Salinity Mobilization and Transport from Rangelands: Assessment, Recommendations, and Knowledge Gaps

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Abstract
The purpose of the salinity project is to improve the understanding of sources and transport mechanisms in rangeland catchments that deliver dissolved solids (salts) to streams within the Upper Colorado River Basin (UCRB) through a review of relevant literature on what is known about the impact of range management practices to reduce salt loading to the UCRB. An important goal of the project was to gain knowledge about how certain land management practices or land conditions may be affecting dissolved-solids yields to streams. Changes in the land and water management can be made to reduce dissolved-solids yields and enhance the health and sustainability of rangeland plant communities and improve water quality. Rangelands cover approximately 40% of the nation, however, there is no coordinated effort to monitor or assess salt mobility, transport and delivery from rangeland uplands to western rivers. Salt transport is a natural process and is the result of complex interactions among soil, vegetation, topographic position, land use and management, and climate. Salt transport occurs when climatic processes (wind, rainfall, and runoff) exceed the soils inherent resistance to these forces. This review of the published literature broadly supports the concept that by controlling soil erosion on rangelands that salt transport to the UCRB would be reduced. However, it is not possible to determine the magnitude or trend in salt reductions that would be derived from proactive conservation/management actions because of the minimal information documenting the benefits from such actions in the peer-reviewed literature. There is a clear need to develop monitoring protocols and research programs aimed at generating standardized and systematic data to develop an effective cost-benefit analysis system to estimate reductions in salt loading from specific conservation/management actions.

Key Words: Salt mobility, Salt Transport, Salinity, Soil Erosion, Rangelands, Mancos Shale

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Cover photo: Top photograph by Ron Nichols, Utah, USDA Natural Resources Conservation Service and bottom photographs by USDA Agricultural Research Service. Photograph on page viii by Ron Nichols, Utah, USDA Natural Resources Conservation Service.

Forward

The purpose of the salinity project is to improve the understanding of sources and transport mechanisms in rangeland catchments that deliver total dissolved solids (salts) to streams of the Upper Colorado River Basin (UCRB) (Fig. 1). Relevant research conducted outside the U.S. is also included. In addition to documenting the physical and chemical processes involved in salt mobilization and transport, an important goal is to gain knowledge about how certain land management practices or land conditions may be affecting dissolved-solids yields to streams. These changes in the land and water management can be made to reduce dissolved-solids yields and enhance the health and sustainability of rangeland plant communities and improve water quality.

Management practices searched for in the literature include soil property control (e.g., planting, stabilization, reclamation), vegetation control (e.g., aeration, disking, prescribed grazing, prescribed burning), hydraulic structures and hydrogeomorphic controls (e.g., constructed wetlands, riparian buffers, bank stabilization), and access control (e.g., fencing, offroad vehicles, heavy use).

Minimal peer reviewed literature exists that specifically documents the reductions in salt mobilization and transport from federal rangelands as a result of implementing rangeland management practices in the UCRB. Therefore, we expanded the literature search to include published literature that addressed fundamental hydrologic and erosion processes which are documented in the annotated bibliography developed to support this review entitled*: Salinity Mobilization and Transport: Hydrologic and Aeolian Processes and Remediation Techniques for Rangelands Salinity Mobilization and Transport* (Gagnon 2014). This bibliography is available online at the USDA National Agricultural Library.

It is well documented that on rangelands the amount, kind, and distribution of vegetation and ground cover are often the only factors that can be cost-effectively manipulated to alter surface runoff and soil erosion. In the "Selected References of Broad Relevance" section of the associated salinity bibliography, citations were included that reference the dominant impacts of practices (e.g., grazing) that can directly impact runoff and soil loss. These references were retained even if the original work was not conducted on saline soils to guide the reader in potential impacts this practice might have on salinity transport through altering surface runoff and soil erosion processes.

The USDA Agricultural Research Service (ARS) and Natural Resources Conservation Service has also completed an annotated bibliographies on grazing land conservation practices, conservation practices that impact wildlife (*Effects of Agricultural Conservation Practices on Fish and Wildlife: A conservation Effects Assessment Project* (CEAP) bibliography and wetlands (*Wetlands in Agricultural Landscapes*) that are available online at the USDA National Agricultural Library website and can be consulted for the current research for more detailed references on specific conservation practices then presented here. In addition, USDA has completed a synthesis of benefits and impacts of selective conservation practices on western rangelands (Briske, 2011) and on pasture lands (Nelson, 2012) that are available online. By combining these resources the user will have access to the most up-to-date information on publications addressing range management practices and their potential impacts and benefits. These additional resources will allow the user to make inferences on the reductions in salt loading to the Colorado River Basin from management actions.

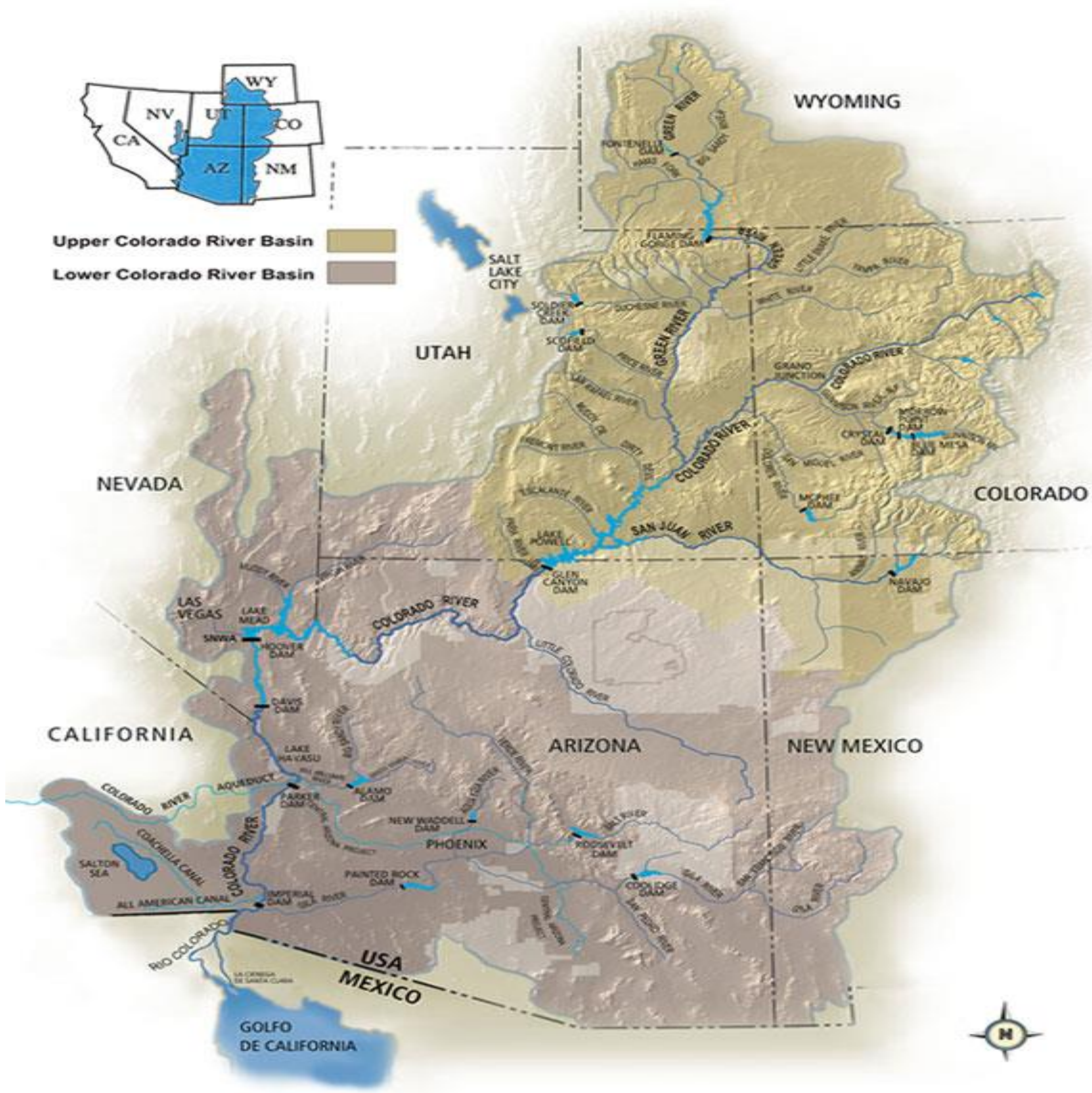

***Figure 1*. Upper Colorado River Basin**
(*Source:* http://www.gcdamp.gov/aboutamp/crb.html).

Executive Summary

The review of published literature broadly supports the concept that controlling soil erosion on federal rangelands would reduce salt transport to the Upper Colorado River Basin (UCBR). However, it is not possible to determine the magnitude or trend in salt reductions that would be derived from proactive conservation/management actions because of the minimal information and data available to document benefits from such actions in peer-reviewed literature. The biophysical environment of the UCRB is dynamic as evidenced by high interannual climatic fluctuations, encroachment by native woody species, invasion by exotic invasive plants, an increase fire frequency and severity, exploration for oil and gas, and increased recreation that is occurring across the basin. These dynamic fluctuations drive change in plant communities and the hydrologic response that controls salt mobility and transport.

There is a clear need to develop monitoring protocols and research programs aimed at generating standardized and systematic data to be able to develop an effective cost-benefit analysis system to estimate reductions in salt loading from specific conservation/management actions. Better understanding sediment and salt transport processes in saline environment is needed and could be achieved through rainfall simulation experiments using state-of-the-art rainfall simulation technologies specifically developed to quantify soil erosion and salt solute transport processes on rangelands. This is very clear for the spatial scale of the UCRB and the time frames necessary to document benefits in arid and semi-arid landscapes. It may require a decade to determine if the management action was successful due to the erratic nature of precipitation and length of time to determine if vegetation has responded positively to the treatment in the UCRB.

Understanding the complex partitioning of solutes between surface and subsurface processes is key to understanding the effect of rangeland management practices on salt delivery to surface waters. In this context, soil erosion/water quality models are valuable tools to assess the role of rangeland management practices on salt transport to surface waters. Since the dynamic interaction of management practices – precipitation – salt pickup and transport are synthetically handled in these models, it is possible to predict the effect of a given practice on net salt transfer from saline uplands to surface waters. This information can then be used to match management practices with salt source areas. Finally, long term watershed continuous monitoring projects are needed to validate the effectiveness of rangeland management practices at reducing salt delivery to the Colorado River and its tributaries.

Key findings from the synthesis of available literature on salt mobility and transport within the UCRB are:

Hydrology of the UCRB

- Annual precipitation patterns in the UCRB are controlled by orographic processes leading to wetter, and therefore more vegetated areas at higher elevation and water-deprived areas at lower elevations.
- Elevation has little effect on storm intensity in the UCRB, e.g., short duration storms are as intense in the driest parts of the basin as they are in the wetter parts.
- The complexity of erosion and especially deposition processes in rangelands often leads to high variability in erosion response from rangeland plant communities. However, it can be summarized that net sediment delivery from rangeland hillslopes is mainly controlled by both the proportion of bare ground (detachment function) and the connectivity between bare ground patches (conveyance function). Processes that control soil erosion in rangelands also control nutrient and solute (including salts) pick up and transport by water.

The physiographic salt problem in the UCRB

- Two main ecoregions with contrasting morpho-climatic conditions exist within the UCRB: The mountainous or orographically influenced regions including the Central Rocky Mountains, the Southern Rocky Mountains, Southwestern Plateaus, Mesas, and Foothills and the arid low lands and plateaus including the Colorado Plateau, the Cool Central Desertic Basins and Plateaus and the Warm Central Desertic Basins and Plateaus.
- Because of the low levels of annual moisture characterizing the arid low lands and plateaus, salts and other dissolvable solids are not removed from soil profiles but tend to persist in an upward-downward cycle whereby downward migration occurs during infiltration processes rapidly followed by upward migration in evaporative fluxes. Salinity delivery to surface waters is among priority resource concerns in these areas.
- Several dominant geologic formations have been identified as major contributors of dissolved mineral salts to the UCRB. The Mancos, Sego, Mount Garfield and Eagle Valley Evaporates and Paradox formation were formed during the late Cretaceous Mancos Sea and have been identified as major contributors of soluble salts to the Colorado River Basin.
- As source of surface water salinity, the Mancos shale formation has traditionally received more attention than other formations likely due to the spatial dominance of this geologic formation in the UCRB.

Transport processes

- The physical process of salt transport by wind to river systems can be perceived as an enrichment function where transported salt-laden sediments by wind erosion are (1) directly deposited to the surface of water bodies for further dissolution and incorporation in total salt load or (2) transported and deposited on soil surface as available sources ultimately draining to water bodies.

- Interaction between water and wind transport processes results in a feedback mechanism that could potentially yield greater transport of material than predicted by either wind or water transport alone. Better understanding of both erosion and deposition processes is therefore essential to wind and water erosion integration and to accurate assessment of overall site vulnerability and salt transport.
- Salt transport mechanism in arid and semi-arid environment has often been inferred from observed or known sediment transport functions through a positive relationship. Surface water salinity is assumed to be mainly controlled by two processes: salt concentration and salt pick-up.
- Salt mobilization and transport processes in surface water are assumed to be analogous to mechanisms controlling sediment production; an assumption that underpins most recommended surface salinity control measures.
- The high evaporation levels characterizing the arid and semiarid regions of the UCRB promote a phenomenon called salt efflorescence which plays a central role in surface water salinity.
- Subsurface reemergence (e.g., seepage, baseflow, etc.) occurs in areas where precipitation is high enough to sustain shallow ground water recharge which ultimately intercept the ground surface in concentrate flow pathways (streams, rivers, etc.). In the UCRB, areas where subsurface reemergence is a prevalent phenomenon are those outside the arid zones.
- Two types of subsurface salt reemergence are distinguished in the UCRB: point sources loads as highly saline springs discharging directly into surface waters and diffuse salt load associated with baseflow generation processes.

Management practices effect on salt loading

Abiotic alterations

Contour furrowing and land surface alterations

- Contour furrows have been found to be potentially effective in promoting salt entrapment.
- Contour furrows life expectancy is approximately 10 years and is usually effective for rainfall return rates less than 10 years. In large rainfall events contour furrows may fail and concentrate runoff, soil erosion, and salt transport.
- No peer review literature was found on using pitting, water spreaders, land imprinting or similar soil surface alteration practices and their impacts on salt mobility and transport in the UCRB.

Gully plugs

- No consistent trend in salt accumulation along channel bottom upstream and downstream of gully plugs has been reported.
- Gully plugs have a life expectancy of approximately 25 to 35 years, require consistent maintenance, and additional costs associate with disposing of trapped sediments and salts.

Soil amendments

- Superabsorbent polymers (SAP) (e.g., Polyacrylamide) have been demonstrated to increase soil water storage and infiltration rates on agricultural lands.
- Gypsum has been successfully used to enhance desalinization on agricultural lands.
- Soil amendment techniques for salinity reduction have applicability at relatively small spatial scales due to their high cost of implementation and are not an economical option to solve salt mobilization and transport problems in the UCRB.

Biotic alterations

Chaining

- Chaining in Pinyon-Juniper woodlands or sagebrush steppe plant communities has not demonstrated any impact on salt mobility and transport.

Grazing

- Hydrologic response to grazing largely parallels those of other ecological variables. Stocking rate and weather factors are the dominant variables that have to be addressed to achieve desired results.
- Proper grazing practices can be used in some locations to augment restoration of rangeland ecosystems or to reduce fuel accumulations and potential fire severity without negatively impacting hydrologic processes.
- Proper grazing management has been estimated to potentially reduce salt loading by 15% in the UCRB on selective Ecological sites.

Fire

- Effects of fire on salt loading to surface water have not been specifically addressed in any of the consulted references.
- The immediate consequences of fire are loss of vegetative cover which increases vulnerability to wind and water erosion, runoff, and potential increase in salt transport.
- Long term effects of fire on hydrology suggest that short term detrimental effect of fire on runoff and erosion wane as vegetation is progressively reestablished.
- Prescribed fire can be used successfully by federal rangeland management agencies for restoration or promotion of specific rangeland goods and services.

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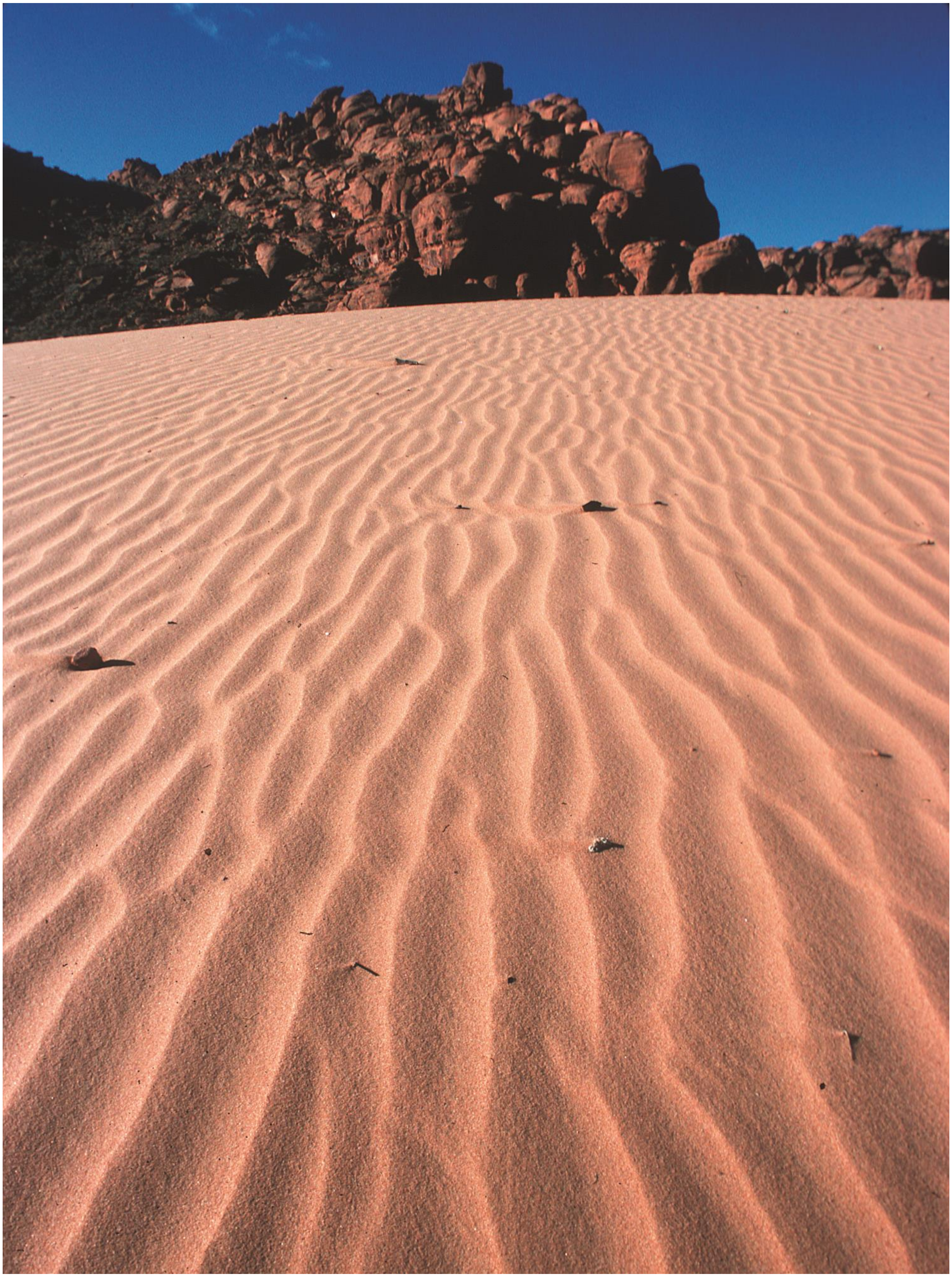


1. Introduction

The Colorado River (CR) and its tributaries provide water to about 33 million people and irrigation water to nearly 4 million acres of land in the United States, as well as an additional 3 million people and a half million acres of land in Mexico (Reclamation, 2011). Damages within the United States have incurred as a result of dissolved solids in the CR and are estimated to be about $383 million per year for conditions observed in 2009 (Reclamation, 2011). The Salinity Control Act authorizes the Secretary of the Department of Interior (DOI) and the Secretary of the Department of Agriculture (USDA) to protect and enhance the quality of water available in the Colorado River for use in the United States and Mexico. Salinity control efforts such as point-sources are reported to have reduced dissolved-solids loading to the CR by about 1.2 million tons per year as of 2010 (Reclamation, 2011). The salinity-control effort has largely focused on reducing dissolved-solids loading from irrigated lands (Reclamation, 2011). About 55% of the loading, however, comes from natural, non-irrigated sources (Kenney et al., 2009) on rangelands. This suggests a significant potential to further reduce dissolved-solids loading to the Colorado River through land- and water-management activities on rangelands. Salinity control planning in Utah indicated that a typical rangeland watershed had approximately 7% to 15% of the area in severely eroding condition. It was estimated that these severely eroding areas yield salts from soil and rock fragments as sediment in runoff and are responsible for approximately 75% to 90% of accelerated sediment/salt yield. Pinyon and Juniper dominated plant communities with little understory were a major source of the sediment (Rasely et al., 1991).

The historical focus on irrigated agriculture combined with the complexity of natural rangelands environment have created a systemic knowledge gap related to rangelands-borne salt delivery to surface waters. The need to reduce the knowledge gap associated with salt transport processes in rangelands has prompted natural resources and land management agencies such as the Bureau of Reclamation (BOR) and Bureau of Land Management (BLM) to invest in efforts aimed at better understanding salt mobilization and transport processes in rangelands and clarifying the effect of rangeland management practices on these processes. Research efforts have been conducted in the past on the topic of salt transport from rangelands to the UCRB but few documents have unified the body of knowledge existing on this topic. An assessment of the state-of-the-science of salt loading to streams from rangelands is needed for identifying management practices that could reduce yields to the UCRB. Specifically, there is a need to improve the understanding of sources and transport mechanisms of dissolved solids in rangelands. This understanding must also include the effects human activities may have on the sources and transport of dissolved solids (salts) because these activities could be modified, or their effects mitigated through management actions that could reduce loading to streams or increase retention within terrestrial environments.

This document has been developed as part of a BLM-BOR funded study with overall objective to gain knowledge about how certain land management practices or land conditions may be affecting dissolved-solids yields to streams, such that changes in the land and water management could be made to reduce dissolved-solids (salts) yields. The study consists of 2 phases, including: 1) an annotated bibliography of literature on sources and transport of dissolved solids (salts) in rangelands and 2) a review of this the annotated bibliography with the goal of developing recommendations in management practices capable of reducing salt loading.

2. Hillslope hydrology in arid and semiarid rangelands of the Upper Colorado River Basin (UCRB)

2.1 Runoff generation

Arid and semiarid areas are characterized by hydrologic cycles with negative water budgets (annual precipitations less than potential evapotranspiration). Since these areas cover a wide range of climatic regions, the type of precipitation controlling runoff vary from winter dominated processes in Northern or high altitude regions to summer convection processes in warmer climates. Annual precipitation patterns in the Western United States show a North-South transition from winter to summer dominated inputs (Branson et al., 1972) with significant implications on hydrologic processes such as streamflow and runoff generation. Overall, the two dominant runoff generation processes in arid and semiarid rangelands are snowmelt and rainfall.

In the UCRB, snowmelt alone has seldom been associated with upland runoff processes. However, dramatic hydrological conditions can occur when snowmelt is accelerated by rainfall (Rain-on-snow or ROS), often leading to significant flooding events. Hydro-meteorological conditions leading to these events have been extensively studied from specific historical cases or monitoring data in other regions of the world. (e.g., Marks et al., 1998; Sui and Koehler, 2001; McCabe et al., 2007). In the Western U.S., ROS events are generally more frequent in the Pacific Northwest compared to the Southwest (McCabe et al., 2007), likely the combined result of a more humid precipitation regime and wide elevation range in the Northwest. Surfleet and Tullos (2013) found that across elevation zones of an Oregon watershed ROS events have a close association with multiyear return peak flows especially in the transient snow zone (350 – 1100 m) where snowpack accumulate and melt several times each winter.

In general, areas located in the transient snow zone along the major mountain ranges of the Western U.S. including areas of the UCRB in the Rocky Mountains physiographic region are likely hydrologically impacted by ROS events. In the UCRB many of these ROS susceptible mountainous areas drain through valleys of highly saline geologic formations such as Mancos Shales where risks of increased salt transport exist. It is important to note however that most research on ROS events have focused on streamflow response and little is known about the effect of these events on hillslope runoff. In theory, hillslope runoff generation from ROS events would be a function of many variables including snowpack depth, amount of heat supplied by rainfall, rainfall duration and air and ground temperature. It is therefore conceivable that under some circumstances, ROS would be associated with increased surface runoff. Results from a rainfall simulation on snowpack by Singh et al. (1997) support this hypothesis of increased runoff due to ROS.

Rainfall is considered the dominant upland runoff generation process in arid and semiarid rangelands (Branson et al., 1972). It is commonly assumed that runoff in arid and semi-arid areas occur as a result of Hortonian overland flow during infrequent but high intensity rainfall events. In the Southwestern U.S. where most of the annual precipitation is received during the summer, a close association exists between runoff and high intensity summer precipitations (Renard, 1970). Similar relationship between runoff and summer convective storms can be inferred from Cooper (1967) who found that the majority of high intensity precipitation events in Southwestern Idaho occurred during the summer as a result of convective storm activities.

Analysis of annual precipitation patterns in the UCRB (Table 1) revealed a positive and strong correlation (0.81) between annual precipitation within the basin (Fig. 2) and elevation (Fig. 3). This reflects the conventional observation that annual moisture distribution in the western U.S. is controlled by orographic processes leading to wetter hence more vegetated areas at higher elevation and water-deprived areas at lower elevation.

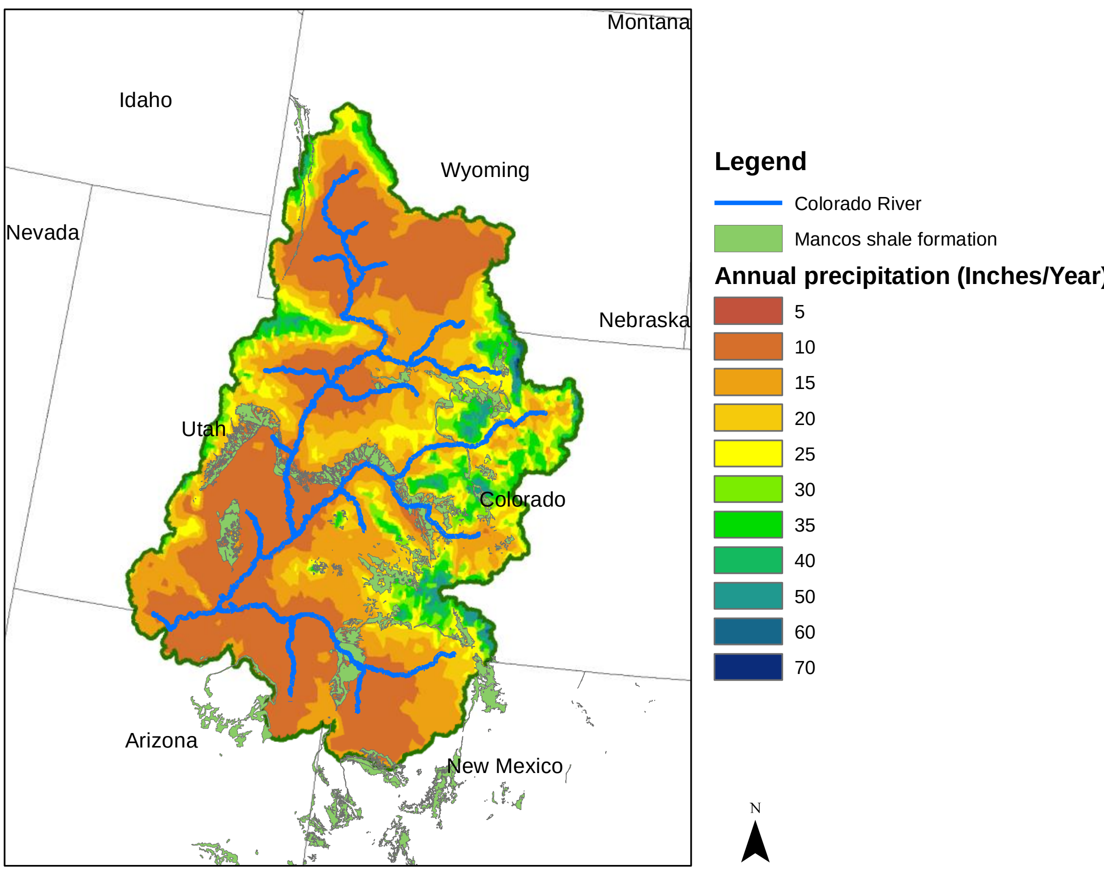


***Figure 2*. Annual precipitation map of the UCRB (*Data source:* NOAA precipitation Atlas)**

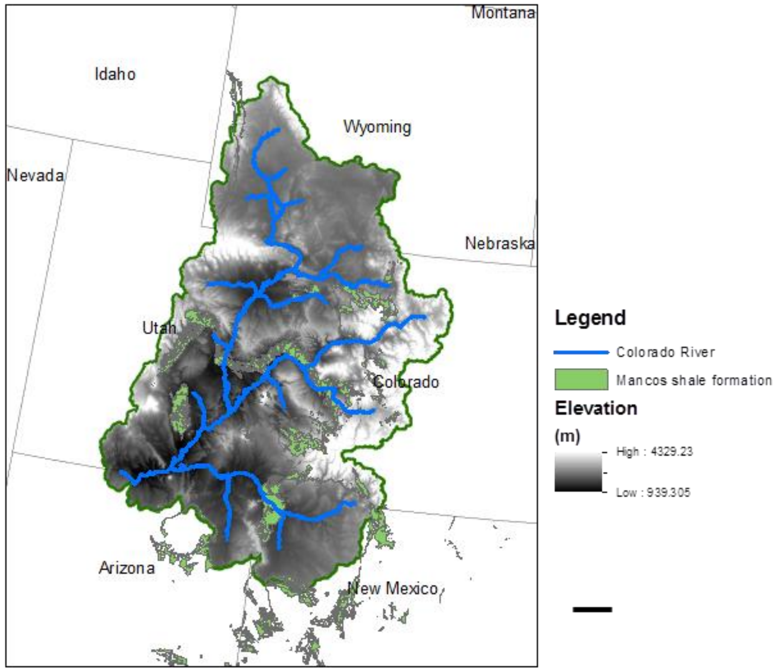


Figure 3. **Elevation map of the UCRB (*Data source*: USGS NED 1 arc second)**

Also, elevation seems to have little effect on storm intensity in the UCRB. Ten year (Fig. 4) and one hundred year (Fig. 5) return storms (30 min intensity) across the basin have coefficient of correlation of 0.52 and 0.45 with elevation and 0.52 and 0.48 with annual precipitation, suggesting that short duration storms are as intense in the driest parts of the basin as they are in the wetter parts.

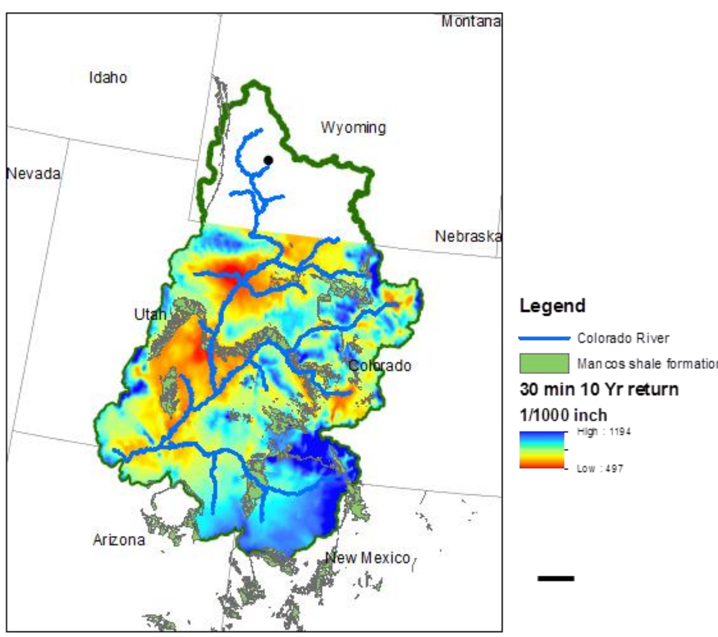


Figure 4. **Ten year return 30 minutes storm intensity map the UCRB (*Data source:* NOAA Atlas 14, missing WY).**

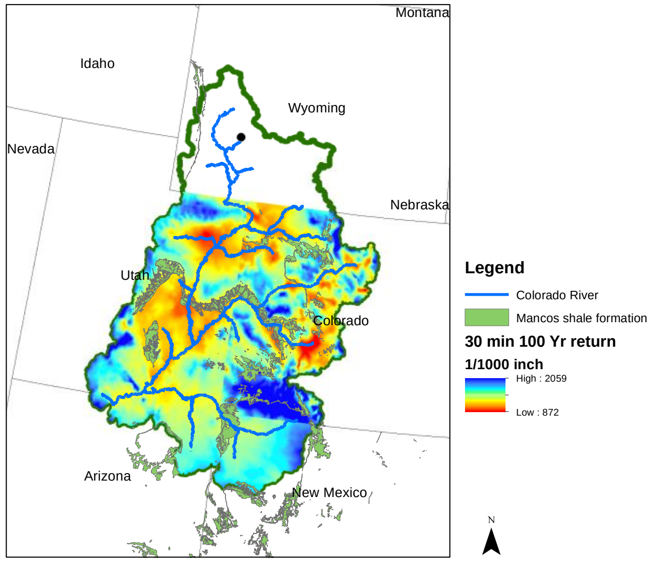


***Figure 5.* One hundred year return 30 minutes storm intensity map the UCRB (*Data source:* NOAA Atlas 14, missing WY)**

***Table 1.* Correlation coefficient between elevation, annual precipitation and storm intensity in the UCRB**

	Annual P	10 Yr	100 Yr	Elevation
Annual P	1			
100 Yr	0.48		1	
10 Yr	0.52	1	-	
Elevation	0.81	0.52	0.45	1

2.2 Runoff and erosion partitioning

Rainfall partitioning into vegetation interception, stemflow and throughfall has been extensively researched. Vegetation interception refers to the portion of precipitation that is retained by plant material (stems, leaves, and branches) and returned to the atmosphere through evaporation. The exact proportion of rainfall intercepted by vegetation is a function of precipitation characteristics and canopy characteristics with values ranging from 20 – 30 % of rainfall (Hamilton and Row, 1949; Slatyer, 1965; Navar and Bryan, 1990; Domingo et al., 1994). Stemflow and throughfall processes are less understood than interception processes likely due to the difficulty associated with the measurement of these processes in shrubland and grassland plant communities. Published values for stemflow proportion range from 5 % to 40 %

(Puigdefabregas, 2005). In general, interception losses reduce runoff volumes and this effect reaches a maximum for short duration intermittent rainfall events while stemflow promotes deep infiltration in the soil directly beneath plant canopies (Branson et al., 1972). The reader is referred to other resources (Branson et al., 1972; Li, 2011) covering more extensively rainfall partitioning processes.

In arid and semiarid rangelands, where vegetation is typically sparse, a synergistic relationship has traditionally been observed between spatial distribution of vegetation and runoff structuring. This vegetation driven spatial heterogeneity (VDSH) (Puigdefabregas, 2005) stems from differential soil development and evolution processes between areas under canopies and bare ground resulting in feedback mechanisms perpetuating or further accentuating the bare ground – under canopy soil dichotomy (Puigdefabregas, 2005). In general, soils beneath plant canopies have been conditioned to act as water, sediment and nutrients sinks whereas bare ground areas act as source. Increased biologic activity, carbon fluxes, and the physical shielding from raindrop impact of the soils under plant canopies promote soil aggregation and improved infiltration compared to bare ground. The importance of this differential soil infiltration in rangeland hydrology was demonstrated by Howes and Abrahams (2003) who found under-shrubs runon infiltration amounted to values as high as 15% of total infiltration in the Southwest U.S. In addition, observations in semiarid rangelands suggest that deposition mounds form upstream of plant clumps as a result of energy losses and changes in transport capacity that accompany overland flow diversion by plant stems. The entrapment of nutrients along with sediments in these mounds creates areas of nutrients concentration where plants thrive spatially alternated by bare or poorly vegetated zones of water and nutrient depletion, forming the premise of the “resource islands” or “vegetation island” concept.

From a hydraulic standpoint, these “vegetation islands” can further exacerbate the flow concentration process (Schlesinger et al., 1990; Schlesinger et al., 1996; Schlesinger and Pilmanis, 1998). Examples of this negative feedback loop are seen most often in shrub-dominated landscapes in the United States, which have formed coppice dunes such as sagebrush (Artemisia spp.), creasotebush (Larrea tridentate, DC. Coville), mesquite (Prosopis glandulosa Torr.), greasewood (Sarcobatus vermiculatus, Hook. Torr.) and in pinyon (Pinus spp.) and juniper (Juniperus spp.) woodlands dominated areas in arid and semi-arid rangelands (Pierson et al., 1994; Spaeth et al., 1994; Schlesinger et al., 1996; Davenport et al., 1998; Eldridge et al., 2004; Li et al., 2013;).

Experimental research at the Walnut Gulch Experimental Watershed in southern Arizona revealed that coarsening of the spatial structure of vegetation in shrublands led to increase in flow concentration and erosion rates (Abrahams et al., 1995; Parsons et al., 1996; Wainwright et al., 2000). VDSH influences not only runoff partitioning into sheet and concentrated flow processes but also seems to control flow characteristics in hillslope rills and channels. The same landscape with uniform disturbance may experience significantly more runoff and soil loss from a similar runoff event due to increased connectivity of bare soils and formation of well-organized concentrated flow paths. These organized flow paths rapidly accelerate runoff velocity and the ability of water to erode and transport sediment and salts downslope (Wilcox et al., 1996; Davenport et al., 1998; Urgeghe et al., 2010).Tongway and Ludwig (1997) found for example that on degraded tussock grasslands, overland flow was concentrated in long straight paths between the grasses. In the good condition grassland overland flow was tortuous, uniformly distributed, and produced less soil loss. Another notable example of VDSH influence on hillslope hydraulics is the finding by Koler et al. (2008) that formation of concentrated flow channels in short grass prairies were followed by significant increase in runoff but not sediment yield.

Using data from hundreds of rangeland experimental plots across the semi-arid Great Basin, Al-Hamdan et al. (2012) proposed a predictive framework characterizing concentrated flow erosion on rangeland hillslopes. Two findings from Al-Hamdan et al. (2012) are highly relevant to improving understanding of VDSH on flow hydraulics: (1) flow velocity increased exponentially with percentage of bare ground (Fig. 6a) on rangeland hillslopes and this increasing effect was magnified by slope steepness; (2) flow width decreased with proportion of bare ground (Fig. 6b) with again a noticeable reducing effect of slope steepness. In other words, runoff tends to concentrate in more narrow channels as vegetation becomes sparse. The widening of flow concentration pathways with increase in vegetation as suggested by Al-Hamdan et al. (2012) seems to reflect the existence of a channel network dictated not by hydraulic stresses exerted by runoff on bare soil but rather by the spatial distribution and structure of vegetation to which this network is in equilibrium.

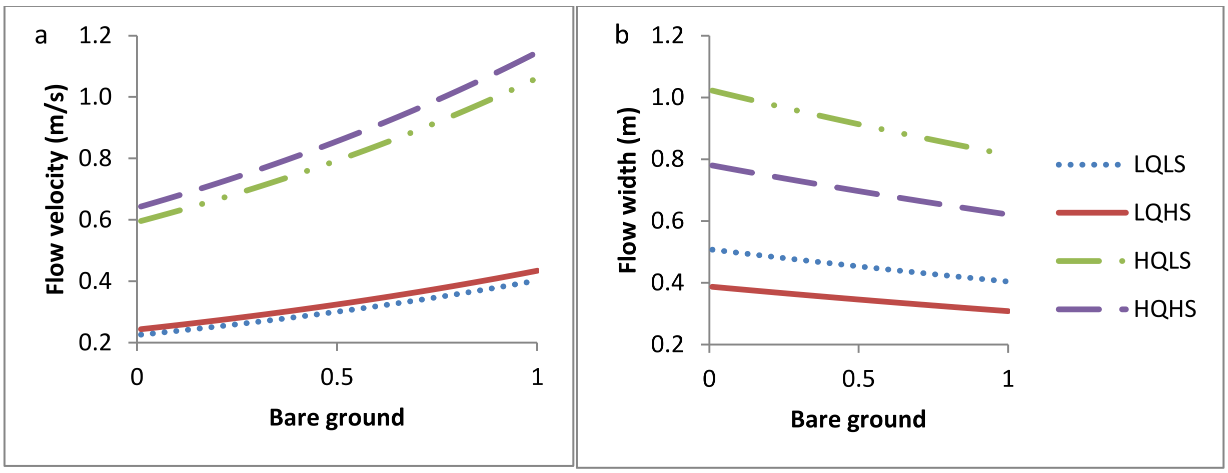


Figure 6. **Flow velocity (a) and flow width (b) as a function of plot bare ground proportion using equations developed by (Al-Hamdan et al., 2012). High and low discharge rate (HQ, LQ) of 1L/s and 0.01 L/s were combined with steep and shallow slopes (HS, LS) of 1% and 40%.**

Hillslope soil erosion occurs on a continuum of scales ranging from aggregate scale processes subjected to raindrop splash to rill and gully scale processes. For the sake of modeling, these processes have however been simplified and lumped into two groups representing: (1) processes occurring outside of channels where the predominant detachment mechanism is raindrop splash detachment due to the typically shallow and broad nature of runoff flow in these areas (splash and sheet erosion) and (2) processes occurring in channels where deep flow exert hydraulic forces sufficient to detach soil particles (concentrated flow erosion). In rangelands, soil erosion typically occurs as the result of intense rainfall events. This is evidenced by Wilcox (1994) who found that annual runoff from erosion plots in intercanopy areas of a Pinyon-Juniper woodland were larger in the winter (as the result of snowmelt) than that in the summer whereas most of the annual erosion was caused by only a few large summer thunderstorms. The action of raindrop impact on bare soil plays therefore a fundamental role in sediment mobilization on rangeland hillslope. The critical role of raindrop impact in semiarid rangeland erosion processes was also demonstrated by Abrahams et al. (1991) in a study aiming at better understanding the downslope pattern of soil loss on a semiarid hillslope. In this study, a 35 m x 18 m semiarid hillslope with relatively homogeneous spatial distribution of vegetation (~ 25% canopy cover), was divided into 3 sections in the downslope direction (0 m – 12.5 m , 12.5 m – 21 m and 21 m – 35 m from the upslope boundary of the hillslope) and sediment concentration monitored at the exit of each section. Abrahams et al. (1991) found in this study that section soil loss which expresses the change in soil loss with respect to downslope distance, increased with slope length in the first section of the hilslope but decreased with distance in the latter hillslope sections. They reported that the observed downslope pattern was consistent with shallow runoff flow in the first section of the hillslope resulting in a greater influence of raindrop impact induced sediment detachment, followed by an increase in flow concentration and flow depth in the latter sections of the hillslope leading to a reduction in raindrop impact effectiveness to detach soil particles. This downslope pattern of soil loss is likely not linear as rainfall intensity and runoff increase. At high runoff flows, flow hydraulic in areas of flow concentration can exceed soil resistance to erosion leading to concentrated flow erosion.

Rills and gullies in rangelands can be perceived as erodible sediment conveyors that would, depending on tortuosity, presence of vegetation in channel paths (VDSH), and other hydraulic factors, transport detached sediments a given distance downslope. Concentrated flow erosion is physically described and modelled as a hydraulic threshold process whereby exceedance of critical flow hydraulic conditions lead to incipient soil particles and aggregate motion on channel bottom and walls although other processes such as headcut migration, wall sloughing, etc. are also considered in concentrated flow erosion. Historically, flow hydraulics in eroding channels has been extensively researched due to the significant implication of such processes in infrastructure (e.g., dams, reservoirs, etc.) management yielding an extensive body of knowledge that has been applied to upland concentrated flow erosion processes. The hydraulic threshold exceedance concept is often expressed in general form as

$$D_{cf} = K_{HP}\left(HP - HP_c\right)^{\alpha}$$

where D_{cf} is the concentrated flow soil detachment rate capacity (kg s^{-1} m^{-2}), K_{HP} is the soil erodibility factor based on the hydraulic parameter HP, HP_c is the threshold value where D_{cf} is insignificant before HP exceeds it, and α is the power exponent (Al-Hamdan et al., 2012). Typical hydraulic parameter used in upland erosion are the flow shear stress (τ_s) expressed in (kg s^{-2} m^{-1}) (e.g., Flanagan and Nearing, 1995; Nearing et al., 1989), stream power (ω) (kg s^{-3}) (e.g., Hairsine and Rose, 1992; Elliot and Laflen, 1993; Nearing et al., 1997), unit stream power (Ω) (m s^{-1}) (e.g., Moore and Burch, 1986; Morgan et al., 1998), unit length shear force (Γ) (kg s^{-2}) (e.g., Giménez and Govers, 2002), and unit discharge (q) (m2 s^{-1}) (Line and Meyer, 1989). For rangelands environments, Al-Hamdan et al. (2012) found that stream power performed better at predicting flow detachment capacity than all other hydraulic parameters. Soil erodibility is affected by many biotic and abiotic factors. Of particular interest in rangelands are biological soil crusts which have significant soil erosion resistance-conferring properties and have extreme susceptibility to disturbance.

Biological soil crusts are a term used to define a collection of nonvascular plants: mosses, algae, lichens, liverworts, and cyanobacteria. The impact of biological soil crusts on infiltration rates and soil erosion is poorly understood and often contradictory. Biological soil crusts can reduce infiltration rates and increase soil erosion by blocking flow through macropores or they may enhance porosity and infiltration rates by increasing water-stable aggregates and surface roughness (Loope and Gifford, 1972; West, 1991; Eldridge, 1993). Disturbance of the soil surface can disrupt biological soil crusts and result in enhanced wind erosion and may or may not affect water erosion processes (Belnap and Gillette, 1998; Eldridge and Koen, 1998; Li et al., 2008; Barger et al., 2006; Belnap et al., 2009). Li et al. (2008) evaluated the interactions between biological soil crusts and runoff on a hillslope with patchy shrub vegetation and reported that in undisturbed areas 53% of the simulated rainfall became runoff from the crust patches and 55% of this was redistributed and absorbed by the shrub patches. In addition, approximately 75% of the sediments, 63% soil carbon, 74% nitrogen, and 45% to 73% of the dissolved nutrients transported in runoff from the crust patches were delivered to shrub patches. The disturbance of crust patches tended to result in the uniform distribution of water over the whole slope with a corresponding reduction in the transport of runoff and nutrients from the crust patches to the shrub patches.

The exact response on runoff and soil erosion and salt transport is a function of site disturbance and level of development of the biological soil crusts (Belnap et al., 2013). When studies are evaluated based on biological crust type and utilizing naturally occurring differences among crust types, results indicate that biological crusts in hyperarid regions reduce infiltration and increase runoff, biological soil crusts have mixed effects in arid regions, and increase infiltration and reduce runoff in semi-arid cool regions. Most research has shown that intact biological soil crusts are effective at reducing soil erosion and transport of soils and associated contaminates (Belnap, 2006). Additional research is required before the role that biological soil crusts play in altering transport of salts (e.g., dissolution of salt crusts by efflorescence) is fully understood. Also, while mechanisms of concentrated flow detachment are well understood, prediction of sediment delivery is often complicated by the less studied deposition processes.

Sediments transported in overland flow channels may be deposited as a result of changes in hydraulic conditions. Sediment transport theories in upland erosional channels follow two main approaches. In the first approach, a transport capacity T_c (Foster and Meyer, 1972; Foster, 1982) is defined as the maximum load of sediment a flow can carry and beyond which deposition processes start. The second approach often referred to as the Harisine and Rose model (Hairsine and Rose, 1992) assumes that both erosion and deposition processes occur simultaneously all the time and the predominance of one process over the other results into net erosion or deposition. Loose deposits of soil are often readily available for wind transport due to low cohesion and aggregate stability. This interaction between water and wind transport processes results in a feedback mechanism that could potentially yield greater transport of material than predicted by either wind or water transport alone. Better understanding both erosion and deposition processes is therefore essential to wind and water erosion integration and to accurate assessment of overall site vulnerability.

However, due to the difficulty to quantify deposition as an independent process to erosion, little work has been done to validate either sediment transport theory. Recent works in laboratory settings using advanced soil microtopography reconstruction technologies (Heng et al., 2011; Nouwakpo and Huang, 2012) have shown that observed sediment transport processes and patterns are consistent with the Hairsine and Rose model. Nevertheless, these studies do not necessarily disprove the transport capacity concept which is still currently used in many physically based soil erosion models. In rangelands, sediment deposition is known to be highly influenced by VDSH but the lack of deposition quantification tool has historically limited understanding of vegetation – sediment transport interactions. The advent of low cost soil surface reconstruction technologies such as digital photogrammetry, structure from motion and even low cost LIDAR technologies provide a unique opportunity to clarify these sediment transport processes.

The complexity of erosion and especially deposition processes in rangelands often leads to high variability in erosion response from rangeland plant communities (Blackburn and Skau, 1974). However, it can be summarized that net sediment delivery from rangeland hillslope is mainly controlled by both the proportion of bare ground (detachment function) and the connectivity between bare ground patches (conveyance function). Processes that control soil erosion in rangelands also control nutrient and solute (including salts) pick up and transport by water.

3. The physiographic salt problem in the UCRB

The generic term salt refers to major earth elements such as calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), chloride (Cl) sulfate (SO_4) and bicarbonate (HCO_3) released during weathering of geologic formations or anthropogenic activities. In the CR, these elements are primarily delivered to surface and ground water through natural or anthropogenic erosion processes although point sources of salinity (e.g., municipal waste, industrial effluent, natural saline seeps and springs, etc.) exist along the CR. Often these elements are quantified as a mix without differentiation between individual species, using specific conductance measurement (EC) or Total dissolved solids (TDS) obtained by evaporation.

The exact contribution of natural processes to the CR salinity is difficult to quantify mainly due to the diversity in geology and salt content of these natural contributing areas (Schaffrath, 2012b). Nevertheless all available estimates suggest salinity loads from natural sources offer substantial margin for salt reduction through land management practices. The Bureau of Reclamation (Reclamation, 2005) estimates that nearly half of the salinity in the CR system originates from natural sources (Table 2). Other studies (Kenney et al., 2009) put this estimate as high as 55% of total river salinity.

Table 2. Sources of salinity in the CRB

Source of salinity	Contribution
Rangeland	47%
Irrigation	37%
Reservoirs	12%
Municipal and Industrial	4%

3.1 Morpho-climatic influence

The UCRB covers a wide range of physiographic regions and are described following NRCS Major Land Resource Area nomenclature (Fig. 7). A summary description of the encountered physiographic regions is presented in Table 3. A close examination of these physiographic regions suggests the existence within the basin of two main ecoregions with contrasting morpho-climatic conditions: The mountainous or orographically influenced regions including the Central Rocky Mountains, the Southern Rocky Mountains, Southwestern Plateaus, Mesas, and Foothills and the arid low lands and plateaus.

In the areas influenced by the Rocky Mountains, the Wasatch range and Unita Mountains, precipitations span a wide range of regimes owing to the wide elevation range covered by these areas. An orographic effect is felt at higher elevations where annual moisture is typically large enough to support coniferous forest, mountain grasses and shrubs. Lower elevations are characterized by aridic regimes owing to a chronic moisture deficit. Most of these areas are only marginally affected by surface water salinity problems. These problems are likely to exist at lower elevation areas receiving low precipitation but conveying substantial surface waters draining from higher elevation zones.

The Colorado Plateau, the Cool Central Desertic Basins and Plateaus and the Warm Central Desertic Basins and Plateaus, form vast expanses of physiographic regions shaped by the Western United States' arid climate. Annual precipitations in these regions are low: 152.4-457.2 mm of precipitation on the Colorado Plateau, 177.8-304.8 mm of precipitation on the Cool Central Desertic Basins and Plateaus and 152.4-1254 mm of precipitation on the Warm Central Desertic Basins and Plateaus. Because of the low levels of annual moisture characterizing these regions, salts and other dissolvable solids are not removed from soil profiles but tend to persist in an upward-downward cycle whereby downward migration occurs during infiltration processes rapidly followed by upward migration in evaporative fluxes. As indicated in Table 3, major soil and water resource concerns in these areas involve salt and sediment erosion processes and are the main sources of salt delivery to the UCRB surface water tributaries. Because these arid and semi-arid regions are mostly rangelands used for livestock (sheep and cattle), wild horses, burros, and wildlife (deer and elk) for grazing, there is an opportunity to significantly impact salt delivery to surface waters through rangeland management practices that involve grazing.

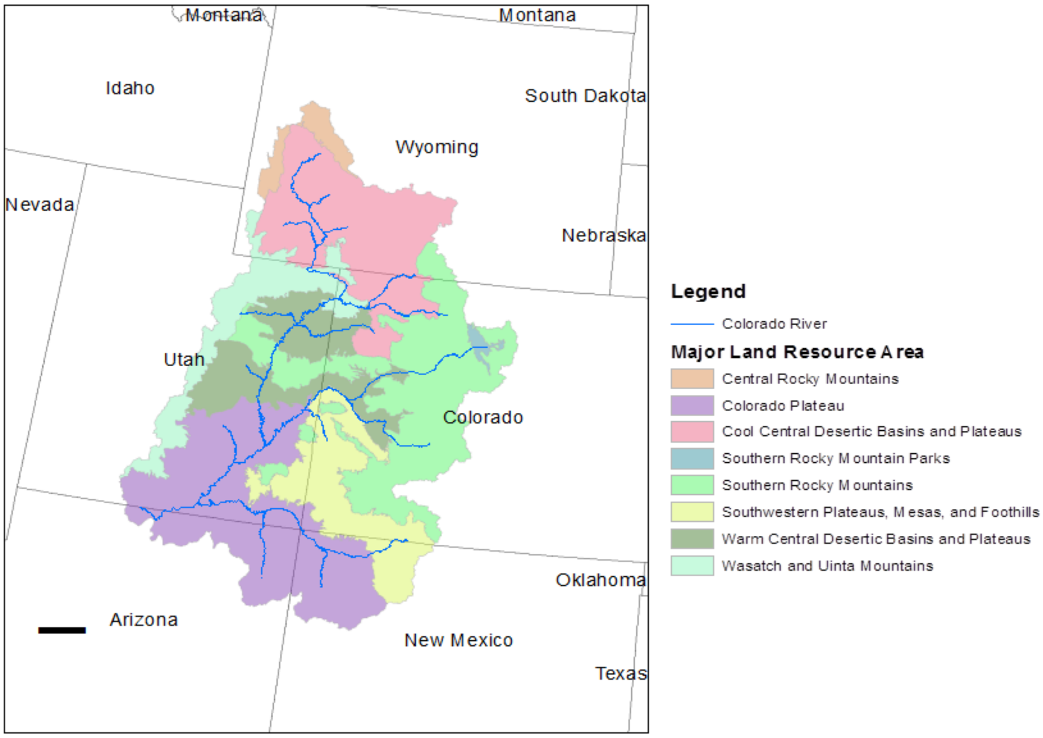


***Figure 7*. Major Land Resource Areas encountered in the UCRB, NRCS, 2013**

Nevertheless, interaction of hydrology, wind, and vegetation in arid and semi-arid rangelands is complicated by various inherent factors. The most vulnerable rangeland areas for soil and salt movement are where annual precipitation is between 100 and 400 mm yr^{-1} (Fig. 8) which limits soil moisture available to sustain plant growth. With low plant density and minimal plant and ground 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 vegetative canopy and ground cover to prevent soil or salt movement from raindrop splash, sheet and rill erosion in the bare connected interspaces (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 t ha^{-1} yr^{-1} on the Colorado Plateau (Langbein and Schumm, 1958). As water erosion is exponentially related to rainfall intensity most of the soil erosion occurs during these rare storm events. Consequently, rilling and arroyo formation is very pronounced in the Colorado Plateau (West, 1983). Interaction between wind erosion/deposition and water erosion, transport, and deposition is poorly understood but linkages do exist and total erosion and transport of salts maybe maximized in arid and semi-arid regions because of limited cover and the steep highly dissected slopes of poorly weathered marine shale's in the UCRB are prone to both types of erosion and transport processes.

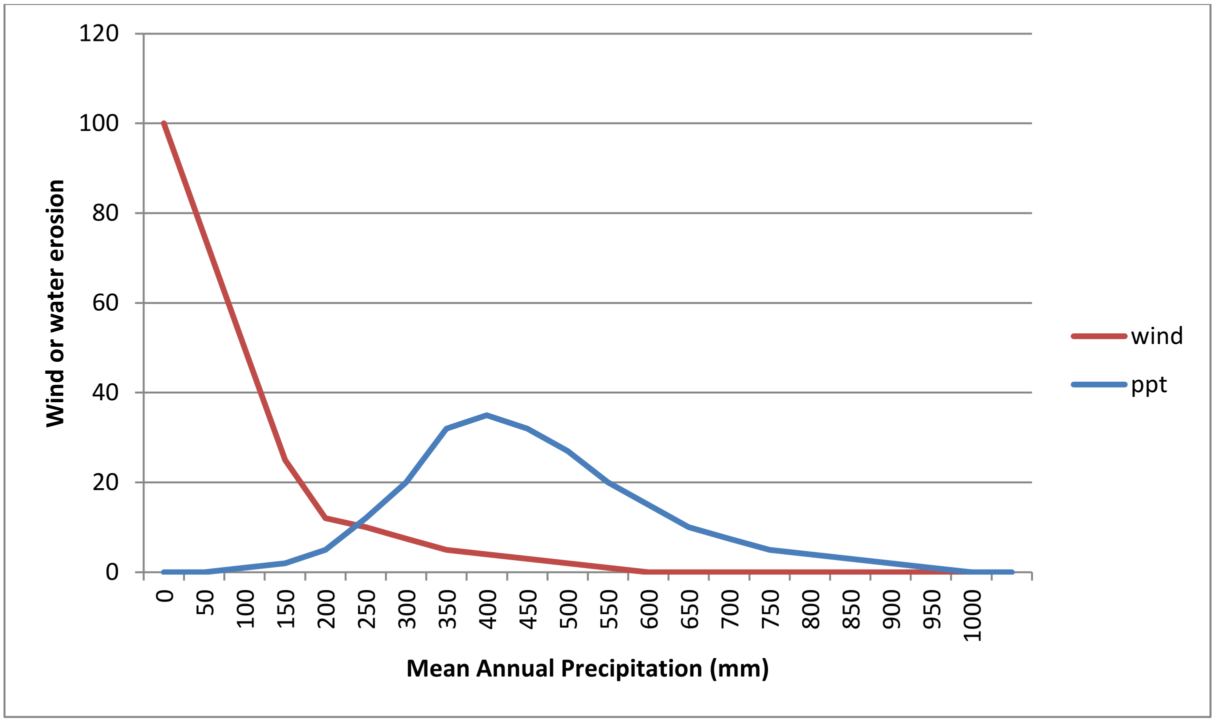


Figure 8. **Conceptual diagram of wind and water erosion with mean annual precipitation for naturally vegetated arid and semi-arid rangelands (Modified from Marshall 1973).**

Table 3. Major Land Resource Areas encountered in the Upper Colorado River Basin

MLRA	Percent of MLRA in UCRB	Precip. (in)	Origin of water used		Predominant water use	Major soils	Major land use	Dominant vegetation	Major soil and water resource concerns
			Ground	Surface					
Central Rocky Mountains	3	25-60	17%	83%	Irrigation (90.8%)	Inceptisols, Alfisols, and Mollisols	Grassland (65%)	Coniferous forests, alpine grasses, forbs, and shrubs	Water erosion, the productivity of the soils, and surface compaction
Colorado Plateau	40	6-18	35%	65%	Irrigation (47.8%)	Alfisols, Aridisols, Entisols, and Mollisols	Grassland (75%)	Desert shrub and woodland at high elevation	High salt and sediment load, low soil organic matter, soil productivity, wind erosion, water erosion, salinity, and sodicity

Table 3 Continued.

MLRA	Percent of MLRA in UCRB	Precip. (in)	Origin of water used		Predominant water use	Major soils	Major land use	Dominant vegetation	Major soil and water resource concerns
			Ground	Surface					
Cool Central Desertic Basins and Plateaus	61	7-12	7%	93%	Irrigation (94.8%)	Aridisols and Entisols	Grassland (94%)	Salt desert shrubs, semi-desert grass and shrubs, Riparian vegetation	Erosion, salinity, and water quality.
Southern Rocky Mountains	56	7-63	8%	92%	Irrigation (83.3%)	Mollisols, Alfisols, Inceptisols, and Entisols	Forest (53%)	Grass and sagebrush at lower elevations; montane and subalpine coniferous forest and some grassland at mid and high altitude	Erosion by wind and water and maintenance of the productivity of soils

Table 3 Continued.

MLRA	Percent of MLRA in UCRB	Precip. (in)	Origin of water used		Predominant water use	Major soils	Major land use	Dominant vegetation	Major soil and water resource concerns
			Ground	Surface					
Southwestern Plateaus, Mesas, and Foothills	53	8-31	18%	82%	Irrigation (89.8%)	Alfisols, Inceptisols, Mollisols, Entisols, and Aridisols	Grassland (80%)	Grass and sagebrush at low elevation; Pinyon-juniper woodland and ponderosa pine forests are at mid elevations; montane and alpine forest at high elevation	Wind erosion, water erosion, maintenance of the productivity of the soils, and management of soil moisture

Table 3 Continued.

MLRA	Percent of MLRA in UCRB	Precip. (in)	Origin of water used		Predominant water use	Major soils	Major land use	Dominant vegetation	Major soil and water resource concerns
			Ground	Surface					
Warm Central Desertic Basins and Plateaus	100	6-10	9%	91%	Irrigation (93.8%)	Aridisols and Entisols, Mollisols at higher elevations	Grassland (95%)	Salt desert shrubs, semi-desert grass and shrubs, Riparian vegetation	Trace element contamination from mining; salinity, sodicity, leaching of selenium and salts into surface and ground water supplies, irrigation-induced erosion, and subsidence resulting from gypsum dissolution
Wasatch and Uinta Mountains	40	15-30	22%	78%	Irrigation (87.1%)	Aridisols, Entisols, Inceptisols, and Mollisols	Grassland (60%)	Conifer, aspen, grass, mountain shrub, and sagebrush-grass vegetation	Wind erosion, water erosion, maintenance of the productivity of the soils, and maintenance of the quality of surface water

3.2 Influence of geology

The salinity problem in the UCRB is exacerbated by geology. Several dominant geologic formations have been identified as major contributors of dissolved mineral salts to the Upper Colorado River. The Mancos, Sego, Mount Garfield and Eagle Valley Evaporates and Paradox formation were formed during the late Cretaceous Mancos Sea and have been identified as major contributors of soluble salts to the Colorado River. These formations contain gypsum and alkaline earth carbonates, and its clay mineralogy is mica, kaolin, smectite, and interstratified mica-vermiculite (Evangelou et al., 1984). Research has demonstrated that major areas of diffuse sources of salts in the soil are also the major sediment contributors to the Upper Colorado River (Laronne and Schumm, 1977) and that solute concentration increase with sediment yield during rilling and rill enrichment due to dissolution of transported sediment particles (Laronne and Shen, 1982).

It is estimated that a significant portion [50% according to Tuttle and Grauch (2009)] of salt delivered to the UCRB is the result of natural erosion processes originates in two major geologic formations: the Mancos Shale formation and the Eagle Valley Evaporite. Figure 9 shows the extent and spatial pattern of the Mancos Shale formation in the UCRB. As illustrated in Fig. 9, even though the spatial extent of these formations is somewhat limited in comparison to other geologic formations, the key to their high contribution to total salinity lies in their proximity to the Colorado River and its tributaries. As source of surface water salinity, the Mancos shale formation has traditionally received more attention than the Eagle Valley Evaporites likely due to the spatial dominance of the former geologic formation in the UCRB.

3.3 Antropogenic influences and trends

Anthropogenic contribution to total salt load is in general associated with disturbance to natural transport processes by urban, agricultural and industrial (e.g., mining) land uses that often tend to increase water salinity levels compared to natural baselines. But the exact contribution of anthropogenic sources to total salt load is confounded by the fact that forest and rangeland which would be considered naturally occurring land uses can also be disturbed by human activity to the point where salt transport processes are altered.

Temporal trends in CR salinity load recorded at Imperial Dam are marked by an unanticipated dramatic decreasing trend starting in the 1940s without significant changes in discharge (e.g., Gellis et al., 1989; Gellis et al., 1991; Bauch and Spahr, 1998). Various reasons have been proposed to explain this downward trend including change in sampling procedures (Thompson, 1982), changes in hydrology in the major salt producing areas (Hereford, 1984; Graf, 1986) and improved land use management namely through reduced grazing pressure (Hadley et al., 1977). The change in hydrology hypothesis was further supported by Gellis et al. (1989)'s Arroyo Evolution Model theory which imparts decrease in CR salt yield to increased sediment storage along aggrading channel bottoms. More recent studies focused on temporal trends in CR salinity especially from natural sources and reported slightly decreasing to absence a trend in salinity (Schaffrath, 2012a).

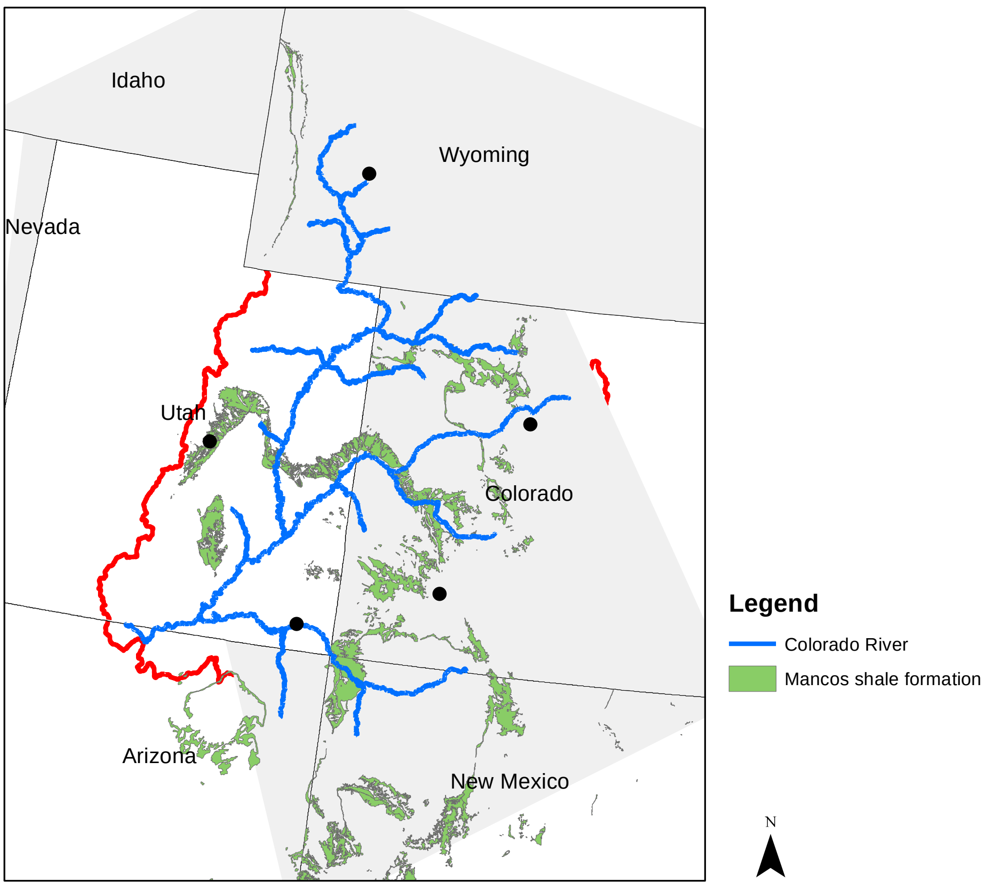


Figure 9. **Map of the state of the UCRB highlighting Mancos Shale geologic formations contributing to most naturally occurring salt in the Colorado River.**

4. Transport processes

Salinization is the process whereby the concentration of dissolved salts in water and soil is increased by natural or anthropomorphic processes. Salt mobilization and transport to surface waters is the result of linked and interactive processes: salt can be transported as a component of wind erosion and directly deposited into water bodies; saline seeps, springs and groundwater may contribute directly to base flow of a water body; and salt may be transported as a function of surface runoff (Fig. 10).

Salt is delivered to surface waters through various transport processes varying in degree of contribution to total salt load. Mechanisms controlling salt transport are often assumed to be similar, to those controlling transport of sediments resulting in a conventional perception that reducing erosion processes would lead to reduction in salt delivery to surface waters. However, because salts are chemically dissolved in water, their persistence in the liquid phase after infiltration has been maximized and deep percolation has occurred makes them potentially available to rivers and stream salinity through subsurface reemergence. In addition, in surface runoff the salt can be dissolved into the runoff water or contained within soil particles and aggregates that are transported to surface water bodies and then dissolved and contribute to salinity of surface waters (Fig. 11). Salt transport is therefore a more complicated process than soil erosion alone. In this section, we examine salt transport mechanisms associated with the two main sediment transport processes (wind and water erosion) and salt delivery through subsurface reemergence.

Figure 10. **Saline spring in northcentral Nevada illustrating salt efflorescence on the edges of the spring.**

Figure 11. **Greasewood coppice dunes illustrating interconnected bare spaces and linked concentrated flow paths that readily transport salt in surface runoff or are vulnerable to wind transport of soils and salt.**

4.1 Transport by wind erosion

Source: **www.usgs.gov**

The physical process of salt transport by wind to river systems can be perceived as an enrichment function where transported salt-laden sediments by wind erosion are (1) directly deposited to the surface of water bodies for further dissolution and incorporation in total salt load or (2) transported and deposited on soil surface as available sources ultimately draining to water bodies.

Surface runoff and soil loss from wind and water on many rangelands is not uniformly distributed across the landscape and is concentrated in bare interconnected interspaces or on steep ridges (Puigdefabregas, 2005; Okin et al., 2009). When wind passes over the sharp-crested badland ridges found within the UCRB a Bernoulli effect below the ridge-crest accelerates the wind resulting in sufficient shear force to detach and lift the soil crust exposing loose soil that is easily detached and transported downhill (Godfrey, 1997). Wind erosion selectively transports smaller particles, causing an enrichment of transported materials in fine size fractions compared to the original source material. This enrichment process has been found to control soil salinization through salt-enriched deposits blown from distant (up to 100 Km) dried lakes or playas source areas (Sánchez et al., 1998; Abuduwaili et al., 2008; Konyushkova et al., 2010). While dried lake beds are rarely connected to the surface water network draining to major rivers such as the CR, windblown lake bed may deposit on catchments draining directly to major rivers or tributaries. Nevertheless, the exact contribution of wind erosion in salt delivery to the CR has not been quantified. This salt-enrichment function was evaluated in all references in the context of soil formation or geomorphology where the long time scales involved allow for substantial amount of salt to accumulate and become significant components of soil formation processes. It is likely that wind deposition of salt does not contribute appreciably to annual river salinity in the UCRB.

4.2 Transport by water erosion

Source: **www.blm.gov**

Arid and semi-arid environments have specific characteristics that confer unique properties to solute and sediment transport processes in these environments. Compared to humid morpho-climatic regions, lower annual precipitations in arid and semi-arid environments result in lower ground cover, a property inversely related to erosion. Consequently, sediment transport processes in arid and semi-arid regions are more likely to be transport limited due to the lower amount of precipitations rather than supply limited as it is often the case in humid zones with well-established ground cover. Also, the infrequent nature of precipitation combined with the occasional occurrence of high intensity storms often leads to flash floods where ephemeral channels are temporarily connected to the surface channel network.

Studies have shown that ephemeral channels in arid and semiarid regions are much more efficient at transporting sediments than their perennial counterpart in humid and sub-humid environments (e.g., Laronne and Reid, 1993; Reid et al., 1996) possibly due to the virtually unlimited supply of readily available sediments overwhelming transport decay functions such as channel bed armoring (Reid et al., 1996). It is therefore conceivable that like sediments, solute (such as salt) transport processes in arid and semi-arid environment are distinctively different from those prevailing in humid regions, an assumption supported by Walling and Webb (1986).

Salt transport mechanism in arid and semi-arid environment has often been inferred from observed or known sediment transport functions through a positive relationship. Surface water salinity is assumed to be mainly controlled by two processes: salt concentration and salt pick-up (Bauch and Spahr, 1998). Salt concentration results from the decrease in runoff volume through diversions, storage or infiltration, increasing river and stream salinity as further addition of salt occurs along the water course on a smaller water volume. In contrast, salt pick-up which is the most studied process of the two, involves the increased transfer of salt from saline soil to runoff through processes such as accelerated erosion without substantial change to runoff volume.

A close relationship exist between soil erosion processes and salinity and this was demonstrated by various authors (e.g., Sunday, 1979; White and Hawkins, 1980; Shen, 1981; Lin et al., 1984). Salt mobilization and transport processes in surface water are assumed to be analogous to mechanisms controlling sediment production; an assumption that underpins most recommended surface salinity control measures. A classification equivalent to sheet and concentrated flow erosion in the case of sediments has even been used by a few authors (e.g., Hawkins et al., 1977; Gifford et al., 1978) to categorize salt loading processes based on the hillslope mass transfer mechanism controlling salt mobilization and transport. Hawkins et al. (1977) distinguished for example overland flow salinity from microchannel salinity sources and suggested that the ladder source of salinity was the dominant surface mobilization and transport process in the UCRB. Concentrated flow erosion (rilling or ephemeral channel erosion) has also been associated with significant increase in salt pickup by some authors (e.g., White and Hawkins, 1980; Shen, 1981; Jackson et al., 1984), a condition which is often exacerbated by the presence of salt efflorescence (Riley et al., 1982a).

The high evaporation levels characterizing the arid and semiarid regions of the UCRB promote a phenomenon called salt efflorescence which plays a central role in surface water salinity. When water is removed from the soil through evaporation, transpiration or hydrolysis it leaves the salt behind in the soil. An extreme form of soil salinization can occur in the UCRB when there is groundwater discharge or a high water table is maintained, that is high in mineralized soil water, and evaporation continues to occur resulting in the minerals precipitating at the soil surface (efflorescence) and forming an extensive salt crusts on the soil surface (Fig. 11 and Fig. 12). Bowles et al. (1982) suggest that this process was especially significant in channels and explained up to 7.5% of the salt load in the Price River sub-basin, of the UCRB.

Figure 12. **Salt crust from efflorescence on desert soil in central Utah.**

Other relevant topics in relation with surface water salinity in the UCRB include: geomorphologic identification of salt storage and pickup processes (e.g., Ponce, 1975; Riley et al., 1979; Hadley, 2012) and kinetic of salt dissolution from solid phase (sediments) to aqueous phase (e.g., Laronne, 1977; Laronne and Schumm, 1977; Laronne and Shen, 1982).

Although salt pickup and transport by water erosion contributes to a significant portion of salinity to the UCRB, subsurface contribution was found to be the dominant natural process of salt delivery to surface waters in the UCRB (Hadley, 2012).

4.3 Subsurface reemergence

Source: **www.usgs.gov**

Subsurface reemergence (e.g., seepage, baseflow, etc.) occurs in areas where precipitation is high enough to sustain shallow ground water recharge which ultimately intercept ground surface in concentrate flow pathways (streams, rivers, etc.). In the UCRB, areas where subsurface reemergence is a prevalent phenomenon are those outside the arid zones.

Two types of subsurface salt reemergence are distinguished in the UCRB: point sources loads as highly saline springs discharging directly into surface waters and diffuse salt load associated with baseflow generation processes. Studies related to the salt contribution of groundwater to the UCRB by (e.g., Warner et al., 1985; Shirinian-Orlando and Uchrin, 2000) suggests that baseflow salt load accounts for 55% of the basin’s annual salt load. A non-negligible portion of this base-flow contribution emanates however from stream channel erosion of marine shales (e.g., Mancos shales), implying a potentially smaller contribution of subsurface processes to surface water salinity.

The literature search revealed no consistent pattern in the topics related to subsurface processes. A wide range of approaches have been used and a variety of mechanisms have been examined in the consulted references. Nevertheless, one observation worth noting is the relative abundance of studies (e.g., Suarez, 2005; van Genuchten and Simunek, 2005; Stonestrom et al., 2007) focusing on the development of technologies to measure or model subsurface solute transport processes, probably due to the inherent difficulty to measure subsurface processes.

5. Management practices effect on salt loading

A governing principal of land management is that changes in land cover result in changes in watershed condition and response. Land management practices influence runoff, salinity, and soil erosion on rangelands because they affect plant distribution, biological diversity, canopy and ground cover, and soil properties. Since solute mobilization and transport processes are intertwined with soil surface hydrology and erosion processes, the key to salinity reduction from rangelands has been conventionally assumed to be in controlling soil movement through vegetation manipulation as the primary management action.

From the current literature search and synthesis effort, it became obvious that the main knowledge gap in understanding the effect of rangeland management practices on salt loading in surface water is the lack of scientific data. The scarcity of scientific data was particularly underscored by Riley et al. (1982b) who was confronted with an undermining lack of necessary pretreatment data to evaluate the potential impact of range management practices on salt transport. Nevertheless many authors have closely associated salt loading with sediment loading in rangeland environment (e.g., Hawkins et al., 1977). It is often assumed that practices that reduce erosion and store sediments in these environments will inherently reduce salt loading (Bureau of Land, 2004). This synthesis reviews rangeland management and improvement practices that have been studied for their effect or potential effect on salt loading in the Colorado River Basin.

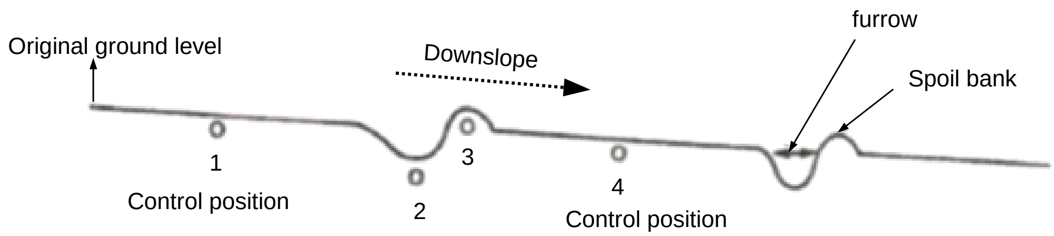
5.1 Abiotic alterations

5.1.1 Contour furrowing

This practice involves converting a level soil surface into a series of ridges and furrows along the contours of the landscape (Bates et al., 2005), allowing soil to retain water and retard runoff. Since contour furrows were found to be an effective land treatment practice to reduce runoff in rangelands (Branson et al., 1966) and sediment production (Gifford et al., 1977), it is conceivable to hypothesize that this practice may have an effect on salt loading and redistribution along the furrowed hillslope.

Riley et al. (1982b) measured surface runoff quality from the Coal Creek (a sub-watershed of the Price River basin) 15 years post implementation of contour furrowing and found lower TDS compared to other sub-watersheds (Soldier, Wattis, and Grassy trail subwatersheds) where this practice was not implemented. Due to the absence of before treatment data and the spotty nature of the post treatment data however, Riley et al. (1982b) were unable to unequivocally attribute the lower TDS to contour furrowing.

Hawkins et al. (1977) looked at the effect of contour furrowing on the spatial redistribution along the furrowed hillslope. Soil samples were taken at different positions along upslope, downslope and inside the furrows. On three out of eleven study sites they found a significant furrowing effect on spatial distribution of salt. Two of the significant results indicated a higher concentration inside the furrows while the third significant case suggested the opposite trend.



Cross section of furrowed hillslope showing relative position of sampling points (Hawkins et al., 1977)

On eight of the eleven sites they found a higher salt concentration in the top layers of non-saline soils compared to the bottom layers, suggesting that contour furrowing may promote salt entrapment in non-saline soils.

Table 4. **Number of references found on "contour furrowing" associated with key concepts**

Associated concepts	Number of references	Most recent year
"Contour furrowing" and salinity	6	1979
"Contour furrowing" and hydrology / water erosion	5	1985
"Contour furrowing" and wind erosion	0	-

5.1.2 Gully plugs

A gully plug is a small earthen dam constructed at one or more locations along the gully to provide grade control and retain sediments (Schaffrath, 2012b). Gully plugs and rock structures have been used for centuries to mitigate soil erosion problems (Lenzi and Comiti, 2003; Xiang-zhou et al., 2004; Castillo et al., 2007) by controlling the geomorphic grade of the area and the velocity of the runoff water. A side benefit of these structures is in capturing water and its use in subsistence agriculture (Norton et al., 2002) or in revegetating the area with natural rangeland vegetation (Nichols et al., 2012). Hessary and Gifford (1979) conducted a series of experiments to study the effect of various range improvement practices including gully plugs on salt loading to surface waters in the UCRB. They compared salt accumulation in different layers of soil along channel bottom upstream and downstream of a series of gully plugs to that measured in upland areas in the vicinity of the gullies. Even though some significant differences were found among sampling locations, no consistent trend in salt accumulation with sampling position was found as the result of gully plug installation. Gifford et al. (1977) utilized contour furrows and gully plugs to retain runoff and sediment on Mancos Shale site in Utah and this technique was successful in retaining sediment. Life expectance of the treatment was 12 and 33 years for contour furrows and gully plugs, respectively.

In the 1930's the US Government through the Civilian Conservation Core establish numerous, earthen, rock, and brush structures (e.g., gully plugs) to reduce soil erosion in northern New Mexico. When the sites were reevaluated in 1990's it was reported that 60% of the 47 structures had breached and, 65% of the structures were more than 50% full of sediment. Reasons for breaching of all structural types was related to piping, scour immediately below the structures, under sized design for size for the drainage area, and poor maintenance (Gellis et al., 1995).

Gully plugs can be effective in reducing runoff and sediment deliver out of the watershed. However, they should be viewed as an engineering solution of last resort as they are costly to install, require frequent maintenance of the structure, and require the sediment be removed and placed in an appropriate place frequently. Failure to provide this maintenance will result in failure of the structure and all trapped sediment and salt will be then remobilized and transferred downstream. The need to install a gully plug structure indicates that the uplands are unstable and unsustainable. In general, it should be less expensive to stabilize the uplands through vegetation management then than through costly engineering solutions.

Before

After

Photo: **Dennis Hoffman, Texas AgriLife Blackland Research and Education Center, Temple, TX.**

Table 5. **Number of references found on "gully plugs" associated with key concepts**

Associated concepts	Number of references	Most recent year
"Gully plugs" and salinity	4	1986
"Gully plugs" and hydrology / water erosion	3	1979
"Gully plugs" and wind erosion	0	-

5.1.3 Access control

Source: **www.blm.gov**

Access control entails a host of measures regulating animals, people and vehicle traffic in an area. In the context of this synthesis, access control refers specifically to the exclusion of vehicles (Off Highway Vehicles, OHV) from rangelands. In most consulted references, the effect of OHV exclusion was assessed by comparing disturbed to undisturbed areas.

Here again, none of the consulted references specifically related OHV-disturbed rangelands to salinity production. One of the references (Dohrenwend, 2003) addressed OHV-disturbance in Mancos shale rangelands, a study which may have a high relevance with regards to salinity considering the demonstrated high salinity production potential of Mancos shale rangelands. This section of the synthesis is therefore based on the studies that addressed changes in rangelands hydrologic processes in response to OHV disturbance.

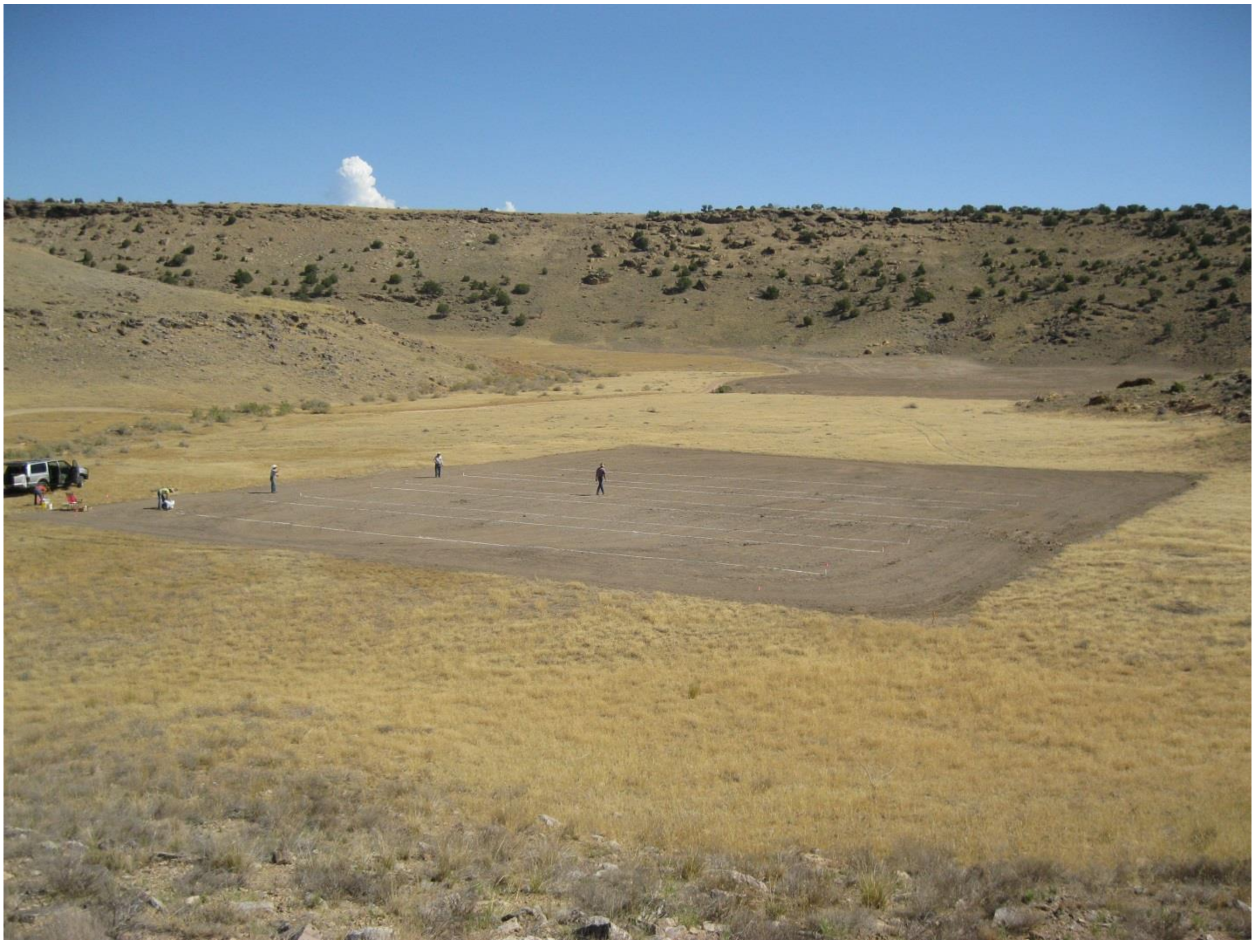
All consulted references suggest that OHV use on rangelands often result in land degradation and accelerated erosion. Nevertheless, the magnitude of damage incurred by OHV-disturbed rangelands compared to undisturbed sites varied between studies. Dohrenwend (2003) reported erosion rates five times higher on OHV-disturbed Mancos shale hillslopes compared to native erosion rates while Goodloe (2006) suggested erosion rates 26 times soil loss tolerance levels due to OHV activity in the Panoche hills area of California. Increase in erosion rates due to OHV have been related to dramatic changes in soil surface hydraulic characteristics (Iverson, 1980). In fact, Iverson (1980) estimated 13-fold decrease in Darcy-Weisbach friction factors and 5.5 fold increase in Reynolds numbers, two trends suggesting increase in runoff erosivity.

Table 6. **Number of references found on OHV or "Off Road" associated with key concepts**

Associated concepts	Number of references	Most recent year
OHV / "Off Road" + salinity	1†	2003
OHV / "Off Road" + hydrology / water erosion	5	2006
OHV / "Off Road" + wind erosion	1	2006

† *Disturbance in Mancos shale rangeland*

5.1.4 Soil amendments



Source: **www.blm.gov**

A soil amendment is defined as "*Any material such as lime, gypsum, sawdust, compost, animal manures, crop residue or synthetic soil conditioners that is worked into the soil or applied on the surface to enhance plant growth*" (Soil Science Society of America, 1997). The literature search revealed a number of references dealing with the use of various amendments to improve soil hydrologic properties. Superabsorbent polymers (SAP) have been studied for their potential to transform degraded lands into arable lands by promoting in-soil water storage and infiltration (Hüttermann et al., 2009). Polyacrylamide (PAM), a form of SAP soil conditioners, have been successfully used to significantly reduce runoff in laboratory (e.g., Yu et al., 2003), cropland (Zhang et al., 1998) and semi-arid rangeland (Fox and Bryan, 1992). Since a non-trivial relationship exists between runoff and surface water salinity, the exact nature of the effect of SAP application on salinity is difficult to infer. Another type of soil amendment covered in the consulted literature is gypsum which has been shown to be effective at enhancing soil profile desalinization in irrigated agriculture (Khosla et al., 1979). While gypsum may have potential in rangeland at reduce soil salinity, this specific topic has not been the object of any of the consulted references.

Soil amendment techniques for salinity reduction have applicability at relatively small spatial scales due to their high cost of implementation and are not an economical option to solve salt mobilization and transport problems in the UCRB.

Table 7. **Number of references found on SAP or polyacrylamide or gypsum associated with key concepts.**

Associated concepts	Number of references	Most recent year
SAP or polyacrylamide or gypsum + salinity	0	-
SAP or polyacrylamide or gypsum + hydrology / water erosion	5	2009
SAP or polyacrylamide or gypsum + wind erosion	0	-

5.2 Biotic alterations

5.2.1 <u>Chaining</u>

***Source*: www.blm.gov**

Chaining consists of pulling heavy chains (40 to 90 pounds per link) behind two crawler-type tractors in a U or J shaped pattern to crush brittle brush and uproot woody plants (Bureau of Land, 2004)

The effect of chaining on salt concentration in surface waters of the upper Colorado river basin was investigated by Hessary and Gifford (1979) who found no consistent pattern between salt concentration in areas where chaining was applied on pinyon-juniper and sagebrush and that observed in untreated areas. The lack of consistent difference between treated and untreated sites was attributed to the fact that salt concentration on pinyon-juniper and sagebrush sites are generally not considered to pose a salinity threat to major river systems. Nevertheless, demonstrated effects of chaining on soil hydrologic processes (e.g., Gifford and Shaw, 1973) suggest that this practice might have practical application as salinity control measure.

Table 8. **Number of references found on chaining associated with key concepts**

Associated concepts	Number of references	Most recent year
Chaining and salinity	3	1979
Chaining and hydrology / water erosion	4	2001
Chaining and wind erosion	0	-

5.2.2 Grazing

Source: **USDA-ARS**

Grazing as a range management practice implies a host of activities promoting the consumption of standing forage by domestic animals. The effect of grazing on rangeland hydrology has been well documented and inferential relationships to salinity have also been proposed. Grazing may influence hydrology through (1) vegetation alteration and (2) direct soil surface property modification as a result of animal trampling.

Knowledge regarding the hydrologic impacts of grazing is limited and based largely on anecdotal observations or poorly replicated experiments. In general, the effects of livestock grazing on hydrologic resilience are associated with the degree to which grazing pressure affects surface susceptibility and/or the fire regime (Gifford et al., 1978; Wood and Blackburn, 1981; Thurow et al., 1986; Thurow et al., 1988; Thurow, 1991;Trimble and Mendel, 1995). Grazing pressure that substantially reduces vegetation and ground cover and/or compacts and disturbs surface soils will likely increase losses of water and soil resources through water and wind erosion processes (Greene et al., 1994; Trimble and Mendel, 1995; Field et al., 2011). Soil compaction (increased bulk density) and disturbance associated with intense and/or repetitive grazing will increase runoff and erosion, and these effects are strongly influenced by the season of use (Gifford et al., 1978; Branson and Miller, 1981; Warren et al., 1986a; Greenwood and McKenzie, 2001; Daniel et al., 2002; Teague et al., 2011). High intensity grazing, particularly over multiple years, can alter plant composition such that the biotic structure triggers long-term site degradation through abiotic-driven losses of water and soil resources (Warren et al., 1986b; Warren et al., 1986c; Schlesinger et al., 1990; Greene et al., 1994; Rietkerk and Van de Koppel, 1997; van de Koppel et al., 1997; Ludwig et al., 2007; Turnbull et al., 2008; Turnbull et al., 2012). West et al. (1984) reported that after 13 years of no livestock grazing in west central Utah that desirable perennial vegetation had not been reestablished despite a trend of increased precipitation over the length of the study. They concluded that the site had transited to a stable shrub dominated site. The concept that removing livestock would return the plant community to the original sagebrush-native shrub-grass assemblage was unlikely. Direct manipulation of the site is mandatory if rapid return to the desire plant community is desired. Belnap et al. (2009) reported that grazed watersheds in southeast Utah had significantly more soil loss from wind than ungrazed watersheds. When comparing soil losses among the sites they determined that biological soil crusts were the most important in predicting site stability followed by perennial plant cover.

Extensive woody plant encroachment and subsequent amplified runoff and soil erosion across much of the western US have been partially attributed to intensive grazing and an associated decrease in wildfire activity during the 20th Century (Buffington and Herbel, 1965; Grover and Musick, 1990; Bahre and Shelton, 1993; Miller and Wigand, 1994; Archer et al., 1995; Miller, 2005; Romme et al., 2009; Pierson et al., 2010; Turnbull et al., 2010a; Turnbull et al., 2010b; Turnbull et al., 2012; Van Auken, 2000; Van Auken, 2009). Overall, vegetation, soil properties, and the associated hydrologic/erosion responses to grazing can vary tremendously depending on inherent characteristics of the respective ecological site, pre-grazing rangeland condition, and the grazing prescription (Branson and Miller, 1981; Thurow et al., 1986; Thurow et al., 1988; Thurow, 1991; Milchunas and Lauenroth, 1993; Trimble and Mendel, 1995; Burke et al., 1999; Emmerich and Heitschmidt, 2002; Castellanos et al., 2005; Vermeire et al., 2005; Field et al., 2011; Teague et al., 2011). In many cases, proper grazing can be used to augment restoration of rangeland ecosystems or to reduce fuel accumulations and potential fire severity without negative ecohydrologic impacts (Briske, 2011).

Bentley (1978) published an extensive review examining the influence of grazing on rangeland vegetation. The recurring theme from this review relates to the threat of overgrazing on ecosystem health suggested by many studies in terms of: temporary or permanent loss of vegetative cover especially during droughts, decline of desirable species through selective browsing, dominance of less desirable species, etc. For example, Bentley (1978) observed that during the severe droughts of 1933-1939 and 1952-1955 that prevailed in the great plains, loss of vegetative cover on heavily grazed grassland ranges was nearly double that on moderately grazed ranges and more than double that on un-grazed ranges. Erosion decreases significantly as plant lifeform changes from short grass to midgrass to tall grass (Thurow et al., 1986; Thurow et al., 1988) as a function of grazing intensity. Grazing management practices impact soil erosion and salinity transport on rangelands through their influence on the type, amount, and distribution of cover (Gifford et al., 1978). By reducing both canopy and ground cover and increasing the number and size of bare soil patches, improperly applied grazing management practices increase the risk that a site will be eroded by both raindrop and concentrated flow processes. In the northern, central, and southern plains grasslands the runoff and erosion potential of a site are closely related to management activity. Prolonged heavy continuous grazing results in significant change in plant community structure in which the more productive tall- and mid-grasses are replaced with less productive short-grasses resulting in increased surface runoff and soil erosion (Rauzi et al., 1968; Thurow et al., 1988). Other studies have concluded that proper grazing and brush management practices result in infiltration, surface runoff, and soil loss characteristics similar to those of ungrazed landscapes (Blackburn et al., 1982; Blackburn, 1983; Weltz and Wood, 1986a; Weltz and Wood, 1986b).

The conventionally accepted wisdom is that ground cover is negatively related to runoff production and erosion (e.g., Hanson et al., 1970; Moore et al., 1979; Thurow et al., 1986; Wine et al., 2012) and presumably to surface water salinity (e.g., Moore et al., 1979; Bentley et al., 1980). Nevertheless, no consensus exists on the magnitude of change in hydrologic properties imputed to grazing probably due to the diversity of research methodologies published in the literature. Numerous authors have evaluated the impacts of grazing and its impact on runoff and soil loss on the Badger Wash watershed near Grand Junction Colorado. They reported that very heavy grazing did increase runoff and sediment yield (Lusby et al., 1964; Lusby, 1970; Lusby, 1979). However, Thompson (1968) reported that after 10 years with exclusion of grazing, infiltration rates were lower in both the grazed and ungrazed watershed. They found that time of year the sample was collected had more influence on infiltration rates than grazing. Branson and Owen (1970) reported that runoff from all 17 watersheds was directly related to percent of bare soil. Sediment yield was not significantly related to bare soil. They also reported that time of year and when vegetation was sampled (spring vs. fall) had significant impact on the ability to predict runoff.

Using runoff and sediment monitoring data (1956 – 1966) from the Badger Wash Basin, CO., (Lusby and Reid, 1964) found that grazing increased total watershed runoff 1.3 to 1.45 fold and sediment yield 1.8 fold. Local soil properties have also been used to quantify the impact of grazing on hydrology. Bentley (1978) reviewed an extensive list of studies demonstrating a positive correlation between vegetation health indicators (e.g., ground cover and plant successional development) and infiltration rate. Intensive grazing for example may cause reduce in ground cover which would in turn expose a larger area of the soil to raindrop impact causing surface sealing, increased bulk density and decrease in infiltration rate (e.g., Thurow et al., 1986; Wilcox and Wood, 1988).

Vegetation composition has a direct influence on water balance and ground cover (Moore et al., 1979) and has been proposed as a potential factor controlling runoff. Hanson et al. (1970) observed a predominance of short grasses and sedges on heavily grazed watersheds while lightly grazed watersheds showed a mixture of grasses with a large proportion of western wheatgrass. Thurow et al. (1986) demonstrated that the presence of trees (oak in the study) in pastures promotes increased infiltration and lower erosion. In an analysis aiming at proposing salt reduction alternatives in UCRB rangelands, Bentley et al. (1980) recognized the dependence of watershed hydrology on vegetation composition by assuming that 1% of bare soil would result in 17.3 mm (0.68 inch) increase in runoff in most studied vegetation communities and 60.2 mm (2.37 inches) in Shadescale-Galleta grass and Big sagebrush – Shadescale communities. The paucity of observed data linking vegetation state and composition to salt production in runoff limits however any knowledge in this domain to be inferred from the know effect of grazing on hydrology. Besides the lack of observed data, understanding the impact of grazing on salinity is further complicated by the confounding effect of animal trampling on runoff generation and salinity.

One of the most referenced soil property changes resulting from animal trampling is bulk density increase by compaction leading to decrease in infiltration rate and potentially increase in erosion (e.g., Bentley, 1978; Warren et al., 1986c; Hiernaux et al., 1999). The negative effect of trampling on soil properties is exacerbated when grazing occurs in riparian zones (e.g., Belsky et al., 1999; Flenniken et al., 2001). In fact a review of literature on grazing influence on stream and riparian ecosystems by Belsky et al. (1999) revealed many studies reporting negative impacts but none reporting potential benefits on these ecosystems. Some studies have however shown in some cases (e.g., George et al., 2002) no apparent effect of grazing on stream morphology.

Because inappropriate grazing management may lead to rangeland degradation and potentially increase surface water salinity, prescribed grazing management has been proposed as a key control in reducing salinity. Generally, the greater the bare soil amount, the greater the erosion rate. Levels of cover necessary for site protection against accelerated soil loss range from 20% in Kenya (Moore et al., 1979) to 100% for some Australian conditions (Costin, 1959). Most studies indicate that cover of 50 to 75% is probably sufficient (Packer, 1951; Orr, 1970; Gifford et al., 1978). Bentley et al. (1980) suggested that moderate grazing (40% – 60 % utilization of forage plants) during winter when the soil is frozen would result in less compaction and disturbance by trampling while periodic rest from grazing (rest-rotation) would also ensure healthy plant communities and the buildup of litter to protect soil from erosion. Bentley et al. (1980) estimated a potential salt reduction of 15% in the UCRB from careful grazing management.

Hydrologic response to grazing largely parallels those of other ecological variables in that stocking rate and weather are the dominant variables that have to be addressed to achieve desired results. In many cases, prescribed grazing management can be used to augment restoration of rangeland ecosystems or to reduce fuel accumulations and potential fire severity without negatively impacting hydrologic processes (Briske et al., 2011).

***Table 9.* Number of references found on grazing associated with key concepts**

Associated concepts	Number of references	Most recent year
Grazing and salinity	14	2009
Grazing and hydrology / water erosion	42	2013
Grazing and wind erosion	1	-

5.2.3 Fire

***Source*: www.blm.gov**

The ecology of North American rangelands depends strongly on fire (Fuhlendorf et al., 2011). The consensus about fire within the rangeland community is that native fire regimes have been altered by various human induced factors. Two significant trends have been reported in relation to these shifts in fire regimes: (1) intentional suppression of fire or reduction in fuel load through grazing has led to invasion of woody plants and (2) increased fire frequency as a result of invasion of exotic herbaceous species (e.g. *Bromus tectorum*, Cheatgrass) (Fuhlendorf et al., 2011). In some cases, fire has been used or prescribed by various rangeland management agencies for restoration of historical rangeland conditions or promotion of specific rangeland services.

Effects of fire on salt loading to surface water have not been specifically addressed in any of the consulted references and this synthesis presents what was found in relation to runoff and sediment production. From this literature search, immediate consequences of fire cited on rangeland hydrologic processes include loss of vegetative cover, increasing vulnerability to wind and water erosion and physiochemical changes in the soil surface layer depending on burn severity resulting in temporary water repellency and increased runoff (e.g., Wright et al., 1976; Glenn and Finley, 2010; Pierson et al., 2011). Long term effects of fire on hydrologic processes has been seldom studied as suggested by the low number of references (3) found on this topic. This might be explained by the fact that in general, long term effects of range vegetation modification practices such as fire can be inferred from the hydrologic properties of the vegetation type targeted by the practice. Most published long term effects of fire on hydrology suggest that short term detrimental effect of fire on runoff and erosion wane as vegetation is progressively reestablished. Prescribed fire can be used successfully by various rangeland management agencies for restoration or promotion of specific rangeland services successfully (e.g., Wright et al., 1976; Knight et al., 1983; Garza Jr and Blackburn, 1985). Wright et al. (1976) has however found that recovery from the initial detrimental effect of fire is lengthened on steeper slopes to 15 to 30 months or more compared to 9 to 15 months of recovery time on moderate slopes.

Fire alters hydrologic processes by altering the geospatial structure of plants and removal of biomass and thereby increasing surface susceptibility to transport of salt by increasing runoff and soil loss by wind and water on bare soils immediately following the fire (Fig. 13). The destruction of organic matter in soils during a wildfire can alter soil structure and aggregate stability, increase bulk density and pH, and decrease porosity and infiltration capacity and rates (Giovannini and Lucchesi, 1997; Hester et al., 1997; Stoof et al., 2010; Mataix-Solera et al., 2011) . Fire can also damage and/or kill invertebrates, microorganisms, and mycorrhizae fungi in the surface soil with extremely hot fires. These organisms facilitate soil aggregation, nutrient cycling, and infiltration rates and capacities (DeBano, 2000; Shakesby and Doerr, 2006; Mataix-Solera et al., 2011). Physical soil crusting may occur after fire in soils that are high in clay. This can reduce water infiltration rates and water availability and slow recovery after fire (Mills and Fey, 2004; Snyman, 2002). Soil health and quality is also degraded by increased rates of soil erosion and surface runoff following fire (Emmerich and Cox, 1994; Pierson et al., 2011; Shakesby, 2011; Williams et al., 2013). If not mitigated, accelerated soil erosion can degrade an ecological site to such a state that it can permanently alter its form and function (Herrick et al., 1999). Fires may also increase water repellency of soils and remove vegetation cover, which can increase the probability of flash floods (DeBano, 2000; Reed and Schaffner, 2007; Pierson et al., 2011; Cannon et al., 2011). A detailed and comprehensive review of fire effects on vegetation and soils of the Great Basin region is provided by Miller et al. (2013).

The impact of fire on hydrologic and erosion processes largely depends on the spatial arrangement of burn severity, bare soil exposure, degree of water-repellency created, rainfall intensity, and storm patterns (Al-Hamdan et al., 2011). Rare, often unexpected, rainfall event(s) may trigger a nick-point along the hillslope and facilitate the formation of a concentrated flow path (rill). On rangelands, these concentrated flow paths facilitate water accumulation and accelerate soil erosion (Al-Hamdan et al., 2012). If left unchecked, these concentrated flow paths can remove enough soil to result in the site crossing an ecological/hydrologic threshold and becoming permanently degraded (Urgeghe et al., 2010; Pierson et al., 2013). Intense rainstorms after wildfires may cause flooding and mud-flows and result in extensive damage to property and infrastructure (Pierson et al., 2002; Klade, 2007) . In rangeland and woodland dominated watersheds, Reed and Schaffner (2007) found a 10 fold increase in peak flow rates and soil erosion following fire. The magnitude of these changes was so great they developed a new procedure to estimate potential post-burn flash floods for use by NOAA.

The relative post-fire hydrologic recovery of rangeland plant communities is primarily influenced by the pre-fire ecological state, fire severity, and post-fire climate and land use that relate to vegetation recovery (Kinoshita and Hogue, 2011; Miller et al., 2013). The pre-fire ecological state influences spatial variability in burn severity and post-fire plant recruitment. High severity burns on productive sites may consume nearly 100% of canopy and ground cover, but runoff and erosion rates can return to pre-fire levels within one to three years respectively depending on post-fire plant recovery (Pierson et al., 2008; Pierson et al., 2009; Pierson et al., 2011). Relative hydrologic recovery appears to occur within one to three years post-fire. Burned rangelands will remain susceptible to runoff and erosion during extreme events until overall site characteristics (e.g., live plant and litter biomass) are consistent with pre-fire conditions (Pierson et al., 2011). Arid rangelands with warm/dry soil temperature/moisture regimes may require longer periods to recover hydrologically than cool/moist sites and may be vulnerable to annual grass invasion and subsequent re-burning (Chambers et al., 2007; Brooks and Chambers, 2011; Davies et al., 2012). Post-fire hydrologic recovery is dictated by climate, burn severity and by land use activities that favor or hinder vegetation recruitment and ground cover reestablishment (Wright et al., 1976; Knight et al., 1983; Garza Jr and Blackburn, 1985).

***Table 10*. Number of references found on fire or burning associated with key concepts**

Associated concepts	Number of references	Most recent year
Fire and salinity	0	-
Fire and hydrology / water erosion	14	2011
Fire and wind erosion	1	2008

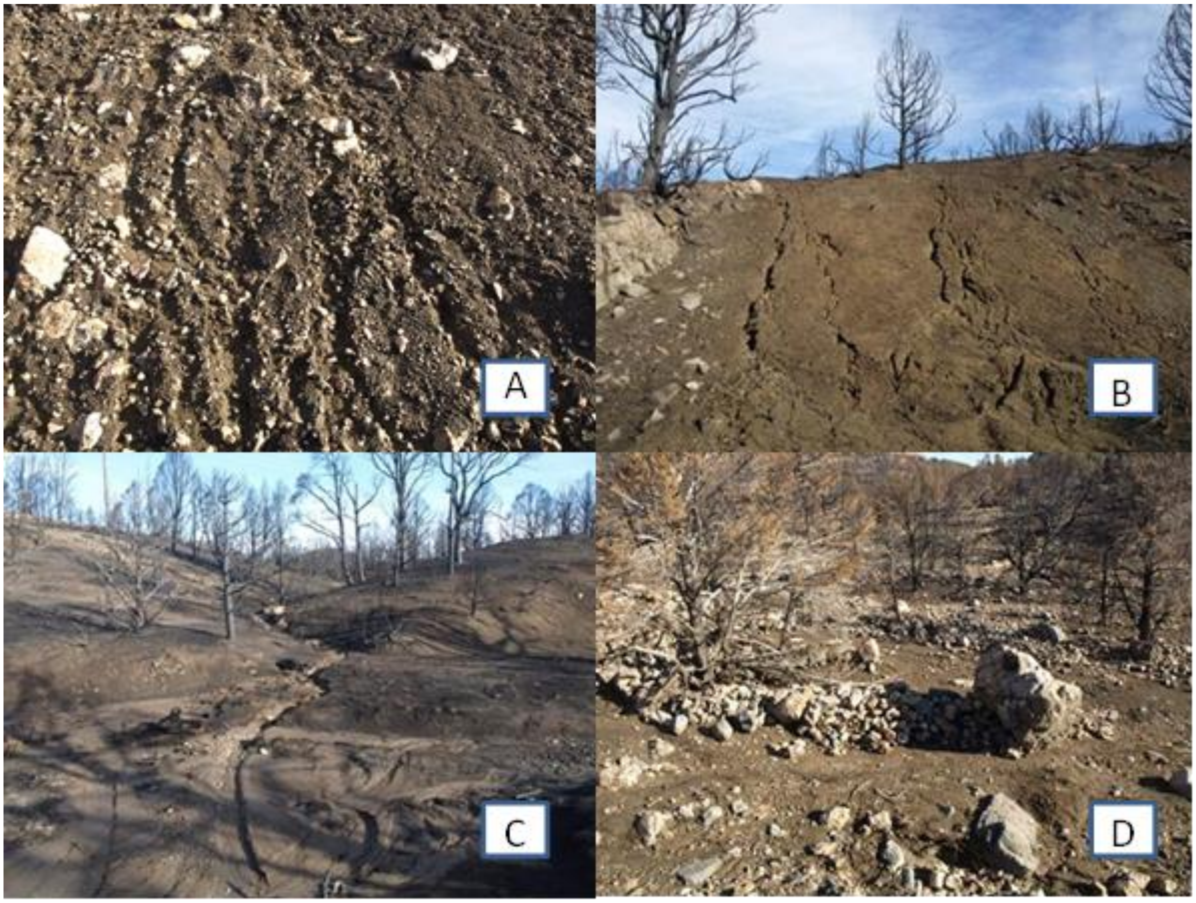


Figure 13. **Great Basin pinyon and Juniper woodland near Gardnerville, NV illustrating rill erosion (A) and (B), (C) channel erosion and deposition in first order channel, and (D) and scoured channel with extensive bed load deposits in main stream channel following a single rainstorm 4 months after a wildfire. These photographs illustrate the vulnerability to accelerated soil erosion for these woodlands sites if the sites are not successfully revegetated the first year following a fire (Photographs by Christo Morris).**

6. Modeling runoff and soil loss on rangelands at the hillslope scale

A new process based model has been developed by the Agricultural Research Service for assessing runoff and soil erosion rates on rangelands that specifically assesses the risk of soil erosion at national, regional, and local scales (Weltz et al., 2008). The RHEM tool was developed based exclusively on data collected from a large number of geographically distributed rangeland erosion experiments (Wei et al., 2007; Wei et al., 2009; Nearing et al., 2011). The unit scale for raindrop splash and sheet erosion utilized to develop RHEM is the rangeland rainfall simulator plot with a minimum size of 2 m by 6 m (long axis pointed down slope). This was done in order to incorporate the scale of rangeland heterogeneity and complexity associated with complex vegetation patterns on most rangeland sites. Source terms for RHEM are based on rangeland data, which models splash and sheet flow effects as the dominant process on undisturbed natural rangelands. Research has indicated that infiltration, runoff, and erosion dynamics are correlated with presence/absence and composition of specific plant taxa, life/growth form attributes (Hanson et al., 1970; Thurow et al. 1986; Andreu et al., 1998; Bochet et al., 1998) and spatial arrangements of the plants (Valentin et al., 1999; Cammeraat, 2004; Imeson and Prinsen, 2004; Ludwig et al., 2005; Puigdefabregas, 2005; Ludwig et al., 2007; Pierson et al., 2011;). An important aspect of the model relative to application by rangeland managers is that RHEM is parameterized based on plant growth form classification using the data that is typically collected for rangeland management purposes (e.g., rangeland health assessments).

RHEM was designed to require minimal input that is readily available for most rangeland ecological sites. RHEM model inputs are surface soil texture, slope length, steepness and shape, dominant plant life form (e.g., shrub, shortgrass, annual grass, etc.), canopy cover, ground cover, and precipitation. Precipitation can be estimated by the model by selecting the nearest weather station within the model interface. RHEM estimates runoff, soil erosion, and sediment delivery rates and volumes at the hillslope spatial scale and the temporal scale of a single rainfall event. The model does not predict the stream channel erosion process. The model does have the capability to estimate concentrated flow induced soil erosion. Validation studies of the ability of RHEM to predict runoff, $r^2 = 0.87$, and sediment yield, $r^2 = 0.50$, show the model is overall acceptable in predicting soil loss on rangelands (Nearing et al., 2011).

Weltz and Spaeth (2012) used RHEM to assess the impact of ecological sites invaded with Ash Juniper (*Juniperus ashei* J. Buchholz), on the Edwards Plateau near Johnson City, Texas, USA. They determined that applying conservation to return the invaded site to reference conditions could reduce soil loss by up to 6 fold depending on the runoff return period evaluated. Weltz et al. (2014)used RHEM to estimate the impact of changing from one state to another for two different plant community types. For a typical Wyoming sagebrush site near Austin, NV, water-induced soil loss was 2.4 to 3 times lower than it was on a burned site previously dominated by cheatgrass. In addition to greater soil loss, the burned cheatgrass site had 1.2 to 1.6 times more runoff during intense summer thunderstorms. Runoff and soil loss from the cheatgrass dominated site was estimated to be slightly elevated over the Wyoming sagebrush site at current potential. In a mountain sagebrush site that had been encroached by pinyon and juniper trees, the type and distribution of canopy and ground cover are altered relative to the Current Potential State. In the Current Potential State, more uniformly distributed vegetation makes concentrated flows unlikely and minimizes soil loss and runoff. When pinyon and juniper trees invade and canopy closure advances, the understory cover (grasses and forbs) declines (Miller et al., 2000). This further increases the probability of concentrated flows in the connected bare spaces and results in accelerated runoff and soil erosion (Pierson et al., 2011). After a wildfire, runoff may increase on the order of 4 to 10 times, and soil loss can increase 4 times, increasing the probability of downstream floods. These results are consistent with those reported by others that sites encroached by pinyon and Junpier trees, both pre and post fire, have increased potential for accelerated soil erosion (Pierson et al., 2011; Pierson et al., 2013). The degree to which fire increases runoff and erosion from Great Basin rangelands is determined by the spatial arrangement of burn severity (amount of vegetation and ground cover removed), inherent ecological site characteristics, such as, soil depth and slope steepness, and the intensity and duration of the precipitation event.

The RHEM tool was used to estimate runoff and erosion at the hillslope scale for over 10,000 NRI sample points in 17 western states on non-Federal rangelands (USDA-NRCS, 2011). The national average annual erosion rate on non-Federal rangeland was estimated to be 1.4 ton ha^{-1} $year^{-1}$. Nationally 20% of non-Federal rangelands generate more than 50% of the average annual soil loss. Over 29.2 x 10^6 ha (18%) of the non-Federal rangelands might benefit from treatment to reduce soil loss to below 2.2 ton ha^{-1} $year^{-1}$. National average annual erosion rates combine areas with low and accelerated soil erosion. Evaluating data in this manner can misrepresent the magnitude of the soil erosion problem on rangelands. Between 23% and 29% of the Nation's rangelands are vulnerable to accelerated soil loss (soil erosion > 2.2 ton ha^{-1} $event^{-1}$) if assessed as a function of vulnerability to a runoff event > 25 years. Hernandez et al. (2013) reported that RHEM could effectively assess the influence of foliar, ground cover, plant life-form, soils, and topography on current soil erosion rates using data from USDA National Resources Inventory (NRI on-site data collection) in southern Arizona. Results suggested that the model could be further improved with additional measured experimental data on infiltration, runoff, and soil erosion within key ecological sites in order to better quantify model parameters to reflect ecosystem changes and risk of crossing interdependent biotic and abiotic thresholds. The results of Hernandez et al. (2013) from southern Arizona and national assessment of soil erosion (USDA-NRCS, 2011) indicated that RHEM can be used to assess the relative erosion rates on rangelands and can be used to assess the potential benefits of conservation and land management practices.

Belnap et al. (2013) evaluated the RHEM model to and its effectiveness for estimating runoff and soil loss on biological soil crust dominated sites in Utah. They reported that RHEM model, once calibrated, predicted that sites with the least development of biological soil crusts had the highest amount of soil loss and that erosion potential increase by a factor of 10 as slope gradients increase from 0% to 10%. The model results indicated that as biological soil crust increased soil loss decreased. The RHEM model results also illustrated how soil erosion potential rises as antecedent soil moisture levels rise.

RHEM model must consider not only the total coverage of biological soil crusts but also the level of development of the biological soil crust to be effective in predicting runoff and sediment loss in the UCRB. New field data must be collected to address the increase in soil erodibility found on saline and sodic soils, validate the influence of biological soil crusts and concentrated flow processes that initiate rilling, and determine the influence of spatial distribution of vegetation (canopy gap) to effectively model changes in water quality (salinity) and predict the benefit of management actions designed to reduce salt mobilization and transport across the UCRB.

7. Concluding remarks and recommendations

Salinity in the Colorado River emanating from natural rangelands areas is primarily controlled by geology. Rangeland areas with high salt contribution to the Colorado River are likely to be located in highly saline geologic formations. In the UCRB, the Mancos Shale and to a lesser extent the Eagle Valley Evaporite formations have been identified as dominant contributors to Colorado River salinity and it is consequently widely accepted that efforts to reduce natural rangeland-borne salinity in the Colorado River should target these highly saline rangeland areas.

Bibliographic references covering salt transport processes revealed a strong emphasis on water erosion and subsurface hydrology processes as the main driving mechanisms of salt delivery to surface waters. The role of wind erosion on salt delivery to surface waters has been assumed to be that of an ancillary enrichment function through which salt laden dust emission from highly saline sources such as dried endorheic lake bottoms (playas) deposit in remote areas draining to surface waters. Current salt reduction strategies from rangelands are based on the premise that salt delivery to surface water is empirically related to sediment transport processes. Nevertheless, erosion reduction is often associated with decreased runoff and increased infiltration. In highly saline environments where salt-enriched percolated water intercepts surface water, erosion reduction alone might not be sufficient.

The key knowledge gap found in this bibliographic search relates to the understanding of the effect of rangeland management practices on salt delivery to surface waters. Perhaps this knowledge gap is associated with the intricate surface-subsurface salt processes existing in highly saline environments. Most attempts to improve our understanding of rangeland management practices effects on salinity are hindered by a severe lack of data and future research endeavors should focus on better understanding salt pickup and delivery processes in targeted saline environments.

Salt pickup processes are currently inferred from the assumed relationship with sediment transport in saline rangelands. Sediment transport on saline soils is however a poorly understood process due to the exacerbating effect of salt content on soil erodibility. As a result, major physically based soil erosion models such as the Water Erosion Prediction Project (WEPP) model or the Rangeland Hydrology and Erosion Model (RHEM) have been developed using data excluding saline and sodic soils. Better understanding sediment transport processes in saline environment is therefore needed and could be achieved through rainfall simulation experiments using state-of-the-art rainfall simulation technologies specifically developed to quantify soil erosion and salt solute transport processes on rangelands.

Recent developments in soil erosion research technologies at the USDA-ARS now offer the opportunity to monitor soil erosion and salt transport processes at high spatial and temporal resolutions. High temporal soil erosion monitoring is achieved with automated runoff and sediment sampling system and is greatly augmented by spatially distributed soil erosion monitoring using digital photogrammetry or structure from motion. The advantage of the latter development is that sediment erosion and deposition areas can be accurately assessed and their role in sediment transport processes precisely understood. This new development allows for a systematic assessment of vegetation density and three dimensional arrangements from erosion plot surface models and a better understanding of the role of vegetation in sediment transport. Real time salt transport is monitored using specially designed wireless electrical conductivity probes deployed in erosion plot to track salinity change at the soil surface. Using this new technology, an extensive amount of data can be collected from highly saline rangeland environments to better understand sediment and salt transport processes. More importantly, this data will provide the necessary foundation to develop accurate erosion computation routines for saline soil to include in RHEM or other hydrologic and salt transport models.

Understanding the complex partitioning of solutes between surface and subsurface processes is key to understanding the effect of rangeland management practices on salt delivery to surface waters. In this context, soil erosion models are valuable tools to assess the role of rangeland management practices on salt transport to surface waters. Since the dynamic interaction of management practices –precipitations– salt pickup and transport are synthetically handled in these models, it is possible to appreciate the effect of a given practice on net salt transfer from saline uplands to surface waters. This information can then be used to match management practices with salt source areas. Finally, long term watershed continuous monitoring projects are needed to validate the effectiveness of rangeland management practices at reducing salt delivery to the Colorado River and its tributaries.

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