Daniel Rath EcoGeo 2020

Salinity, Soils, and our efforts to manage both in the Colorado Basin

Introduction

The Colorado River transports an estimated 14.8 million acre-feet of water yearly, providing water to over 40 million people in 7 different states (Colorado, Utah, Arizona, Nevada, California, Wyoming and New Mexico) and 2 countries (USA and Mexico) (Udall and Overpeck 2017). The sheer volume of its flow through a relatively dry area (US Geological Survey 2002) means that the Colorado is relied upon to simultaneously support agricultural, entertainment, industrial, hydropower and municipal use, providing economic benefits of up to $1.4 trillion per year(United States Bureau of Reclamation 2013). The agricultural industry is particularly dependent on the Colorado, as limited rainfall in the Colorado Basin drives farmers to use almost 14 million acre-feet of water from the river watershed per year for irrigation (Maupin, Ivahnenko, and Bruce 2018). This water usage supports almost 15% of the nation’s crops, and 13% of its livestock production (United States Bureau of Reclamation 2017).

Deciding who gets to use how much of the Colorado has led to issues like water rights, introduction of non-native species, and increasing salinity becoming controversial topics among conservation professionals, nearby landowners and governments alike. Of the myriad environmental issues surrounding use of the Colorado River’s water, salinity is the most serious, causing an estimated 500 million dollars in damage each year and contributing to the Colorado’s status as one of the world’s most stressed rivers (Gardner and Young 1988). The historical salinity load of the Colorado (1940-1980) was approximately 9.3 million tons of salt per year, which has decreased to 7.7 million tons of salt per year from 2005-present (United States Bureau of Reclamation 2013). Approximately 50% of this salt load is due to the inherent salinity of the underlying marine sediments and geologic formations such as salt domes, which manifests in numerous saline springs (Rumsey et al. 2017). The remaining 50% of the salt load comes from agricultural irrigation and the numerous diversions that reduce streamflow below Glen Canyon Dam (United States Bureau of Reclamation 2005).

The United States is required, by treaty, to provide Mexico with 1.5 million acre-feet of water from the Colorado each year with an annual average salinity of no more than 115 ppm higher than the water behind Imperial Dam (United States Bureau of Reclamation 2017). This means that salinity control measures need to be implemented across the entire Colorado watershed in order to ensure sufficient water quality by the time the water reaches Mexico. Current salinity control programs remove an estimated 1.3 million tons of salt per year from the Colorado river, with an additional 340,000 tons of salt needing to be removed by 2035 to meet water quality standards (United States

Bureau of Reclamation 2017). Even though salt removal efforts only need to be stepped up by 26%, many current projects are reaching the end of their effective lifespans. This looming crisis may jeopardize the US' treaty obligations, and requires the deployment of novel solutions in the upcoming decade.

This paper will explore factors affecting the United States' ability to reach its salinity goals by discussing:

1) Natural sources of Colorado River salinity
2) Anthropogenic sources of Colorado River salinity
3) Salinity mitigation efforts and future outlooks.

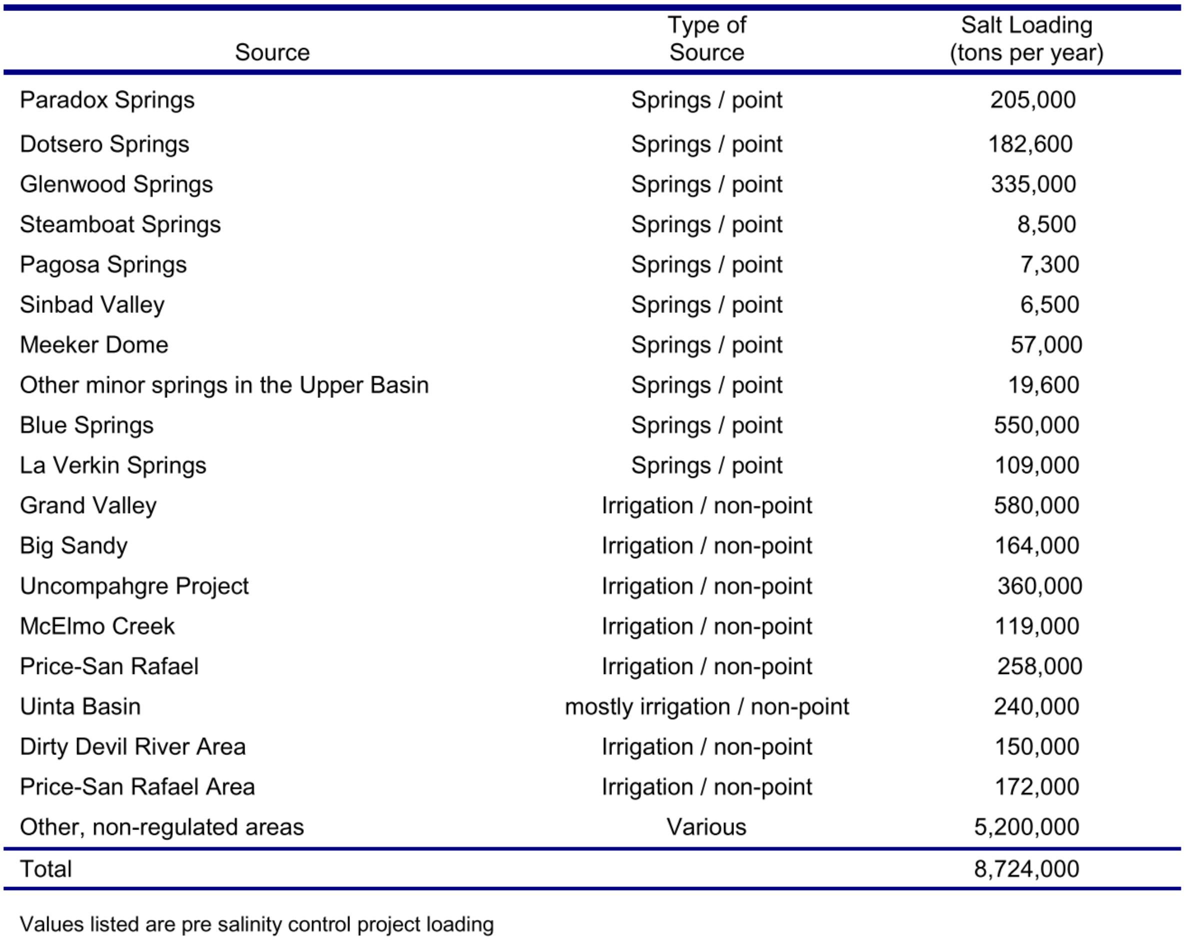
In doing so, this paper's goal is to show that additional controls on salinity will require a understanding of seasonal variation in salinity, a clear accounting of the ways in which our man-made systems both contribute to and mitigate salt loads, and an appraisal of how much salinity management is feasible in the future.

Natural Salinity Sources

Salinity (also called Total Dissolved Solids or TDS) is the mass of dried ionic constituents in a given volume of water that pass through a 2um sieve. While this definition is suitable for water bodies, it is difficult to apply to the soil, where water may exist only in pores (Environmental Protection Agency 2020). Soil salinity assessments often use electrical conductivity of the soil instead as a proxy for salinity. This electrical conductivity can be affected by ionic constituents such as metal ions, sulfate, carbonates and chloride, but can also include organic contaminants, especially in highly industrialized areas (Clark 1965). TDS can be expressed as a concentration (mass/volume, mg/L) or as a load (mass/time, tons/year). The elements that make up the largest proportion of solutes in soil, ground and surface water are calcium (Ca), magnesium (Mg), sodium (Na), potassium (K), chloride (Cl), sulfate (SO_4), and bicarbonate (HCO_3). These solutes are generally water-soluble, though precipitation of calcium and sodium can occur at higher pH values (Lundström, van Breemen, and Bain 2000).

A recent study has shown that TDS concentrations in the lower Colorado River undergo natural cycles of high and low salinity. These cycles are linked to the amount of rain received in the headwater regions (Tillman et al. 2019). Above average rainfall produces greater amounts of runoff and corresponding decreases in salinity at upper basin monitoring sites, as well as in Lake Powell. Lower amounts of rainfall have the opposite effect, producing less runoff and raising salinity levels. This inverse relation is a result of higher salinity inputs from baseflow and agricultural return flow during low-flow periods, and lower salinity inputs from snowmelt during high-flow periods. Lake

Powell integrates these tributary inputs and salinity concentrations during high-flow periods, controlling the salinity near Lees Ferry through Glen Canyon Dam releases. Natural sources of salinity in the Colorado come from the dissolution of carbonate minerals in the underlying rocks such as calcite ($CaCO_3$) and dolomite ($CaMg(CO_3)_2$) releasing calcium, magnesium, and bicarbonate ; gypsum ($CaSO_4 \bullet 2H_2O$) and anhydrite ($CaSO_4$) releasing calcium and sulfate ; halite (NaCl) releasing sodium and chloride; and silicate minerals releasing sodium, calcium, magnesium, potassium, and bicarbonate. Clay minerals in soils can also release sodium or potassium ions from their surfaces or interlayers as they weather (Tuttle and Grauch 2009). Formations such as the Mancos Shale in Colorado, a mudrock that accumulated in offshore and marine environments, contribute large amounts of dissolved gypsum and sodium sulfate. Dissolution of these minerals is driven by the movement of water through cracks and poorly consolidated bedrock material (Giggy 2018), exemplified in the TDS concentrations at Blue Springs, Dixie Hot Springs, and in the Paradox Basin (Fig. 1).



Source	Type of Source	Salt Loading (tons per year)
Paradox Springs	Springs / point	205,000
Dotsero Springs	Springs / point	182,600
Glenwood Springs	Springs / point	335,000
Steamboat Springs	Springs / point	8,500
Pagosa Springs	Springs / point	7,300
Sinbad Valley	Springs / point	6,500
Meeker Dome	Springs / point	57,000
Other minor springs in the Upper Basin	Springs / point	19,600
Blue Springs	Springs / point	550,000
La Verkin Springs	Springs / point	109,000
Grand Valley	Irrigation / non-point	580,000
Big Sandy	Irrigation / non-point	164,000
Uncompahgre Project	Irrigation / non-point	360,000
McElmo Creek	Irrigation / non-point	119,000
Price-San Rafael	Irrigation / non-point	258,000
Uinta Basin	mostly irrigation / non-point	240,000
Dirty Devil River Area	Irrigation / non-point	150,000
Price-San Rafael Area	Irrigation / non-point	172,000
Other, non-regulated areas	Various	5,200,000
Total		8,724,000

Values listed are pre salinity control project loading

Fig 1. *Salt loading sources to the Colorado River (1971 values). Taken from (United States Bureau of Reclamation 2017)*

The opaque, turquoise waters of Blue Spring (Fig 2.), which flow through the Redwall and Muav limestone units, pick up large amounts of sodium, potassium and chloride before issuing into the Little Colorado River. The springs flow at an average of 160,000 acre-feet/yr, with an average salinity of 2,500 mg/L and contribute about 550,000 tons per year of salt load to the Colorado River (Cooley 1976). These springs are the largest point source contributors of TDS to the Colorado River system (United States Bureau of Reclamation 2005). The Virgin River in Utah has relatively low salt concentrations until it flows past the Dixie Hot Springs, which have a TDS concentration of 7,350-9,850 mg/L. This high salt content is due to elevated levels of sodium and chloride coming from groundwater flow from the base units of the Navajo sandstone, and contributes about 106,000 tons of salt to the Colorado per year (Gerner, Thiros, and Susan 2014). In Paradox Basin, pressure induced dome formation on Mesozoic halite and gypsum deposits several hundred feet thick caused the formation of a salt anticline (Tuttle et al. 2014a). Separated by thin units of black shale, dolomite and anhydrite, these salt beds contain valuable potash and hydrocarbon deposits, but also are the cause of the naturally-occurring brine that can contribute over 100,000 tons of salt per year to the Dolores River, a tributary of the Colorado (Shope and Gerner 2014). Due to the large quantity of salts still present in the sedimentary bedrock, mitigation of these natural salinity sources is difficult, expensive, and of limited effect.

Fig 2. *Water issuing from Blue Springs, Colorado. Note the turquoise, opaque water, a function of large amounts of dissolved minerals.*

Anthropogenic Salinity Sources

Agricultural use

Most (60%) of the agricultural land in the Colorado Basin is used either for rangeland or alfalfa production(United States Bureau of Reclamation 2009). Due to inadequate levels of rainfall, agricultural water needs must be satisfied with irrigation. Plants absorb water from the soil via osmosis, and are therefore able to exclude salts from root uptake selectively (Minhas et al. 2020). Application of slightly saline irrigation water results in the deposition and concentration of salts in the root zone (Vengosh 2003). This salt concentration effect is exacerbated by the process of soil formation (Jenny 1980).

This permeation of the soil profile with salts is an unavoidable consequence of soil formation in dry areas, and that salt will remain immobile unless it is dissolved and transported by water movement (Smedema and Shiati 2002). It is unfortunate then, that the main method of combatting salt accumulation in soil is leaching via extensive watering, which can reduce salinity in upper regions of the soil by moving most salts to groundwater or surface water (Phogat et al. 2020) which then adds water into the river(?). Irrigation canals can also intensify the problem by causing seepage and deep percolation. Additional pathways for salt liberation are all centered around contact between water and salts, including poor drainage, which causes evaporation and concentration, and rising water tables, which mobilize salts deeper in the soil profile (Minhas et al. 2020).

Municipal use

Municipal areas consume water, depleting flows and increasing salinity concentrations (United States Bureau of Reclamation 2017). Above, I outlined the many minerals present in the water in the basin, which make the water too mineral-heavy for human use. When this hard water is used for municipal purposes, it must be softened, which further increases sodium chloride release in wastewater (Seo et al. 2010). Increased demand for energy also drives exploitation of the Colorado Basin’s geological deposits, often requiring fracking or drilling, which can mobilize saline aquifers that were previously trapped between layers of shale. Oil wells can produce up to 25 million barrels of saline water per month, most of which is discharged back into the river. (Tuttle et al. 2014a, 2014b).

Salinity Mitigation

Natural Salinity Mitigation

Colorado River salt loads need to be decreased by an additional 340,000 tons/year, which requires the expansion of existing salinity control projects. The greatest progress will come from mitigating anthropogenic salt sources, as salinity inputs from natural sources such as saline springs and seeps are essentially inexhaustible, leading to a need for projects with a scope of decades to centuries.

Currently existing efforts to mitigate natural salt inputs into the river are poor long term solutions. One example is the Paradox Valley facility, where naturally occurring brine has been pumped up and injected 2.9 miles underground into the Mississippi Leadville Formation in order to reduce saline base- and groundwater flow to the Colorado (Giggy 2018). It has been estimated that this project accounts for around 7% of the total salinity mitigation occurring yearly in the Colorado River basin, preventing approximately 95,000 tons of salt from reaching the river per year. However, the injection of this brine into deep geologic formations has had the unexpected side effect of lubricating and adding pressure to fault lines, resulting in a series of small earthquakes between 2014-2018, and culminating in a 4.5 magnitude quake in late 2019. The danger of a potential major earthquake from the brine pumping has led to planned shutdown of the plant, with a number of potential but unclear alternative salinity control measures, including drilling a new well or using evaporation ponds to collect salt. These measures are costly and are expected to greatly impact future budgets of the Colorado Basin Salinity Control Program, potentially jeopardizing upcoming projects (United States Bureau of Reclamation 2019).

Anthropogenic Salinity Mitigation

Salinity control efforts aimed at anthropogenic sources have found more success. Salinity management in the Colorado Basin is split between three organizations: Natural Resouce Conservation Service (NRCS), Salinity Control Program for Reclamation, and the Bureau of Land Management (BLM). These three agencies collaborate on projects such as lining or replacement of irrigation canals to prevent seepage, installation of efficient irrigation methods like drip or sprinkler irrigation, and increasing double cropping and mulching to reduce crop water requirements (Cadaret et al. 2016).

Due to the large impact that erosion has on increasing salt loads, reducing erosion via grazing systems that incorporate increased cover, appropriate seasons of use, and riparian protection have become a preferred salinity control technique. (Daryanto et al. 2018). In areas where salinity limits the maximum potential plant cover, erosion control efforts may be more difficult. In these cases, often where watersheds are so degraded that normal land management techniques are ineffective, using mechanical soil treatments and structural features may be the best option. Mechanical soil treatments include contour furrowing, ripping and rangeland pitting, while structural features include rangeland dikes, retention and gully plugs, and retention reservoirs (Ricci et al. 2020).

Reservoirs may play a particularly important role in salinity mitigation. According to a 2020 study by Deemer et. al, water bodies such as Lake Powell can have large impacts on TDS transport and dynamics by modulating salinity transport, as well as concentrating TDS through evaporation. Collection of saline water in these lakes, combined with increases in pH due to heat, sulfate and iron reduction, have resulted in calcite precipitation and burial in the lake sediments (Fig. 3). Biotic uptake of salts can also occur, with diatoms and plankton using calcium carbonate as a basis for their skeletal structure. The reduction in TDS from calcite precipitation in Lake Powell alone is equal to 50% of all salinity control programs in the Colorado basin. This effect is in addition to Lake Powell’s tendency to retain higher salinity water during periods of low flow, and then to release that higher salinity water gradually over periods of higher flow (Deemer, Stets, and Yackulic 2020).

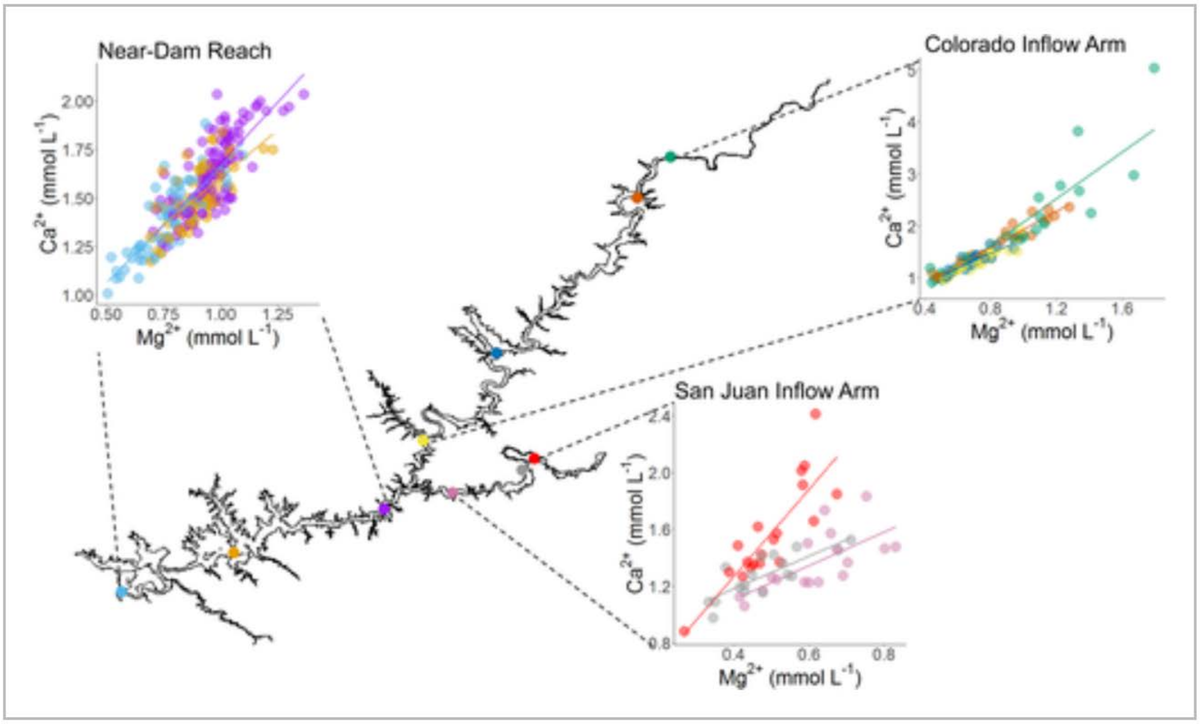


Fig 3. *Comparison of Ca/Mg concentrations in Lake Powell during the summer months (2013). Values in the upstream sites (San Juan Inflow, Colorado Inflow) that fall below the regression line are consistent with calcite precipitation. Taken from (Deemer, Stets, and Yackulic 2020)*

While primary methods of salinity control are focused on reducing salt inputs to the river, direct removal of salts is a last resort. The Yuma Desalting Plant (YDP) was built to recover bypassed irrigation drainage water so that it can be returned to the Colorado River and delivered to Mexico in partial satisfaction of the Mexican Water Treaty of 1944. To date this desalting plant has operated only three times, and the prohibitive cost of updates and repairs has rendered it potentially unviable for future efforts (U.S. Bureau of Reclamation 2008).

Summary/Conclusion

Salinity in the Colorado River Basin is a major concern that causes millions of dollars in economic damages through reduced crop yields and infrastructure damage. A large portion of the salinity entering the Colorado River is natural due to the saline nature of the marine sediments forming the bedrock for much of the basin. However, approximately 50% of this salinity is also due to anthropogenic impacts, including irrigation, erosion, and consumptive use. Application of water for soil salinity control issues can alleviate salinity issues in the short term, but often liberate salts deeper in the profile that flow back into the Colorado River. Management strategies include increasing irrigation efficiency, prevention of saline groundwater flows, and maximizing ground cover to reduce erosion. Natural processes such as the precipitation of calcite in Lake Powell also contribute to salinity reduction. Despite this, novel salinity control programs will need to be developed to meet the stated 2035 goals of removing an additional 340,000 tons of salt/year from the Colorado River system.

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