Process-based modeling of upland erosion and salt load in the Upper Colorado River Basin

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Introduction

The Colorado River is a vital municipal, agricultural and ecological resource in the United States and Mexico but is susceptible to detrimental salinity levels. The U.S. Bureau of Reclamation estimates that damages due to salinity of the Colorado River are estimated at $385 million per year. Over 55% of sediment and salts entering the Colorado River is of natural origin with a significant contribution from accelerated soil erosion on federal rangelands.

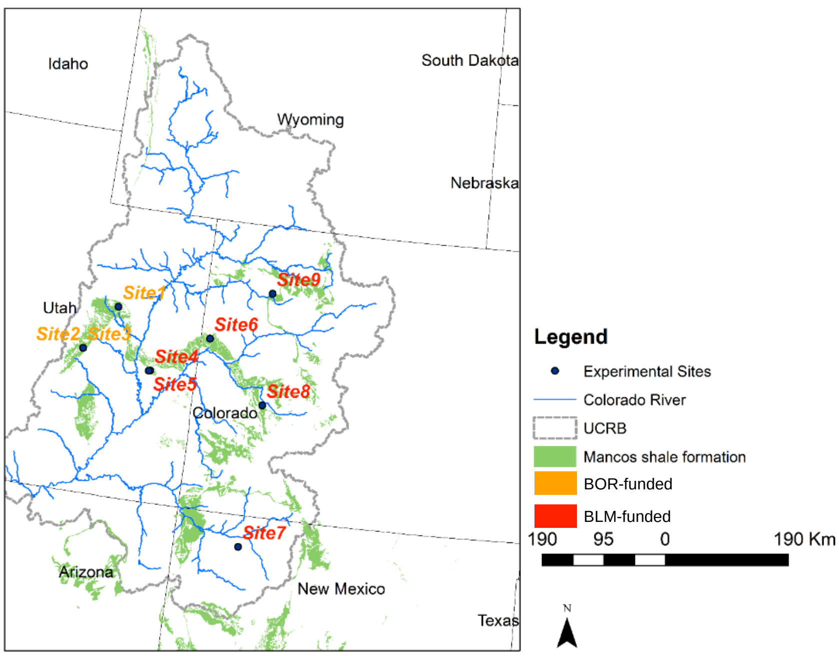

Figure 1 Map of the Upper Colorado River Basin (UCRB) showing the Mancos shale geologic formation and experimental sites funded by the U.S. Bureau of Reclamation (BOR) and the Bureau of Land Management (BLM).

High salt transport in these rangelands is imputed to a marine geologic history of the area resulting in salt-rich geologic formation. One such geologic formation is the Mancos shale (Figure 1) which has been described as one of the dominant sources of salt transport to the Colorado River. Knowledge on salt pickup and transport processes is limited to a few studies linking salt transport to soil erosion. As a consequence of this knowledge gap, no tool exists to satisfactorily predict salt load to surface waters in the Upper Colorado River Basin (UCRB). In this study, we aim to develop parameter estimation equations that are valid on saline rangeland sites for use in the Rangeland Hydrology and Erosion Model (RHEM).

Methods

RHEM was specifically developed by the U.S. Department of Agriculture to predict runoff and erosion on Rangelands. The model predicts runoff and erosion using physically-based flow routing, detachment and transport equations. The parameters of which are derived from estimation equations developed from rangeland data to reflect rangeland conditions. Because the original data used to develop RHEM did not include any saline or sodic (high in sodium) soils, new experimental data was collected at saline and sodic sites of the UCRB to test current RHEM equations and develop better parameter estimation functions. Data from rainfall simulation experiments at 9 sites in the UCRB (Figure 1) were used to develop these predictive equations. At each experimental site, rainfalls of intensities corresponding to the 2-, 10-, 25- and 50-year return frequency for the area were simulated at a rate of 1 event per plot, resulting in a total of twelve plots per site. Plot dimensions were 6 m x 2 m. During each rainfall event, traditional soil erosion measurement data (runoff rate and volume, soil loss and sediment concentration) were collected along with information on soil salinity and sodicity represented by Electrical Conductivity EC and Sodium Adsorption Ratio (SAR).

New equations for estimating the soil effective hydraulic conductivity (Ke) and the splash and sheet erodibility (Kss) on saline and sodic soils were developed. A Markov Chain Monte Carlo optimization was used to find the best Ke and Kss values that minimized error in runoff and soil loss prediction respectively. These optimum Ke and Kss values were then compared to current compared to the values of these parameters estimated by current RHEM equations by calculating corrective terms as differences and ratios between optimum and estimated values. The corrective terms were then regressed against vegetation characteristics and soil physiochemical properties to identify statistically significant factors controlling deviations of saline/sodic sites from RHEM parameter-estimation equations. The new Ke and Kss equations for saline / sodic sites were constructed by combining predictive equations for the corrective terms with the original RHEM parameter-estimation equations. Runoff and soil loss prediction performances of the new equations were compared to the original RHEM equation and evaluated with the Nash-Sutcliff Efficiency (NSE), the coefficient of determination (R^2) and the percent bias (PBIAS). Model performance was evaluated on 36 calibration plots and 36 validation plots originating from 6 of the 9 experimental sites. Data from the remaining 3 sites were used for independent validation.

Results and discussion

Differences between the equations for estimating the effective hydraulic conductivity (Ke) and the splash and sheet erodibility (Kss) on saline/sodic rangelands and the original RHEM equations for Ke and Kss are shown in in Table 1. Overall the effective hydraulic conductivity was amplified on saline / sodic sites compared to that predicted by the original RHEM Ke estimation equation. The splash and sheet soil erodibility was a function of the soil Sodium Adsorption Ratio SAR.

The performance of the newly developed saline RHEM equations for Ke and Kss are compared to the original RHEM equations in Figures 2 and 3 for the calibration data. Overall, the new Ke and Kss equations improved runoff and soil loss predictions as evaluated by all performance metrics.

Table 1. Estimation equations for the effective hydraulic conductivity (Ke) and the splash and sheet erodibility (Kss) used by the Rangeland Hydrology and Erosion Model (RHEM) on non-saline and saline / sodic sites. Parameters *a* and *b* are fitting parameters, *basal* and *litter* are the ground cover fraction occupied respectively by the base of plants and by litter. *SAR* is the Sodium Adsorption Ratio.

Parameter	Original RHEM	Saline / sodic sites
Effective hydraulic conductivity	$Ke = a \exp\left(b\left(basal + litter\right)\right)$	$Ke = a \exp\left(1.554b\left(basal + litter\right)\right)$
Splash and sheet erodibility	$Kss = Kss_{RHEM}$	$Kss = Kss_{RHEM} + \left(642.4\ SAR\right)$

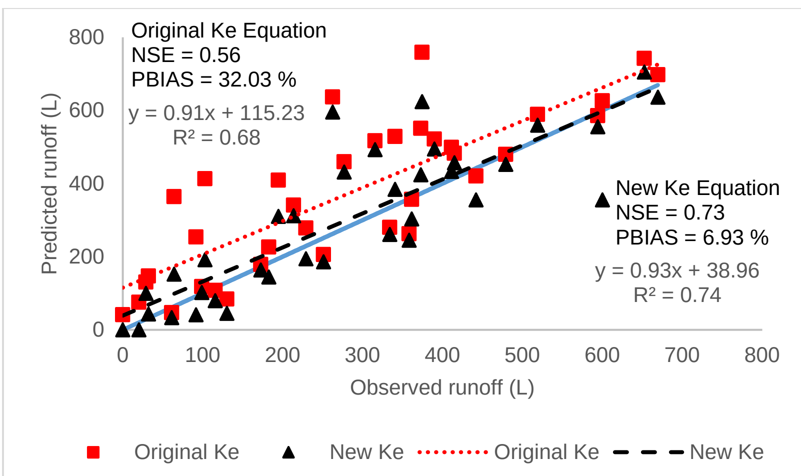

Figure 2. Observed vs. predicted runoff on 36 rainfall simulation calibration plots using current RHEM parameter estimation

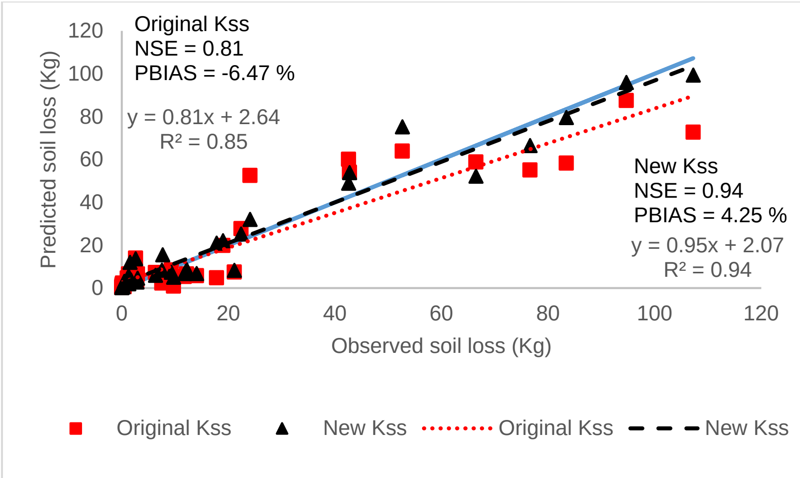

Figure 3. Observed vs. predicted soil loss on 36 rainfall simulation calibration plots using current RHEM parameter estimation equations

Performance improvements observed on the calibration data were sustained on the validation data (Figures 4 and 5).

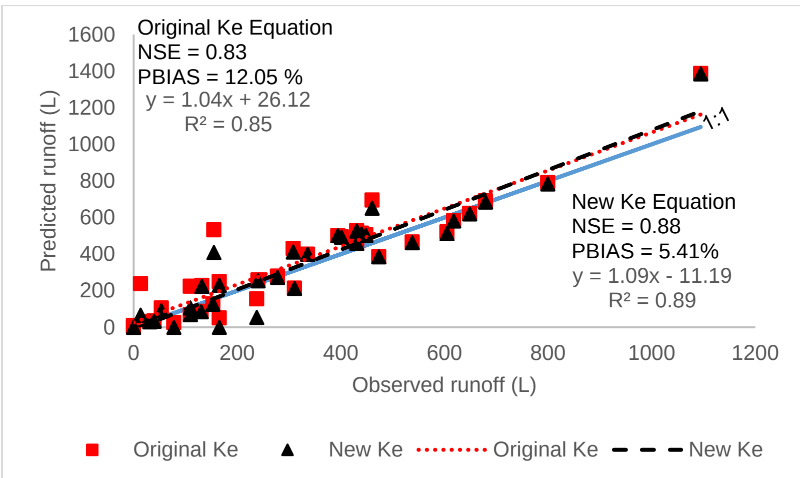

Figure 4. Observed vs. predicted runoff on the 36 validation data points using the current and the newly developed estimation equation for the hydraulic conductivity Ke

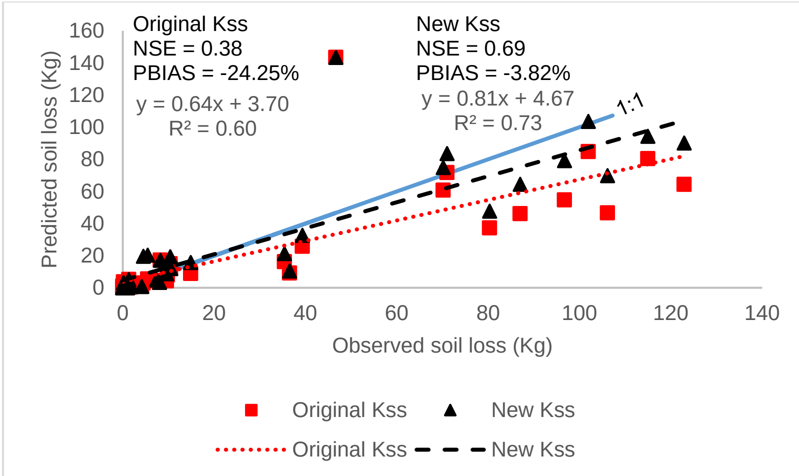

Figure 5. Observed vs. predicted soil loss on the 36 validation data points using the current and the newly developed estimation equation for the sheet and splash erodibility, Kss

A strong linear relationship was found between soil loss and total dissolved solids (a measure of salinity) in runoff with a coefficient of determination of 0.94.

$$TDS = 2.36 \times SL + 0.99$$

where TDS (10^{-3} kg) is the total dissolved solids and SL is the soil loss (kg).

With this model, soil loss data predicted with RHEM on saline / sodic sites were used to calculate TDS content in runoff (Figure 6). As shown in Figure 6, the TDS values calculated from soil loss data modeled with newly developed equations closely matched the 1:1 line when plotted against observed TDS values.

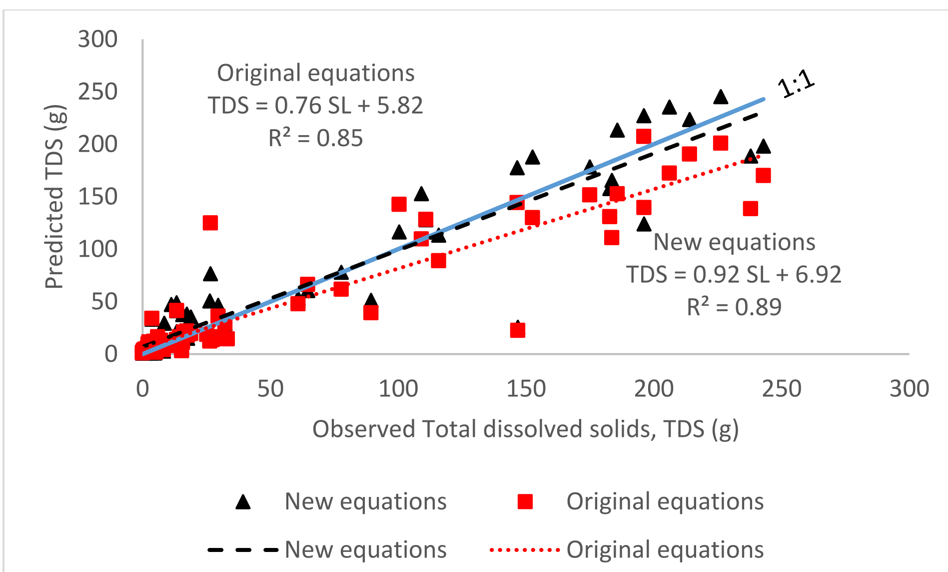

Figure 6. Observed vs. predicted total dissolved solids (TDS) on the 72 data points using the current and the newly developed estimation equations for Ke and Kss

Summary and conclusions

The newly developed equations for the effective hydraulic conductivity and the splash and sheet erodibility adequately captured infiltration, runoff and erosion processes on saline rangelands. The performance of the RHEM model at predicting runoff and soil loss was improved with the usage of the new equations compared to the original equations. Overall, the effective hydraulic conductivity was greater on these saline rangelands compared to that predicted by the non-saline RHEM equation. Erosion was overall greater on these rangelands and was a positive function of the Sodium Adsorption Ratio. A linear function between soil loss and total dissolved solids in runoff was used to predict salt load from soil loss data. These new equations will be integrated in a new version of the RHEM model to provide a tool for land and water resource managers to evaluate erosion, runoff and water quality on salt-affected rangelands.