Effectiveness of sediment control structures relative to spatial patterns of upland soil loss in an arid watershed, Wyoming

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Abstract

Rainfall simulation experiments have been used to identify the variables that control rates of gross soil erosion in upland areas of the Fifteenmile Creek drainage in Wyoming. Rates of gross soil erosion were found to be most closely related to slope gradient, vegetation density, and soil texture. These variables were mapped for the drainage and digitized files of these maps were combined in a geographic information system to depict the spatial pattern of soil mobilization. Gross soil erosion in badland areas was found to be extreme when compared to the remainder of the drainage. Neither structural nor non-structural sediment control strategies are well-suited to these badland areas. Engineering structures to control sediment export had been constructed in poorly chosen locations at extreme and unnecessary expense to taxpayers. © 1999 Elsevier Science B.V. All rights reserved.

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1. Introduction

Fifteenmile Creek contributes less than 1% of the mean annual flow to the Bighorn River but 75% of the mean annual suspended sediment load, rendering the Fifteenmile Creek drainage as one of the most prolific producers of sediment in the state of Wyoming (Fig. 1; Ostresh et al., 1990). Fifteenmile Creek was identified as a “red flag” drainage in need of an aggressive sediment control program by the USDI Bureau of Land Management in the 1960s (Cooper, 1979). At a cost of US$2 million to taxpayers over a 10-year period, the following structural controls were implemented: 34 sediment detention dams, 110 reservoirs, and 21 spreader dikes. In addition, 2486 ha were contour-furrowed, grazing allotments were readjudicated, and 14,000 animal-mouths of grazing pressure were eliminated. Yochem and Rosenlieb (1978) evaluated suspended sediment concentrations in response to these measures using 20 years of streamflow and sediment data from a gauging station on Fifteenmile Creek near its confluence with the Bighorn River. They concluded that a 25% reduction in sediment concentrations could be directly attributed to the watershed improvements. However, recent inspection of the structures revealed that many have failed from lack of maintenance, reintroducing stored sediment back into the channel.

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Fig. 1. Location of the Fifteenmile Creek drainage within the Bighorn Basin, State of Wyoming. View is oblique from south to north. For scale, the dimensions of Wyoming are 586 km east–west by 447 km north–south.

More importantly, the poor performance of the Fifteenmile Creek sediment control program can be blamed on the failure to systematically identify nonpoint sources of sediment for optimal placement of sediment control structures. The objectives of this paper are to: (1) determine the land surface factors that influence upland sediment production, and (2) identify those portions of the drainage that contribute the majority of upland soil mobilization. This paper does not examine solute export, sediment delivery from upland areas, or sources of sediment production from the streamside riparian zone.

Fifteenmile Creek is a 1350 km² drainage in the Bighorn Basin of north–central Wyoming (Fig. 1). The basin has a median elevation of 1500 m and is situated in the rainshadow of the Absaroka Range to the west. The basin is a cold desert environment (Köppen BWK climate type) with a mean annual temperature of 7°C and mean annual precipitation of 200 mm of which approximately 10% falls as snow and 40% falls as summer rain (Martner, 1987). Locally intense summer thunderstorms occur throughout the drainage, commonly generating a large portion of the mean annual precipitation. Vegetation is occasionally absent, but where present it is dominated by shrubs, low grasses and forbs and cacti. Sagebrush (Artemesia spp.) and saltbush (Atriplex spp.) are the predominant shrub species found in the upland areas. Blue grama grass (Bouteloua gracilis), a sod-forming grass, and rhizomatous wheatgrass (Agropyron spp.) are the prevailing grasses and prickly pear (Opuntia polycantha) is the principal cactus. The drainage is underlain by the Willwood Formation, Eocene claystones and sandstones which have been eroded into badlands topography (Fig. 3). Soils range from clayey to sandy as a function of parent materials such as shale, mixed alluvium, siltstones and sandstones. In addition, the soils are alkaline and classified as aridisols (Knox et al., 1979). Drainages with these characteristics of cli-
Grazing of livestock has been the dominant land use in the drainage for over 100 years and livestock are often cited by environmentalists and scientists as the culprit for the extreme rates of sediment production from Fifteenmile Creek. The degree to which grazing has altered the prehistoric plant communities of the Bighorn Basin has not been well-established. Dorn (1976) used repeat photography and historical journals to conclude that vegetation density and composition have been essentially unchanged. Others have reviewed the literature which demonstrates that livestock in similar geographic settings eliminate native grasses in favor of shrubs and bunch grasses, accelerating upland runoff and erosion (e.g., Lusby, 1970; Satterlund, 1972; Cooke and Reeves, 1976; Branson et al., 1981; Graf, 1985). Whether the extreme suspended sediment loads can be attributed to grazing or to background production is an important question to resolve for the Fifteenmile Creek drainage because of the implications for sediment control strategies.

2. Methods

Because of the large size of the Fifteenmile Creek drainage, field studies focused on the Middle Fork of Fifteenmile Creek, with an area of 109 km². All terrain types are represented in the Middle Fork drainage. To establish a stratified sample of sites for field studies, the Middle Fork drainage was divided into landscape units using a computer-generated overlay of maps of slope gradient class, vegetation communities, and soil type. Slope gradient class was determined by the authors from 1:24,000 scale topo-
graphic maps using the contour spacing method (Marsh, 1991); six slope classes were mapped. Vegetation communities (classes by dominant species and cover) and soil type (classes by dominant texture) were determined using unpublished range site class maps of the USDI Bureau of Land Management (Knox et al., 1979; Iiams, 1983). The maps of slope class, vegetation, and soil texture were digitized with vector-based ArcInfo software. IDRISI software was also used to convert the vector-based files into raster-based files with a cell size of 100 m by 100 m. A total of 37 study sites were selected in a random-stratified process to represent the range of landscape units identified in the overlay process.

A rainfall simulator was constructed to conduct runoff and soil loss experiments at each of the 37 sites (Fig. 4). Logistical constraints of remote access, steep slopes, frequent winds, and lack of turbid-free water dictated the need for a simulator that was portable, easy to operate, durable and with a low rate of water consumption. Therefore, a drop-forming rainfall simulator design was chosen that is similar in structure to the Tahoe Basin simulator developed by Munn and Huntington (1976). The frame for the rainfall simulator was constructed of lightweight aluminum plate and square tubing. By extending the upper portion of the frame and/or by raising the legs of the frame, the height of drop fall can be adjusted from 1.8 m to 2.6 m. The adjustable legs, constructed of steel thread rod, are also used for leveling the simulator on slopes. Plywood sides were installed on the frame to shield the falling drops during times of light to moderate winds. However, a small area near the top of the simulator was left unshielded to allow some turbulence to enter and randomize the drop distribution pattern. Following the advice of Moeyersons (1983), a gutter trough near the base of the structure captured any drops falling outside the 0.61 m by 0.61 m plot area. A sheet metal border was used to define the plot perimeter. At the downslope end of the plot, a funnel trough was placed to direct runoff and sediment into sample containers.
A sheet of galvanized metal was also used to cover the plot while setting up the experiment. Our simulator utilizes a Plexiglas water chamber designed after the one by Chow and Harbaugh (1965). The dimensions of the chamber, and of the plot below, are 0.61 m by 0.61 m and embedded in the chamber are 576 polyethylene tubing tips with a 0.58 mm inside diameter and 0.97 mm outside diam-
Fig. 5. Trough used to collect runoff and sediment from 0.6 m × 0.61 m plot at the base of rainfall simulator. Photo by R.A. Marston.

meter. The tubes produce drops with a diameter of 3.2 mm. The rate of water entering the chamber from a 25-l reservoir, located above the drop-forming chamber, and the resulting rate of drop formation are controlled by a flow meter.

Our simulator produced 3.2 mm drops which fell from a constant height of 2.3 m. The maximum velocity of these drops was 5.7 m s⁻¹ (Epema and Riezebos, 1983). A storm intensity of 760 mm h⁻¹ for a 1-h duration storm was used. This design storm, held constant through the study (so as to isolate differences in terrain controls on runoff and soil loss), produced a total kinetic energy for each plot of 456 J, equivalent to a natural 1-h duration storm of 47 mm. This event is approximately the 50-year/1-h event for the nearest weather station at Worland, but it is an event that occurs nearly every summer at some point in the drainage.

Replicate experiments were conducted at each site for a total of 74 experiments. During each 1-h experiment, water-sediment samples were collected at 5 min, 15 min, 35 min and 55 min in order to observe time-dependent changes. Analyses of the water-sediment samples was performed in the Soils Laboratory of the Department of Geography and Recreation at the University of Wyoming. Samples were analyzed for volume (ml) by weight and sediment concentrations (mg l⁻¹) by evaporating the water and determining the weight of sediment in the sample. Solutes were not measured. The total runoff and sediment for the 1-h experiment was calculated by integrating the curves of runoff vs. time and soil loss vs. time.

The following site variables were measured:

1. Vegetation density: using the point-intercept method on photographs of the plot (Mueller-Dombois and Ellenberg, 1974),
2. Litter density: as above,
3. Slope gradient: using a slope pantometer,
4. Surface soil texture (0 cm to 4 cm): sample acquired adjacent to the plot and transported to the soils lab for analysis with a hydrometer.
A quantitative index of soil texture was derived by taking a weighted average of percentage sand (0.5 mm–2 mm), coarse silt (0.005 mm–0.5 mm), fine silt (0.002 mm–0.005 mm), and clay (<0.002 mm). An ordinal scale was then used to classify the soil on a scale of 1 to 4, with 1 being sand and 4 being clay.

Stepwise multiple regression was used to develop separate estimates of runoff (ml min⁻¹) and soil loss (g min⁻¹) using the four variables listed above.

3. Results

The range of values found for site variables and experimental data is presented in Table 1. The rate of soil loss varied during the 1-h experiment, usually increasing up to 15 min, then reaching a steady state (Fig. 6). By comparing two sites where all variables are similar except one, the control of that variable on soil loss can be discerned. Rates of soil loss were consistently higher on slopes of steep gradient (Fig. 6a). Litter and vegetation density also exerted a strong control (Fig. 6b); these two variables are intercorrelated. On the one site where litter and vegetation density were both 100%, the rate of soil loss declined during the experiment (Fig. 6c). This is attributed to the decline in splash from the downslope end of the plot once the soils had been wetted. Fine silts were eroded earlier and at a greater rate than sands (Fig. 6c).

Stepwise multiple regression yielded the following equation:

\[ \log E = 1.90 + (0.034)S - (0.00916)V + (0.191)T \]

where the variables are as defined in Table 1. The variables are shown in the order they entered Eq. 1.

Because rainfall energy was held constant, but experiments were conducted in a field setting, Eq. 1 differs in forms from many splash transport models (e.g., Poessen, 1985; Morris, 1986) in that it focuses on factors of erodability. Generally, rates of soil loss were highest on steep slopes, with fine-textured soils, and low vegetation–litter cover, a combination of site variables which leads to the formation of badlands. The equation is significant at the \( p < 0.001 \) level with a \( r^2 \) of 0.72. Slope gradient alone explains 62% of the variance in soil loss. Soil loss was highest in fine silts and clays, contrary to the findings of Poessen (1981) who found the highest detachability in fine very well-sorted sands. We suspect that soil erodability is controlled by several site characteristics which are important in the Fifteenmile Creek drainage but which have rarely been noted in previous studies. For instance, soils of the Bighorn Basin commonly have indurated calcic horizons close to the surface, limiting percolation. Salts in surface soils at concentrations less than 3% were found to disaggregate fine soils. Second, soil surface crusting was observed on many plots, a feature which enhances runoff but also counters erosion by increasing resistance of the soil surface (Bryan and De Ploey, 1983; Poessen, 1987). Third, small soil mounds form around the base of bunch grasses and cacti, concentrating surface runoff from sheetwash into rill-forming flows. Rock fragments also imparted the same effect in some experimental runs, an effect described by Poessen (1990). Therefore, microroughness plays a role in enhancing soil loss which may be more important than the role of soil factors which affect infiltration (Imenson, 1983). Because of these factors and the small plot size of our simulator, use of the Modified Soil Loss Equation (Mulkey, 1980) was

<table>
<thead>
<tr>
<th>Variable</th>
<th>Mean</th>
<th>Standard error</th>
<th>Maximum</th>
<th>Minimum</th>
</tr>
</thead>
<tbody>
<tr>
<td>Vegetation density, V (%)</td>
<td>49</td>
<td>25</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Litter density, L (%)</td>
<td>31</td>
<td>27</td>
<td>100</td>
<td>0</td>
</tr>
<tr>
<td>Slope gradient, S (%)</td>
<td>9.5</td>
<td>9.4</td>
<td>34</td>
<td>1</td>
</tr>
<tr>
<td>Soil texture index, T (1 = sand, 2 = coarse silt, 3 = fine silt, 4 = clay)</td>
<td>2.3</td>
<td>0.5</td>
<td>3.6</td>
<td>1.5</td>
</tr>
<tr>
<td>Runoff (1 h⁻¹)</td>
<td>10.0</td>
<td>7.0</td>
<td>24.4</td>
<td>0</td>
</tr>
<tr>
<td>Soil loss (g h⁻¹)</td>
<td>377</td>
<td>608</td>
<td>2860</td>
<td>2</td>
</tr>
</tbody>
</table>
found to be of no utility in evaluating spatial patterns or rates of soil loss in this study.

The variables in Eq. 1 had been digitized in raster format, so it was possible to combine them in their proper mathematical relation using IDRISI software. Results were displayed using a 3-D algorithm developed for IDRISI output by Dr. Larry Ostresh of the University of Wyoming Department of Geography and Recreation (Fig. 7). In this manner, the spatial pattern of estimated soil loss can be displayed, as tried previously by Vold et al. (1985) in British Columbia. In some areas, rates of soil loss were calculated for regions with slope gradients greater than could be sampled with our rainfall simulator. From this figure, it is evident that rates of soil loss vary significantly within the drainage as a function of slope gradient, vegetation cover, and soil texture. The badlands in the south-central portion of the drainage, 8.5% of the drainage by area, contributed 62% of the total soil loss. In contrast, the low relief, better vegetated lowlands in the eastern portion of the drainage, 30% of the drainage by area, con-
tributed only 5.5% of the total soil loss. The remainder of the drainage contributes sediment in quantities roughly proportional to area. The total gross upland erosion for the 50-year/1-h storm is 202,000 tonnes.

4. Discussion and conclusions

A portable rainfall simulator has been used in the field to identify the relative importance of land sur-
face variables controlling upland rates of gross soil erosion. The most important variables controlling gross soil erosion were slope gradient, vegetation density, and soil texture. These results are consistent with variables identified by Meeuwig (1970) and Blackburn and Skau (1974) who used rainfall simulators to investigate upland sediment production in semi-arid drainages. Other, more detailed analyses of soil crusting, dispersible clays, and microroughness caused by vegetation may add to the ability to estimate soil loss in future studies in this geographic setting. The key variables identified in this study are variables that could be altered by land management techniques.

A geographic information system and computer-aided mapping have been used to identify the spatial pattern of upland soil mobilization on the scale of the drainage basin. A GIS can be used to combine variables with their proper weighting as determined from multiple regression. Badlands eroded in the Willwood Formation, 8.5% of the drainage by area, account for 62% of the gross soil erosion. This result compares favorably with the study by Campbell (1977) who found that badlands only occupy 2% of the Red Deer River drainage but contribute 80% of the total suspended sediment load.

Possible measures for controlling sediment production from Fifteenmile Creek include increasing vegetation cover and/or constructing sediment control structures. Increasing vegetation cover would be limited to those areas of the drainage where soil and slope conditions would allow vegetation to recover. Unfortunately, it is unlikely that vegetation cover could be improved or even established in the badland areas which account for the greatest sediment production. Vegetation buffer strips might prove effective between the base of badland areas and ephemeral channels. Additional structures would be most effective if constructed adjacent to badlands areas; many of the structures constructed in the 1960s are situated in areas of low sediment production. Straw bale or sandbag sediment traps would be more effective than the low earthen dams which are easily eroded once filled with sediment. The effective life of sediment detention dams, reservoirs, and spreader dikes adjacent to badlands is likely to be short without frequent maintenance. Because of the extreme rates of background erosion occurring in Fifteenmile Creek drainage, high rates of sediment production should continue. Downstream users of the water from the Bighorn River will have to continue to manage for the negative effects of this suspended sediment, including increased costs for municipal water treatment, damage to fisheries, and reduced storage volume in a downstream reservoir.

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