

## WEB-BASED RANGELAND HYDROLOGY AND EROSION MODEL

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**Abstract:** The Rangeland Hydrology and Erosion Model (RHEM) is a newly conceptualized model that was adapted from relevant portions of the Water Erosion Prediction Project (WEPP) Model and modified specifically to address rangelands conditions. RHEM is an event-based model that estimates runoff, erosion, and sediment delivery rates and volumes at the spatial scale of the hillslope and the temporal scale of a single rainfall event. It represents erosion processes under normal and fire-impacted rangeland conditions. Moreover, it adopts a new splash erosion and thin sheet-flow transport equation developed from rangeland data, and it links the model's hydrologic and erosion parameters with rangeland plant community by providing a new system of parameter estimation equations based on diverse rangeland datasets for predicting runoff and erosion responses on rangeland sites distributed across 15 western U. S. states. A dynamic partial differential sediment continuity equation is used to route sediment along the hillslope, with sediment source terms to represent the detachment rate of concentrated flow and rain splash and sheet flow. Recent work on the model is focused on representing intra-storm dynamics, using stream-power as the driver for detachment by flow, and deriving parameters for after fire conditions. Additional work to the model is continuing on the RHEM system: a new component has been developed to estimate erosion in probabilistic terms for risk-based management decisions; it will be improved to allow for orographic effects on precipitation by incorporating existing technology based on PRISM and CLIGEN; the model will be improved for application to both undisturbed and disturbed conditions across the western US. The purpose of this paper is to present the Web-based RHEM system and demonstrate the tool for assessing annual runoff and erosion changes for each community phase of the Limy Upland 12-16" p.z. Ecological Site (ES) within Major Land Resource Area 41 (MLRA 41), southeastern Arizona, USA.

## INTRODUCTION

Rangelands are estimated to cover approximately 31% of the United States (Havstad *et al.*, 2009), and developing tools for assessment of those lands is a critical resource management need. Predicting soil erosion is common practice in rangeland management for assessing the effects of management practices and control techniques on soil productivity, sediment delivery and offset water quality. Effective decision-making requires the integration of knowledge, data, simulation models and expert judgment to solve practical problems, and to provide a scientific basis for decision-making at the hillslope or watershed scale (National Research Council, 1999). Over the last 50 years the federal government has spent millions of dollars on the creation of spatial datasets and model development. While these simulation models are used extensively in research settings, they are infrequently incorporated into the decision-making process. One aspect of erosion modeling is the continued use of simpler, empirically-based erosion models (e.g. USLE, MUSLE, and RUSLE) instead of more complex, physically-based models (e.g. WEPP, DWEPP, EUROSEM). Reasons for the exclusion include: data requirements are usually only attained in research settings; deriving model input parameters is extremely time consuming and difficult; and the models are difficult to use with the current interfaces.

This problem can be addressed with improvement to model interfaces, lookup tables for model parameters, and internal file management. However, as erosion models continue to become more complex and integrate with other technologies, users will be required to have experience in GIS, computer operating systems, remote sensing, Internet

search engines for data gathering, and graphics, as well as good foundation of erosion processes knowledge. One solution to this problem is the development of Internet-based applications (Kingston *et al.*, 2000; Elliot, 2004; Flanagan *et al.*, 2004).

A Web-based interface for the Rangeland Hydrology and Erosion Model has been developed by the USDA-Agricultural Research Service, Southwest Watershed Research Center in Tucson, Arizona to assist different professional or stakeholder groups to develop, understand and evaluate alternative soil conservation strategies. It was built with the following goals in mind: 1) simplify the use of RHEM; 2) manage users sessions; 3) centralize scenario results (model runs); 4) compare scenario results; and 5) provide tabular and graphical results.

This paper describes the current status of the RHEM Web-based interface, and provides an example application of the software.

## MODEL DESCRIPTION

**Rangeland Hydrology and Erosion Model Concepts:** RHEM computes soil loss along a slope and sediment yield at the end of a hillslope (Nearing *et al.*, 2011). Splash and sheet erosion is described as a process of soil detachment by raindrop impact and surface water flow, transport by shallow sheet flow and small rills, and sediment delivery to larger concentrated flow areas such as arroyos. Sediment delivery rate from hillslopes is computed by using an improved equation developed by Wei *et al.* (2009) using rangeland runoff and erosion data from rainfall simulation experiments. Concentrated flow erosion is conceptualized as a function of the flow's ability to detach sediment, sediment transport capacity, and the existing sediment load in the flow. The appropriate scale of application is for hillslope profiles. Details of the model have been published (Nearing *et al.*, 2011; Al-Hamdan *et al.*, 2012a, 2012b, 2013, 2014).

RHEM has been applied successfully to illustrate the influence of plant and soil characteristics on soil erosion and hydrologic function in MLRA 41 located in the Southeastern Basin and Range region of the southern U. S. (Hernandez *et al.*, 2013); assess non-federal western rangeland soil loss rates at the national scale for determining areas of vulnerability for accelerated soil loss using USDA Natural Resources Conservation Services (NRCS) National Resources Inventory (NRI) data (Weltz *et al.*, 2014); predict runoff and erosion rates for refinement and development of Ecological Site Descriptions (Williams *et al.*, 2014).

**Model Parameter Estimation:** The RHEM model requires 13 input parameters grouped in three categories: rainfall, soils, and slope profile. An important aspect of the model relative to rangeland application by rangeland managers is that RHEM is parameterized based on four plant lifeform classification groups (annual grass and forbs, bunchgrass, shrubs, and sodgrass) (Nearing *et al.*, 2011). RHEM is continuing to evolve and improve, in RHEM V [2.2], a new set of parameter estimation equations were developed based on the regression equations of Rawls *et al.* (1982), as a function of soil texture, litter percent cover and basal percent cover to estimate effective hydraulic conductivity for the Smith-Parlange infiltration equation. The link <http://apps.tucson.ars.ag.gov/rhem/> provides further details about the equations to estimate effective hydraulic conductivity for the Smith-Parlange infiltration equation.

## WEB-BASED RHEM INTERFACE

In this section, we describe the Web-based interface for RHEM and its components for assessing runoff and erosion changes under several land management alternatives. It was designed as a shared application to assist in the decision-making processes and to offset the software and data requirement typically required in a desktop application.

**Software Architecture:** The RHEM Web-based tool has been developed based on the Model-View-Controller\* (MVC) software architectural pattern which promotes the separation between the application logic and the presentation or user interface. This software architecture style allows for future application modifications and updates to be more flexible, encouraging code modularity, code reuse, and data integrity. CodeIgniter\* was the web application framework selected to implement MVC in the RHEM Web Tool. CodeIgniter\* is a lightweight and high-performance web application framework written in PHP with a rich set of libraries that facilitate the

implementation of user authentication, web page caching, data persistence, session management, and application security. These features added agility to the development of the RHEM Web Tool.

**Hardware Architecture:** The RHEM Web Tool has been created based on a well-established three-tier architecture which is a client-server architecture in which the application presentation, processing, and data management functionalities are physically separated. The three tiers are: 1) the presentation tier, 2) the application logic tier, and 3) the data tier. For the RHEM Web Tool, the presentation tier is the user or client's PC whereas the application logic tier is powered by a Dell Xeon\* 3GHz Windows\* 2008 Server running IIS7. The data tier is powered by a Dell Xeon 3GHz Windows 2008 Server machine running MySQL\* 5.1

\*Trade names and company names, included for the reader's benefit, do not imply endorsement or preferential treatment of the product listed by the USDA or The University of Arizona.

**Overview of the Web-based system:** Figure 1 illustrates the operations performed within the system and the numbers on the inside of the circle show the sequence in which they are performed. First the user accesses the application through an Internet browser interface, and must register to use the application and to be notified of any major updates, and to allow the user to save and edit scenarios that they create. The following steps describe the sequence of actions to run the model: 1) create a new scenario, 2) select a climate weather station, 3) select a soil texture class, 4) provide a description of slope and topography characteristics, 5) provide estimates of foliar canopy cover and ground cover characteristics, 6) run new scenario, and 7) perform comparison of scenarios.

Once the user has logged in, they can create a new scenario within the Define Scenario Panel (1 in Figure 1) 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. 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.

The second step involves entering the climate data to parameterize the simulation model. In the Climate Station Panel (2 in Figure 1) two dialog boxes are available, in the State dialog box select the state of the project location and in the Name 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. Climate data is obtained via the CLIGEN climate generator [Zhang and Garbrecht, 2003]. 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.

In the Soil Texture Panel (3 in Figure 1), 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 (Al-Hamdan *et al.*, 2013), and the maximum initial concentrated flow erodibility coefficient (Al-Hamdan *et al.*, 2014).

To characterize the topography of the hillslope profile, the Hillslope Profile Panel (4 in Figure 1) 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 length 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. 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.

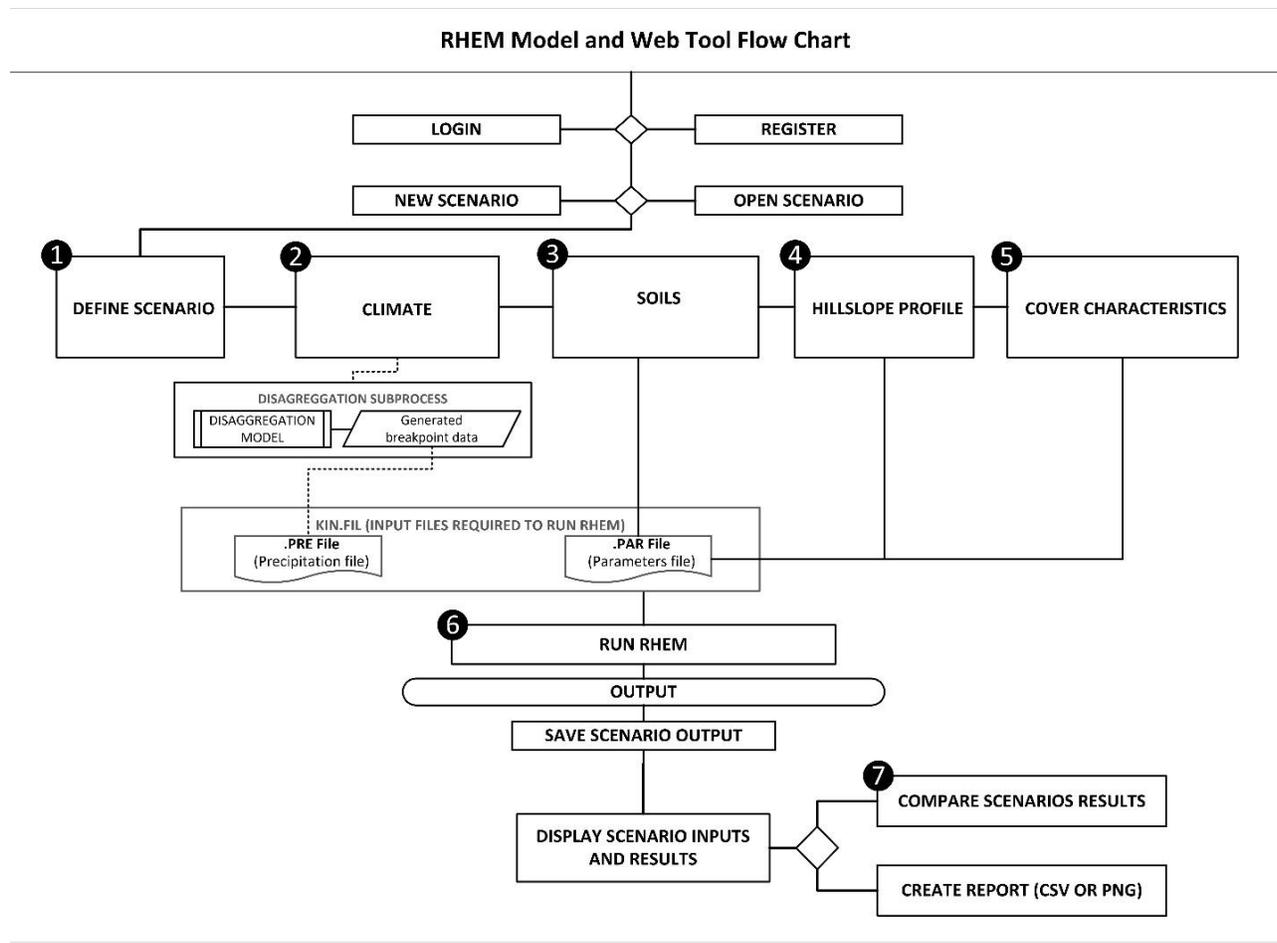


Figure 1. RHEM Web-based system schematic.

The Cover Characteristics Panel (5 in Figure 1) presents nine 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 communities: bunchgrass, shrub, sodgrass, and annual grass and 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 are defined as follows: rocks, plant litter, plant basal area, and biological soil crust.

The Run Panel (6 in Figure 1) 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.

The Comparison Panel (7 in Figure 1) allows the user to compare up to five existing scenarios.

### MODEL APPLICATION

The remainder of this paper will be comprised of an example application of the RHEM Web-based interface, and examining how it can be used to evaluate the hydrologic response of plant communities to management and disturbances as conceptualized within a State-Transition Model (STM) of an Ecological Site Description (ESD).

**Experimental Site:** We 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. The mapping unit consisting of a complex of Loamy Upland and Limy Slopes covers much of the northeastern portion of the watershed, including the grass-dominated study area known as Kendall.

According to Skirvin et al. (2008), the Kendall Grassland is a desert grassland, historically dominated by black grama (*Bouteloua eripoda*), side-oats (*B. curtipendula*), hairy grama (*B. hirsute*), tangle-head (*Heteropogon contortus*), curly mesquite (*Hilaria berlanderi*), and the exotic South African bunchgrass, Lehmann lovegrass (*Eragrostis lehmanniana*). Soils at the Kendall site are in the Elgin-Stronghold complex and are dominated by Stronghold series, which are gravelly fine sandy loams, classified as coarse-loamy, mixed, superactive thermic Ustic Haplocalcids (Breckenfeld *et al.*, 1995). The climate of the area is semiarid with annual precipitation of 345 mm and a highly spatially and temporally varying precipitation pattern dominated by the North American Monsoon. Monsoon storms are typically characterized as short-duration, high intensity, localized rainfall events. Mean annual temperature is 17.7°C.

Potential problems with Limy Slopes include invasion by Lehman lovegrass (*Eragrostis lehmanniana*) or the shrub species dominant on Limy Upland. With long-term erosion, Limy Slopes can lose their mollic cap and degrade to a Limy Upland site with calcic material at the surface (Robinett, 1992). Loamy Upland, found on 1 to 15 % slopes, is very prone to invasion by Lehmann lovegrass, as well as mesquite (*Prosopis sp.*). Both Limy Slopes and Loamy Upland have a much greater natural potential to produce grass than Limy Upland, with up to 85% of the annual production on undisturbed sites coming from grass and grasslike species (Robinett, 1992).

A STM for the Limy Slopes ecological site is shown in Figure 2. The model for this site includes 4 states. The ecological states are outlined by bold black rectangles. Plant community phases are shown by light gray rectangles. Within the Historic Climax Plant Community (HCPC) state, fire and drought could cause temporary shifts between the two plant communities shown. The 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 the both shrub and Lehmann lovegrass (Transition 1a) had appeared in the upland areas around Kendall study area (Heilman *et al.*, 2010). The vegetation was beginning to transition from the HCPC state toward the Lehmann state as small shrub trees 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).

If the principal management objective is to minimize runoff and erosion, one might favor the Lehmann state, as this exotic grass can produce up to a third more biomass than native grasses, once established (Robinett, 1992).

**Hydrology and Erosion Model:** The RHEM model was applied to estimate annual runoff and erosion for each plant community phase of the Limy Slopes 12-16" p.z. ES. We applied the methodology developed by Williams *et al.* (2014) for integrating eco-hydrologic information into the ESD, therefore, key information was extracted from the approved NRCS ESD for the Limy Slopes 12-16" p.z. ES (USDA-NRCS 2014) and from the rainfall simulator study conducted by Hamerlynck *et al.* (2012) at the Kendall site. The study by Hamerlynck *et al.* (2012) was carried out on four 2 x 6 m plots that took place from 21 June to 24 July 2008 at the Kendall Grassland site, they recorded and classified canopy cover as grass, shrub, or forb. The relative dominance (% of plant canopy) of the invasive Lehmann lovegrass, all native bunch grasses, and broad-leaved forbs was estimated by dividing the sum of hits for each plant by the total number of plants hits for each plot. Ground cover was recorded as rock + gravel (> 2mm), litter, basal, and bare soil and was measured both under and between canopy cover. They defined litter as dead plant material in contact with the soil surface. Total vegetative canopy cover was 20-26% in low-cover plots and 43-56% in high-cover plots, however, with the former dominated by the invasive South African bunchgrass, Lehmann's lovegrass. Ground cover was similar in terms of litter and basal area.

## MLRA 41-1 (12-16"), Limy Slopes

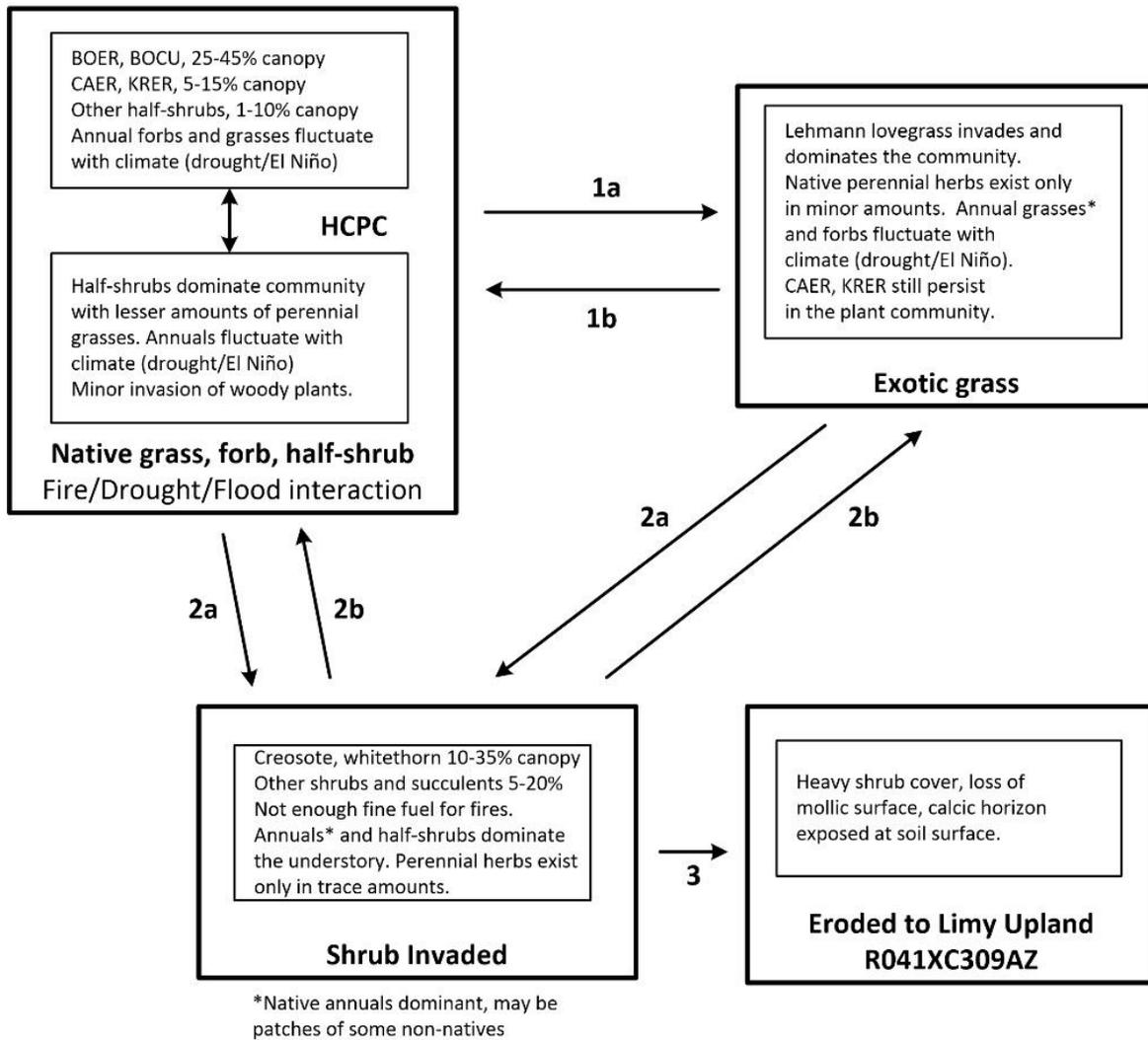


Figure 2. The State and Transition Model for the Limy Slopes 12-16" p.z. ES.

A baseline RHEM model scenario was configured to represent community phases using a CLIGEN station for rainfall inputs (Tombstone, AZ; Station ID: 0222, 1396 m elevation, 335 mm annual precipitation), sandy loam surface soil texture (46% sand, 39% silt, 15% clay), 50-m hillslope length, S-shape slope topography, and 12.5% slope gradient representative of the climate, soil, and topography attributes for the study site. In addition, the ESD provided a basis for foliar canopy and ground cover parameter estimation of the HCPC baseline scenario. Our baseline RHEM model scenario was applied to each plant community phase by adjusting cover characteristics (retaining the baseline climate, soil, and topography data) to reflect changes in the community composition. Foliar canopy cover information on the transition from native grass to Lehmann lovegrass in the STM was obtained from the 2 low-cover plots described in Hamerlynck *et al.* (2012), they pointed out that these plots were dominated by Lehmann lovegrass. Furthermore, foliar canopy cover for the shrub-invaded state was obtained from data presented in the STM. In addition, ground cover information was obtained from rainfall simulator studies on shrub-dominated plots at WGEW (Stone, unpublished data). Based on the description of the Eroded state in the STM (Figure 2), the site potential changes to something resembling to Limy Upland 12-16" p.z. ES, which includes the shrub-dominated Lucky Hills watersheds in the WGEW. Hence, canopy cover data was obtained from shrub-dominated rainfall simulator plots at this site. Ground cover remained similar in terms of rock cover across all states. Table 1 presents a summary of the input parameters of the Kendall Grassland site.

Runoff and erosion rates predicted by RHEM were consistent with published literature on the “Limy Slopes 12-16 p.z.” (Nearing *et al.*, 2007; Polyakov *et al.*, 2010). Simulation results for each scenario are shown in Table 2. In the study by Polyakov *et al.* (2010), they analyzed 58 successfully sampled sediment events during 19 years of observation. Annual sediment yield for different periods varied from 1.64 t ha<sup>-1</sup> to 0.01 t ha<sup>-1</sup>. Hernandez *et al.* (2013) applied the RHEM tool on 134 of the National Resource Inventory (NRI) rangeland field locations with data collected between 2003 and 2006 in MLRA 41. The average annual soil erosion rates varied from 0.20 t ha<sup>-1</sup> to 0.5 t ha<sup>-1</sup> on the “Limy Slopes 12-16” p.z. Nearing *et al.* (2007) estimated average annual sediment yield for the Kendall watershed in WGEW (0.07 t ha<sup>-1</sup>).

Table 1. Summary of input parameters of the Kendall Grassland “Limy Slopes 12-16 p.z.” Ecological Site (NRCS 2014).

SCENARIO INPUTS				
	BASELINE SCENARIO HCPC	SCENARIO 1 ERODED	SCENARIO 2 SHRUB_INVADED	SCENARIO 3 EXOTIC_GRASS
Version				
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 (meters)	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
Shrubs Foliar Cover %	10	35	35	10
Sod Grass Foliar Cover %	0	0	0	0
<b>Total Foliar Cover %</b>	<b>61</b>	<b>35</b>	<b>38</b>	<b>38</b>
Basal Cover %	8	0	3	3
Rock Cover %	16	16	16	16
Litter Cover %	45	9	10	35
Cryptogam Cover %	1	0	0	0
<b>Total Ground Cover %</b>	<b>70</b>	<b>25</b>	<b>29</b>	<b>54</b>

Table 2. Summary of predicted annual average runoff, sediment yield, and soil loss on the Kendall Grassland site “Limy Slopes 12-16 p.z.” ES



Analysis of the RHEM simulation runs on the “Limy Slopes 12-16 p.z.” ES 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 according with vegetation structure and behavior of different plant community phases. That is, an explanation for the difference in runoff and erosion in the HCPC and Lehmann states can be related to the increased water storage on the native bunchgrasses due to the formation of litter dams. 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 (Mitchel and Humphreys, 1987; Nearing *et al.*, 2007). According to Polyakov *et al.* (2010), before the Lehmann lovegrass invasion, the microtopography characteristic for the Kendall site where small terraces formed upslope of large clumps of 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 runoff and sediment yield. The erosion rate in both Shrub-dominated and Eroded scenarios is only slightly different as shown in Table 2.

## FUTURE WORK

Additional work is continuing on the RHEM Web-based interface system, which is currently fully functional for estimating erosion rates on relatively non-disturbed (e.g., fire impacted) scenarios, and a fully functional product including risk assessment and fire impact is expected to be completed by the end of 2015.

RHEM will be improved for application to both undisturbed and disturbed conditions across the western US. This work is intended to allow it to represent disturbed conditions, develop parameter estimation procedures for disturbed conditions. Initial analysis of data from fire-disturbed rangeland sites illustrate the importance of intra-storm dynamics on soil erodibility and the dominance of detachment by small concentrated flow channels as opposed to broad sheet flow. A new component has been developed to estimate erosion, in probabilistic terms, for potential varying management scenarios. Based on a 300-year CLIGEN run, RHEM produces average annual soil loss rates with a probability of occurrence for each RHEM management scenario. In addition, because of the strong orographic effects that dominate spatial precipitation patterns in the western U.S, the model will be improved to allow for orographic effects on precipitation by incorporating existing technology based on PRISM and CLIGEN into the RHEM model system. This capability will also allow for assessing climate change scenarios with the model, building on previous work by the investigators on soil erosion and climate change (Zhang *et al.*, 2012; Nearing *et al.*, 2004).

## CONCLUSIONS

RHEM, as applied in this study with input values reported in the literature, can be a valuable tool for predicting relative measures of runoff and erosion within the ESD framework. However, we caution against interpretation of RHEM results as absolute measures of runoff and erosion given the potential variability in soil loss across widely variable conditions within an individual ecological state or community phase and with increasing spatial scale. It is not possible to parameterize the model for all possible vegetation conditions of a given state or community phase. Rather, we suggest applying the model for average vegetation conditions and utilizing the results to interpret relative hydrologic and erosion function.

The framework of the RHEM tool facilitates the inclusion of new capabilities. Current research includes the integration of new equations for the application of RHEM in disturbed rangelands such as fire to predict surface erosion from postfire hillslopes, and to evaluate the potential effectiveness of various erosion mitigation practices. The RHEM probabilistic approach will be meaningful for land managers when they want to apply RHEM to risk-based management decisions.

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