Modeling Rangeland Watershed Erosion Processes

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Abstract

Most common soil erosion models were developed for agricultural conditions and then modified for rangeland, forest, and other applications. Rill and interrill erosion generally dominate upland agricultural erosion on recently tilled fields. In rangelands, soil is not tilled, rainfall is sporadic, infiltration is high, and the soil surface is covered by vegetation residues and sometimes rocks. Recent research has shown that as rangeland plant species change from the tall grass species that once dominated many plant communities, to short grass species through overgrazing, the hydraulic conductivity of the soil decreases and runoff increases. The net impact of the rangeland surface and plant changes is that upland erosion may be low, and the dominant source of sediment from rangelands may be from channels.

This paper describes a study in southeastern Colorado on sedimentation from rangeland watersheds. The observed rates are compared to predicted erosion rates from a locally developed erosion model, RUSLE, the WEPP model with typical rangeland vegetation and soil scenarios, and the rangeland predictions from the Forest Service WEPP interface and database. The local regression model and the Forest Service WEPP interface best predicted sedimentation from small rangeland watersheds. RUSLE overpredicted sediment yields by a factor of 3, and the WEPP rangeland predictions were 1/6 the observed sediment yields. In a sensitivity analysis with the FS WEPP interface, as cover increases, differences in runoff and erosion between soils decreases.

Introduction

Rangelands, like all land surfaces are susceptible to soil erosion by water. Soil erosion is the process of detachment and transport of sediment particles by an erosive agent, generally wind or water. Soil erosion can reduce upland productivity, and adversely impact aquatic ecosystems and other beneficial uses of surface water.

Erosion Processes. Erosion can occur on upland areas or in channels. The dominant erosion processes in the uplands are interrill (raindrop splash and shallow overland flow), and rill (concentrated overland flow) erosion. In channels, gully processes (headcutting), channel scour, and bank erosion are common. In some conditions, depositional processes in the stream on flood plains may dominate the sedimentation processes. On rangeland, the dominant processes tend to be either rill and interrill on upland sites, and gully and stream erosion during major runoff events.
Role of Management

Vegetation. Vegetation plays a complex and important role in rangeland erosion processes. The amount of vegetation is highly dependent on the seasonal rainfall for within-year growth, and long term climate and management patterns for the mix of plant species.

Vegetation reduces soil water content through evapotranspiration, which is dependent on the availability of soil water and depth of rooting, the climate, and the plant species. Vegetation also produces surface residue as plants drop leaves, or die at the end of the growing season.

Grazing. Grazing reduces the amount of vegetation available to become soil cover. It can also compact the soil, decreasing soil water holding capacity and decreasing infiltration rates, leading to increased runoff.

Compacted soil may be less erodible as has been found on native surface roads (Elliot at al., 1995), but the increased runoff will likely lead to a greater net erosion rate. Also, grazing leads to cattle paths with no vegetation, which can concentrate runoff and initiate the gully formation process.

Soil Properties

Rangeland soils tend to have low erodibilities. They are not disturbed by tillage, as common with agricultural soils. They frequently have a surface with a significant stone cover which is likely due to armoring from many years of water and wind erosion.

The hydraulic conductivity of a rangeland soil appears to vary with the type of vegetation (Flanagan and Livingston, 1999; Franks et al., 1998; Spaeth, 2000). Soils with shrub or juniper coppice communities tend to have the highest conductivities, with tall grass soils somewhat lower, and short grass species the lowest. Conductivities, however, vary widely with texture and cover, as has been observed on forest soils (Robichaud 1996). Figure 1 shows the distribution of hydraulic conductivities from a recent study for different soil textures, cover, and plant communities.

Current Prediction Models

RUSLE. Currently, one of the most common methods to estimate soil erosion on rangelands is with the Universal Soil Loss Equation (USLE) and more recently, the Revised USLE (RUSLE). RUSLE only estimates rill and interrill erosion rates (Renard et al., 1997). The USLE was developed in the Midwestern U.S. for agricultural conditions, but RUSLE has been developed for both agricultural and rangelands. RUSLE was developed to predict upland erosion only, and not delivered sediment. Work is ongoing to improve the ability of RUSLE to predict sediment delivery. It has no stream channel prediction capabilities.

WEPP. The Water Erosion Prediction Project (WEPP) model is a physically-based model that describes the processes that cause erosion (Flanagan and Livingston, 1995). With a daily time step, WEPP grows vegetation, turns vegetation into surface residue, removes vegetation through harvesting or grazing, and calculates a daily soil water balance. For every precipitation event, it determines runoff as a function of soil water content, and sediment detachment, transport, deposition, and delivery. The vegetation can be described in a rangeland or a cropland format.
Rangeland erosion prediction capability was part of the WEPP model from its inception. It models plant growth as a single or double-peak function, and allows removal of vegetation by grazing. A complex interface assists users in specifying grazing times, amounts, and densities, as well as soil, topographic, and climatic attributes of a site. Users have found the interface difficult to use, however, and the rangeland templates provided with the model frequently under predict observed upland erosion.

The cropland format of WEPP models plant growth using the EPIC plant growth model. Growth rate depends on the biomass conversion ratio value input to WEPP for a given plant, solar energy, temperature, and the availability of soil water. Elliot and Hall (1997) have developed a set of templates for the cropland format of the WEPP model to describe typical forest conditions. They chose the cropland format in order to describe the mechanical disturbances associated with road or log skidding activities. The rangeland version does not allow mechanical operations.

The WEPP model is available in two topographic versions, hillslope and watershed. The hillslope version of the model describes a hillslope of specified width, with up to ten different combinations of soil and/or vegetation along a hillslope. The watershed version of the model combines hillslopes with up to twelve channel segments. Control structures, small reservoirs, and sediment basins can also be incorporated into the watershed version.

The WEPP ARS model can be run either from an MS-DOS text-based interface, originally released in 1995, or a Windows interface that has been under development since 1998. Both interfaces include rangeland templates. Both interfaces allow the user to alter any of several hundred input variables necessary for a WEPP run. With this flexibility, however, comes complexity in understanding and

![Figure 1. Observed hydraulic conductivity values for a number of different soil textures, vegetation and surface cover amounts (from Franks et al., 1998)](image-url)
using the interface. Field users seldom have the time to become proficient at using
the interface, so it has not been widely adopted.

To capture the ability of WEPP to model site-specific erosion, while keeping
the interface simple, we have developed a web browser interface that can either be
run over the internet on one of our file servers, or standalone, on a personal computer.
The interface (Forest Service WEPP or FS WEPP) predicts average annual runoff
erosion, and sediment yield values, and also determines annual probabilities of the
occurrence and magnitude of events. FS WEPP uses the “cropland” format to
describe all vegetation scenarios, and its soil database varies soil properties with
texture and type of vegetation (Elliot et al., 2000)

There has been considerable effort in validating WEPP for midwestern and
southeastern agriculture, and some validation for forest conditions. Limited
application of the watershed version of the WEPP model to range has shown that
particular care needs to be taken when determining soil hydraulic conductivity values
(Savabi et al., 1990; van der Zweep and Stone, 1991).

Local Models. There are numerous examples of the development of local models for
erosion prediction, from an extended local database. Recent examples in forests
include WATSED, developed from data collected in the central Idaho mountains
(USDA Forest Service 1990), and the Washington Forest Practices method,
developed by numerous agencies and industry groups for the state of Washington
(Washington Forest Practices Board, 1997). The USGS developed such a model for a
southeastern Colorado rangelands from a cooperative study with the U.S. Dept. of the
Army (von Guerard et al. 1987). A common feature of most of these models is that a
number of factors are identified as important, like soil and land use, and a weighted
average of these factors used to estimate a sediment yield.

Model comparison

Study Site. The U.S. Geologic Survey carried out an water quality study on a 990
km$^2$ rangeland military site in southeastern Colorado (von Guerard et al. 1987, figure
2). The site ranged in elevation from 1326 to 1800 m. The annual precipitation is
about 300 mm, and the soils range from fine to coarse, depending on the parent
material. During the last 100 years, the area has been used for livestock grazing and
later, military maneuvers. The purpose of the USGS study was to evaluate the impact
of military activities on surface and ground water quality.

As part of that study, the USGS measured the sediment that had accumulated
in 48 stock watering ponds on 29 watersheds ranging from 20 to 416 ha. The mean
annual sediment yields from these watersheds ranged from 0.03 t ha$^{-1}$ to 5.97 t ha$^{-1}$.

Selected Watersheds. Five watersheds were selected from the study area for model
comparison. Preference was given to the smaller watersheds where upland erosion
rather than channel erosion processes would dominate, since both the current WEPP
versions and RUSLE are intended to model upland erosion only. The properties of
the watersheds are summarized in Table 1.
Validation Procedure

Certain assumptions were required for each of the models validated, except the locally developed USGS regression model. The main assumptions are presented in table 2. The climate for the two WEPP interfaces, Timpas, CO, was located at the edge of the study site (figure 2). Values from table 2 were entered into the respective models for each watershed, and the results noted. Predicted values for the USGS model were from von Guerard et al. (1987). Overall means, and the error sum of squares were calculated for each model. Runoff amounts had been estimated for two years from three of the selected watersheds. Both versions of the WEPP model predicted runoff for their runs for an average of thirty years.

Results and Discussion

The sediment delivery results are presented in table 3, and the runoff comparisons in table 4. From table 3, the locally developed USGS model, and the FS WEPP model appear to be much better predictors of soil erosion than either RUSLE or the WEPP rangeland model. The USGS model was developed for all of the

Table 1. Properties of model validation watersheds.

<table>
<thead>
<tr>
<th>No</th>
<th>Area ha</th>
<th>Sed Yield t/ha</th>
<th>Soil</th>
<th>Topograp % slope</th>
<th>Slope L m</th>
<th>Cover %</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>39</td>
<td>0.13</td>
<td>loam</td>
<td>2.5</td>
<td>330</td>
<td>50</td>
</tr>
<tr>
<td>7</td>
<td>26</td>
<td>5.97</td>
<td>clay</td>
<td>25</td>
<td>300</td>
<td>35</td>
</tr>
<tr>
<td>27</td>
<td>29</td>
<td>2.57</td>
<td>sand</td>
<td>25</td>
<td>250</td>
<td>30</td>
</tr>
<tr>
<td>38</td>
<td>26</td>
<td>0.98</td>
<td>loam</td>
<td>2.5</td>
<td>250</td>
<td>25</td>
</tr>
<tr>
<td>45</td>
<td>34</td>
<td>2.75</td>
<td>loam</td>
<td>22</td>
<td>300</td>
<td>35</td>
</tr>
<tr>
<td>avg</td>
<td>30.6</td>
<td>2.48</td>
<td>15.4</td>
<td>286</td>
<td>35</td>
<td></td>
</tr>
</tbody>
</table>
watersheds in the area, and may be over-predicting on the selected set as they were the smaller watersheds in the data set.

RUSLE over-predicted soil erosion by a significant amount, particularly on the longer steeper slopes. RUSLE is intended to predict upland erosion, and not sediment delivery, so the predicted values should be greater than the observed values. The magnitude of this difference, however, may be excessive when considering the small size of the watersheds under consideration (averaging 31 ha). The $LS$ factor, which was developed from agricultural research, may be over-compensating for the higher values. The $C$ factor was based on vegetation type and surface cover as suggested in Ward and Elliot (1995). If greater information on the nature of the cover were available, a lower $C$ factor may have been estimated using the guidelines in Renard et al. (1997).

The rangeland templates from the WEPP model appear to under predict sedimentation (table 3) while over predicting the runoff amounts (table 4). As the observed runoff values were for only two years, it is possible that those years may have been drier than the average annual precipitation for the Timpas, CO climate (413 mm). The USGS had stated that the average precipitation was around 300 mm.

The FS WEPP predictions result in the lowest error in sediment delivered, and

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Observed</th>
<th>USGS</th>
<th>RUSLE</th>
<th>WEPP rangeland</th>
<th>FS WEPP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.13</td>
<td>1.09</td>
<td>0.72</td>
<td>0</td>
<td>0.05</td>
</tr>
<tr>
<td>7</td>
<td>5.97</td>
<td>3.88</td>
<td>17.98</td>
<td>1.08</td>
<td>5.34</td>
</tr>
<tr>
<td>27</td>
<td>2.57</td>
<td>3.27</td>
<td>13.26</td>
<td>0.50</td>
<td>4.79</td>
</tr>
<tr>
<td>38</td>
<td>0.98</td>
<td>3.40</td>
<td>1.03</td>
<td>0</td>
<td>0.63</td>
</tr>
<tr>
<td>45</td>
<td>2.75</td>
<td>3.06</td>
<td>19.55</td>
<td>0.50</td>
<td>4.49</td>
</tr>
<tr>
<td>Mean</td>
<td>2.48</td>
<td>2.94</td>
<td>10.51</td>
<td>0.42</td>
<td>3.06</td>
</tr>
<tr>
<td>Error SS</td>
<td>11.7</td>
<td>282.3</td>
<td>34.2</td>
<td>8.5</td>
<td></td>
</tr>
</tbody>
</table>

* From Ward and Elliot (1995)
they are the closest of the two WEPP versions in predicting runoff. There is a small
over prediction of erosion, which may be due to the channel processes that were not
modeled, and an over prediction in runoff, which may be due to differences between
the average climate which ran the model compared to the weather the two years that
runoff was observed.

The two WEPP models both predicted runoff, whereas the USGS model and
RUSLE can only predicted erosion. Not knowing the exact weather that caused the
observed runoff makes detailed comparisons of runoff inappropriate. With both
versions of WEPP, the runoff amount was a function of both topography and
vegetative cover. This feature will make future development of the model for
rangeland runoff, erosion, and channel processes as impacted by upland vegetation
feasible.

**Impact of vegetation on runoff.** From the modeling results, it appears that both
versions of WEPP are able to model the differences of vegetation on runoff. A
sensitivity analysis was carried out to quantify this relationship with FS WEPP. A
typical hillslope with a loam soil, 200 m long, with a 20 percent slope (decreasing to
8 percent at the base) was entered along with the Timpas, CO climate. The
vegetation was set to provide 30, 50, and 80 percent cover for both tall grass and
short grass soil properties. The results of these six runs are presented in figure 3. At
low levels of cover, the effect of the cover on the soil results in large differences in
erosion as well as runoff. At higher levels of cover, both erosion and runoff decline
to the point that there is little difference between the two plant communities.
Apparently, the effects of greater amounts of cover tend to overshadow soil
differences in the WEPP cropland version. Similar conditions where cover dominates
soil properties is common in forests (Robichaud et al., 1993). This may not

![Runoff vs Cover](chart1.png)

![Erosion vs Cover](chart2.png)

**Figure 3.** Impact of cover and vegetation type on predicted runoff and soil
erosion

<table>
<thead>
<tr>
<th>Watershed</th>
<th>Observed</th>
<th>WEPP Rangeland</th>
<th>FS WEPP</th>
</tr>
</thead>
<tbody>
<tr>
<td>1</td>
<td>0.31</td>
<td>2.50</td>
<td>0.4</td>
</tr>
<tr>
<td>27</td>
<td>2.66</td>
<td>15.84</td>
<td>4.7</td>
</tr>
<tr>
<td>45</td>
<td>3.12</td>
<td>7.85</td>
<td>5.5</td>
</tr>
<tr>
<td>Mean</td>
<td>2.03</td>
<td>8.73</td>
<td>3.53</td>
</tr>
</tbody>
</table>
necessarily reflect observations that at similar higher levels of cover, short grass communities may have greater runoff (Spaeth et al., 2000).

**Conclusions**

Rangeland runoff and erosion rates are highly dependent on the type and amount of vegetative cover as well as climate and topography. Three rangeland erosion prediction models, RUSLE, WEPP for rangelands, and FS WEPP for rangelands were compared to observed sedimentation rates on five small southeastern Colorado watersheds. The locally-developed USGS regression model, and the FS WEPP interface gave the predictions most nearly like the observed for sedimentation. FS WEPP interface more closely predicted runoff than did the WEPP rangeland scenarios. Either version of WEPP was able to predict runoff as a function of upland topography and vegetation, making future development of more complex rangeland watershed sedimentation prediction feasible.

**References**


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