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Experimental investigation of the effect of vegetation on soil, sediment erosion, and salt transport processes in the Upper Colorado River Basin Mancos Shale formation, Price, Utah, USA

Erik M. Cadaret [a], Sayjro K. Nouwakpo [b,*], Kenneth C. McGwire [a], Mark A. Weltz [c], Robert R. Blank [c]

[a] Desert Research Institute, Division of Earth and Ecosystem Sciences, Reno, Nevada, USA
[b] University of Nevada Reno, Department of Natural Resources and Environmental Science, Reno, Nevada, USA
[c] U.S. Department of Agriculture, Agriculture Research Service, Great Basin Rangelands Research Unit, Reno, Nevada, USA

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A B S T R A C T

Because of concerns about salinity in the Colorado River, this study focused on saline and sodic soils associated with the Mancos Shale formation with the objective of investigating mechanisms driving sediment yield and salinity loads and the role of vegetation in altering soil chemistry in the Price-San Rafael River Basin. Rainfall simulations using a Walnut Gulch rainfall simulator were performed at two study sites (Ferron and Price, Utah) across a range of slope angles and rainfall intensities to evaluate the relationship between sediment yield, salinity transport processes, and rainfall-induced changes in soil chemistry. Soil at Ferron had substantially greater salinity than Price as expressed in evaluated sodium absorption ratio, cation exchange capacity in soil, sediment, and total dissolved solids (TDS) in runoff. Principal component analysis and *t*-tests revealed that the two sites have different runoff and soil chemistry ions. Greater concentrations of K^+, NO_3^-, and Cl^- were present in soil-under-vegetation microsites compared to interspace soil areas. Soil soluble phase ions generally increased with depth and underwent vertical fluxes at rates proportional to rainfall intensity. Vegetation appears to have a protective effect on the soils from increasing rainfall intensity. Mat-forming saltbush found at Ferron was related most strongly to soil protection. The dissolution of sediment particles in runoff may be a key component of salinity transport processes on the Mancos Shale. Plot-averaged sediment and TDS had a positive linear relationship. The Rangeland Hydrology and Erosion Model successfully predicted TDS in runoff derived from these upland rangelands in central Utah.

1. Introduction

The Colorado River Basin provides water for millions of people in the western U.S. and Mexico. Before substantial settlement of the west occurred, the salinity load of the Colorado River was estimated to be 600–700 ppm (ppm) in the Lower Colorado River Basin (Blackman et al., 1973). Concerns over increase in river salinity led to the ratification of the Colorado River Basin Salinity Control Act of 1974 to meet treaty obligations with Mexico. Since the Salinity Control Act was enacted, total dissolved solids (TDS) has been reduced by about 1.2 million tons per year (Bureau of Reclamation, 2011). Damages within the United States from dissolved solids in the Colorado River still exceed $380 million per year (Bureau of Reclamation, 2005, 2011). The salinity-control effort has largely focused on reducing dissolved-solids loading from irrigated lands (Bureau of Reclamation, 2011). About 55% of the TDS comes from natural, non-irrigated sources on rangelands (Kenney et al., 2009). This suggests there is significant potential to further reduce dissolved-solids loading to the Colorado River through land- and water-management activities on rangelands.

The most vulnerable rangeland areas in the Upper Colorado River Basin (UCRB) for soil and salt movement are where annual precipitation is between 100 and 400 mm per year which limits soil moisture available to sustain plant growth. With low plant density and minimal plant and ground surface cover, arid and semi-arid areas are prone to both wind and water erosion and transport of salts. Arid and semi-arid regions have low plant density which often results in open and connected bare interspaces where aerodynamic roughness is low and fetch length is sufficient to allow for wind erosion and transport of salts (Okin et al., 2009). In addition, there is insufficient vegetation canopy and ground surface cover to prevent soil or salt movement from raindrop slash, sheet, and rill erosion in the bare connected interspaces

Abbreviations: CEC, cation exchange capacity; ID, immiscible displacement; MASL, meters above sea level; PCA, principal component analysis; RHEM, Rangeland Hydrology Erosion Model; SAR, sodium absorption ratio; TDS, total dissolved solids; VCC, vegetation canopy cover; WGRS, Walnut Gulch rainfall simulator.

* Corresponding author.
E-mail address: snouwakpo@unr.edu (S.K. Nouwakpo).

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(Puigdefabregas, 2005). The relatively low vegetation cover combined with high intensity convective rainfall events makes the UCRB one of the most erosive areas of the United States.

Average sediment yield frequently exceeds 3 tons per hectare per year on the Colorado Plateau (Langbein and Schumm, 1958). As water erosion is exponentially related to rainfall intensity, most of the soil erosion occurs during rare spatially distributed convective storm events. Consequently, rilling and arroyo formation is very pronounced in the Colorado Plateau (West, 1983). Interaction between wind erosion and deposition and water erosion, transport, and deposition is poorly understood. Nevertheless, limited vegetation cover and steep, highly dissected slopes of weathered marine shales in the UCRB make these areas prone to both types of erosion and transport processes. Therefore, total erosion and transport of salts maybe maximized in these arid and semi-arid regions. In Utah, 7–15% of the rangeland areas are classified as being in a severely eroding condition, and 20% of these lands are at risk of accelerated soil erosion (Rasely et al., 1991; Weltz et al., 2014). It is estimated that these areas are responsible for 75–90% of the increasing sediment and salt yields in Utah (Rasely et al., 1991).

The Mancos Shale formation spans a wide area in the UCRB in southeast Utah and has been identified as a major producer of sediment, salinity, and selenium to the Colorado River (Evangelou, 1981; Tuttle et al., 2014a, 2014b). One of the tributaries of the Colorado River, the Price River, contributes <1% of the water, but approximately 3% of the salt load in the Colorado River, with a substantial part of the salt load originating from the Mancos Shale formation (Rao et al., 1984). The majority of the Mancos Shale formation is under the control of the federal government (Bureau of Land Management, National Park Service, and the Bureau of Reclamation). This creates an opportunity to reduce salinity through proactive land and water management practices.

Several studies have investigated salinity transport processes on the Mancos Shale formation and how it relates to soil erosion. Laronne and Shen (1982) conducted a study on the Mancos Shale and determined that several factors of solute pickup are related to sediment erosion processes. These factors include: (1) rate of diffusion from soil minerals to runoff water (2) slope, (3) runoff rate, (4) rill development, and (5) dissolution of transported sediment particles. Ponce (1975) conducted a rainfall simulation study on several geologic members of the Manos Shale formation and found statistically significant linear correlations between TDS and sediment in runoff on individual rainfall plots. Ponce (1975) attributed the variability in the linear correlations to the variability in dissolution rates of suspended sediment particles. Evangelou (1981) showed that when concentrations of Ca^{2+} are high in runoff, the release of ions (primarily Na^{+} and Mg^{2+}) on the Mancos Shale is directly related to and regulated by the exchange complex, represented as the cation exchange capacity (CEC), and the relative cation adsorption affinities of the soil minerals. Therefore, Evangelou (1981) attributes CEC as the mechanism driving a substantial increase in dissolved solids from rangelands on Mancos Shale soils. Currently there are few physically-based models that can predict dissolved solids delivery to the Colorado River system. Nevertheless, if as suggested by Ponce (1975); Evangelou (1981), and Laronne and Shen (1982) that one can relate TDS in runoff to sediment concentration, then there is an opportunity to develop a physically-based framework to predict runoff and TDS from modeled sediment outputs.

A companion study to this study was conducted by Cadaret et al. (2016) to determine if Rangeland Hydrology and Erosion Model (RHEM) (Nearing et al., 2011) can be successfully calibrated for runoff and erosion on the saline and sodic soils of the Mancos Shale formation. Cadaret et al. (2016) investigated how the influence of spatial distribution and total vegetation canopy cover affects RHEM model outputs. The calibrated RHEM model runoff and sediment outputs from Cadaret et al. (2016) is used in this study to relate TDS in runoff to sediment concentration and show that a physically-based framework can be used to predict runoff and TDS from modeled sediment outputs.

This paper analyzes data from rainfall simulation experiments that were performed at two Mancos Shale sites in Utah to measure sediment and dissolved solids loading in response to rainfall intensity and soil physical characteristics. These rainfall simulations were used to determine: (1) soil chemistry differences between sites and spatial differences within each site; (2) the altering effect of vegetation on soil properties and infiltration; (3) what drives salinity transport processes; (4) if a relationship exists between sediment yield and salinity transport processes; and (5) if the relationship can be applied to the RHEM (Nearing et al., 2011) using sediment yield as a proxy to estimate runoff and TDS.

2. Material and methods

2.1. Site description and plot installation

Our study sites are located near Price, Utah in the Price-San Rafael River basin (1.1×10^4 km^2). This sparsely populated area within the Colorado Plateau is characterized by an uplifted, eroded, and deeply dissected tableland with a salt-desert shrubland ecosystem. The average annual air temperature is 8.2 °C (January = −15.6 °C, July = 32.7 °C) and average annual precipitation is 227 mm/yr (November = 13.0 mm, September = 29.2 mm). Runoff is generated from spring snowmelt and short duration, high intensity convectional storms during the summer. The two field sites, named Ferron and Price, were selected because of their location on the Mancos Shale formation, accessibility for field operations, National Environmental Policy Act clearance, and variation in vegetation cover, soil properties, and slope. The Ferron field site (111° 7′ 21″ W, 38° 58′ 23″ N) is at an elevation of 1900 MASL and located 74 km south-southwest Price (Fig. 1). The Price field site (110° 36′ 26″ W, 39° 27′ 47″ N) is at an elevation of 1700 MASL and located 23 km southeast of the city of Price.

The Ferron site is located on the Lower Blue Gate member of the Mancos Shale formation (Doelling and Kuehne, 2013) with a soil mapped as Chipeta-Badland complex (USDA-NRCS, 2013) and Calcic Solonchak according to WRB classification (FAO/ISRIC/ISSS, 2006). Ferron contains poorly developed, light-medium gray soil crusts on steep-grade slopes (11.4%–24.5%) with moderate vegetation cover (17.7%–25.2%). Patches of salt efflorescence on the soil surface are abundant at Ferron. The vegetation at Ferron is solely comprised of the salt-tolerant shrub species *Atriplex corrugata* (i.e. mat saltbush) that is mainly distributed on Mancos Shale derived soils (Blauer et al., 1976). The Price field site is located on the Tununk member of the Mancos Shale formation with a soil mapped as Persayo loam (USDA-NRCS, 2013) and Haplic Calcisol according to WRB classification (FAO/ISRIC/ISSS, 2006). Price contains well developed, light gray soil crusts on shallow-grade slopes (0.6%–10%) with sparse vegetation cover (3.3%–17.8%). The predominant salt-tolerant plant species found at Price are *Ephedra viridis*, *Atriplex gardneri*, and *Achnatherum hymenoides*. Both sites had been recently grazed by cattle and antelope as evidence of hoof impressions were visible across the site.

At each field site, three replicates of four rainfall intensities were performed, for a total of twelve 6 × 2 m rainfall simulation plots. Rainfall intensities used in this study were derived from 5 min rainfall amounts for the study area from NOAA's Atlas14 database (http://www.nws.noaa.gov/oh/hdsc/index.html). Rainfall intensities were 50.8 mm/h, 88.9 mm/h, 114.3 mm/h, and 139.7 mm/h respectively for the 2-, 10-, 25-, and 50-year storms. One of the plots at Price (#12) was excluded in this paper because the rainfall simulation duration was unusually long, resulting in significantly greater cumulative runoff. Each plot was aligned along the natural contour of the land, allowing flow concentration toward the center of each plot to existing rills that would carry water down-gradient. At the top and side borders of each plot, steel strips (2 × 0.2 m) were installed to contain runoff within the measurement area. A flume equipped with pressure transducers was installed at the bottom of the plot to monitor runoff discharge. The position of the