning the probability distribution by specifying the 50th, 80th, and 95th percentiles of the reference state enables comparison of yearly soil losses of alternative states for different severity levels. They represent four soil erosion severity levels: low, medium, high, and very high. There is no consensus in the literature on the level at which events should be considered as extremes, so our thresholds are established for practical applications as discussed below.

3.2.1 Modeling Results

Table 8. Percent probability of occurrence of yearly soil losses and soil loss severity.



PROBABILITY OF OCCURRENCE TABLE (yearly soil losses)

	SOIL LOSS SEVERITY CLASS RANGE OF ANNUAL SOIL LOSS (TON/HA)	BASELINE SCENARIO HPC	SCENARIO 1 GRASS	SCENARIO 2 SHRUB	SCENARIO 3 ERODED
🟩	Low X < 0.367	0.5	0.25	0.04	0.01
🟨	Medium 0.367 <= X < 0.655	0.3	0.26	0.04	0.04
🟧	High 0.655 <= X < 1.049	0.15	0.22	0.1	0.05
🟥	Very High X >= 1.049	0.05	0.27	0.82	0.9

HPC
Low soil loss severity
50% probability of < 0.367 ton/ha

GRASS
Very High soil loss severity
27% probability of ≥ 1.049 ton/ha

ERODED
Very High soil loss severity
90% probability of ≥ 1.049 ton/ha

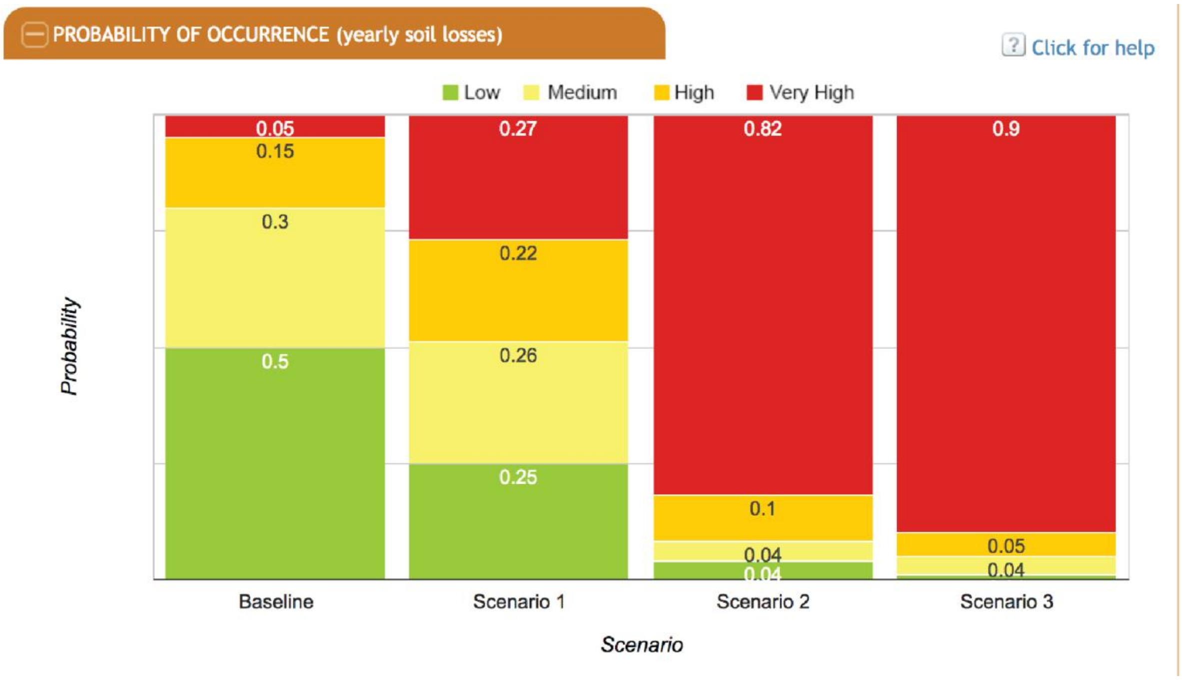


Figure 15. Probability of occurrence for yearly soil loss for all scenarios.

3.2.2 Discussion

In Table 8, the 50, 80, and 95 percentiles for yearly soil loss were determined [$\beta1$= 0.367 (ton/ha), $\beta2$=0.655 (ton/ha) and $\beta3$=1.049 (ton/ha)] from the HPC (designated baseline in this case) empirical cumulative distribution of yearly soil loss values. The mean annual soil losses for the HPC, Grass, Shrub and Eroded states are 0.360 (ton/ha), 0.725 (ton/ha), 2.898 (ton/ha) and 3.949 (ton/ha), respectively (Table 3: Annual averages for precipitation, runoff, sediment yield, and soil loss for scenarios). The probabilities (% probability) of occurrence of yearly average soil loss for each state are presented in Table 8 (note: each of the columns for HPC, Grass, Shrub, Eroded sums of equal to 100%).

Figure 15 represents the probability of occurrence of soil loss for any year for the Low, Medium, High, or Very High categories to occur. Low, Medium, High, and Very High thresholds are based on the 50, 80, and 95 percentiles for probability of occurrence of yearly soil loss for the baseline condition.

For example, in every baseline case it is considered that 5% (in red) of the years for the baseline scenario are categorized as "Very High". The red parts of the bars in the other scenarios represent the fraction of years for those scenarios that also fall in that same range of yearly soil losses as defined by the greatest 5% of the baseline condition.

Note that the output is reporting soil losses and not sediment yields, which will be different. Soil loss is defined as soil detached and moved by raindrop splash, sheetflow, and concentrated flow. Sediment yield is calculated as the amount of soil that is detached and transported off the slope. For uniform slopes all soils that are detached are considered mobile and transported off site. Therefore, soil loss and sediment are equal. When using S-shape or concave slope shapes the slope gradient is reduced at the toe of the slope allowing for potential deposition to occur. Therefore, sediment yield should be less than soil loss on S-shaped or concaved slopes. Deposition can be calculated as the difference between soil loss and sediment yield.

Interpretive Examples from Table 8 and Figure 15 indicate:

- For HPC, there is a 50% annual probability of soil loss being equal to or lower than 0.367 tons/ha; likewise, there is a 5% chance of Very High erosion ≥ 1.049 tons/ha soil loss for any given year. The mean annual soil loss for the HPC state (0.36 tons/ha) falls in the Low soil loss severity class (<0.367 tons/ha).

- For the Exotic grass state, there is 25% chance that erosion will be Low (<0.367 tons/ha); likewise, a 27% chance of Very High erosion being ≥ 1.049 tons/ha for any given year. The mean annual soil loss of the Grass state (0.725 ton/ha) falls in the High soil loss severity class (0.655 to 1.049 tons/ha).

- For the Shrub invaded state, there is a 4% chance that erosion will be Low (<0.367 tons/ha); likewise; an 82% chance of Very High erosion ≥ 1.049 tons/ha. The mean annual soil loss of the Shrub invaded state (2.898 tons/ha) falls in the Very High soil loss severity class (≥ 1.049 tons/ha).

- For the Eroded state, there is a 1% chance that erosion will be Low <0.367 tons/ha; likewise, a 90% chance of Very High erosion ≥ 1.049 tons/ha soil loss for any given year. The mean annual soil loss of the Eroded state (3.949 tons/ha), falls in the Very High soil loss severity class (≥ 1.049 tons/ha). Thus the Eroded site would be evaluated as unsustainable in reference to the baseline HPC site. RHEM results indicate that this state has significantly more years that fall within the Very High soil erosion severity class relative to the HPC condition for the ecological site.

4 Summary

Analysis of the RHEM simulation runs on the “Limy Slopes 12-16 PZ Ecological Site” provides a basis for interpreting the impacts of vegetative canopy cover, surface ground cover, and topography on dominant processes in controlling infiltration and runoff as well as sediment detachment, transport and deposition in overland flow at each state. Our results suggest that RHEM can predict runoff and erosion as a function of vegetation structure and behavior of different plant community phases and amount of cover for the different states. Numerous studies (Castillo *et al*. 1997; Cerdá, 1999; Chartier and Rostagno, 2006; and Barthès and Roose, 2002) have shown that soil erosion decreases as canopy cover increases and that runoff decreases as canopy cover increases. Weltz’s (*et al*. 1998) extensive review of the literature on rangeland cover concluded that ground cover should be maintained above a critical threshold of ~50-60 % to adequately protect the soil surface from erosion. Johansen *et al.* (2001) compiled data from the literature on burned grassland, shrublands, and forest ecosystems and found that sediment yield increased non-linearly as percentage bare ground exceeded 60-70 %. Pierson *et al*. (2009, 2011 and 2013) conducted rainfall simulator experiments on small and large plots on burned sagebrush sites, they reported that the small plot data suggest that the soil on burned sagebrush is relatively protected from high-intensity storm events when ground cover is near 40% (60% bare ground). The large plot rainfall and concentrated flow data, however, suggest that that burned sagebrush sites may remain more susceptible to increased erosion from high intensity or long duration storm events until ground cover is as high as 60% (40% bare ground). The explanation for the difference in runoff and erosion between the HPC and Exotic grass states can be related to differences in cover but also to the increased water storage associated with native bunchgrasses due to the formation of litter dams, intact soil A horizon, greater soil surface horizon depth, and greater soil organic matter content. The grass cover and litter on the baseline state cause water to pond behind small litter and debris dams as it moves downslope, which has the effect of backing up water and allowing more time for infiltration, increased tortuosity of the flow paths that results in reduced overland flow velocities as the water moves around the bunchgrasses (Mitchel and Humphreys, 1987; Puigdefabregas, 2005; Nearing *et al.*, 2007). According to Polyakov *et al*. (2010), before the Lehmann lovegrass invasion, the microtopography was characteristic of small terraces formed from of large clumps of upslope vegetation. With die-out of native grasses and greater spread of Lehmann lovegrass, there were fewer obstructions, which allowed water to move down the slope more rapidly, increasing flow connectivity, runoff and sediment yield. The difference in estimated soil erosion rate between the Shrub invaded and Eroded scenarios is about 1 ton/ha, Table 3. The explanation for the difference in soil erosion rates can be related to the additional foliar canopy and ground cover protection present in the Shrub invaded state as shown in Table 2.

The results from the risk assessment suggest that a shift from the High to Medium soil erosion severity class may be possible if management practices are implemented to promote litter production and reduce runoff and erosion. In contrast, based on the STM, the Eroded and Shrub Invaded states are considered to be so degraded by soil erosion that they have crossed a threshold and now have a different, less productive, potential plant community. These states are within the Very High soil erosion severity class and the probability of bringing them back to the reference state is impossible due to loss of surface soil horizons that control water holding capacity and nutrient availability. Furthermore, once in the Eroded state the concentrated flow/rill network is well established resulting in increased runoff and sediment yield which is self-reinforcing and results in the concentrated flow channels transiting into rills and eventually gullies if no conservation activities are applied.

Figure 16 shows operation of the rotating boom rainfall simulator on rangeland erosion plots in southeastern Arizona.

Figure 16. *Rotating boom simulator used to collect data for development of Rangeland Hydrology and Erosion Model (RHEM). Plots were 3 m (10 ft.) wide by 10.7 m (35 ft.) long.*

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