Saline soils and water quality in the Colorado River Basin: Natural and anthropogenic causes

Gabriel LaHue
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Abstract

Salinity is arguably the biggest water quality challenge facing the Colorado River, with estimated damages up to $750 million. The salinity of the river has doubled from pre-dam levels, mostly due to irrigation and reservoir evaporation. Natural salinity sources – saline springs, eroding salt-laden geologic formations, and runoff – still account for about half of the salt loading to the river. Consumptive water use for agricultural irrigation concentrates the naturally-occurring salts in the Colorado River water, these salts are leached from the root zone to maintain crop productivity, and the salts reenter the river as agricultural drainage water. Reservoir evaporation represents a much smaller cause of river salinity and most programs to reduce the salinity of the Colorado River have focused on agriculture; these include the lining of irrigation canals, irrigation efficiency improvements, and removing areas with poor drainage from production. Salt loading to the Colorado River has been reduced because of these efforts, but more work will be required to meet salinity reduction targets.

Introduction

The Colorado River is one of the most important rivers in the Western United States: it provides water for approximately 40 million people and irrigation water for 5.5 million acres of land, both inside and outside the Colorado River Basin (CRBSCF, 2014). Seven states – Arizona, California, Colorado, Nevada, New Mexico, Utah, and Wyoming – lay claim to the waters of the Colorado River. The contributions of the river to crop and livestock production (13-15% of the national total), electricity generation (4,200 Megawatts), and recreation are enormous, yet the river also faces many challenges, and it is considered one of the most stressed rivers in the world (CRBSCF, 2014; Tuttle and Grauch, 2009). According to the United States Geological Survey (2000), salinity is the biggest water quality issue threatening the basin. The annual average salt load of the Colorado River is nine million tons, enough to fill 1800 Olympic-size swimming pools, and the damages associated with this salinity in the United States are estimated to be $306 million – $750 million (Cohen and Henges-Jeck, 2001; U.S. Bureau of Reclamation, 2005; Tuttle and Grauch, 2009). For most rivers, water flows increase from the headwater of a river to its outlet, but the Colorado River flow decreases below Lake Mead and the Hoover Dam due to diversions, which has significant implications for the salinity of the river (CRBSCF, 2014). The salinity in the headwaters of the Colorado River is less than 50 mg L^{-1}, but it increases to over 900 mg L^{-1} (760 mg L^{-1} in flood years) at the U.S. border with Mexico (Cohen and Henges-Jeck, 2001; U.S. Geological Survey, 2000; Figure 1). An amendment added on to the original treaty with Mexico in 1974 requires the U.S. to deliver 1.5 million acre-feet (MAF) of water to Mexico that is no more than 115 (±30) mg L^{-1} more saline than the water above Imperial Dam, the last major diversion of water within the United States (Cohen and Henges-Jeck, 2001). Given the large economic impacts of salinity in the Colorado River Basin and the treaty obligations of the United States, it is essential to understand the sources of salinity and investigate potential strategies to reduce salt loading to the Colorado River.

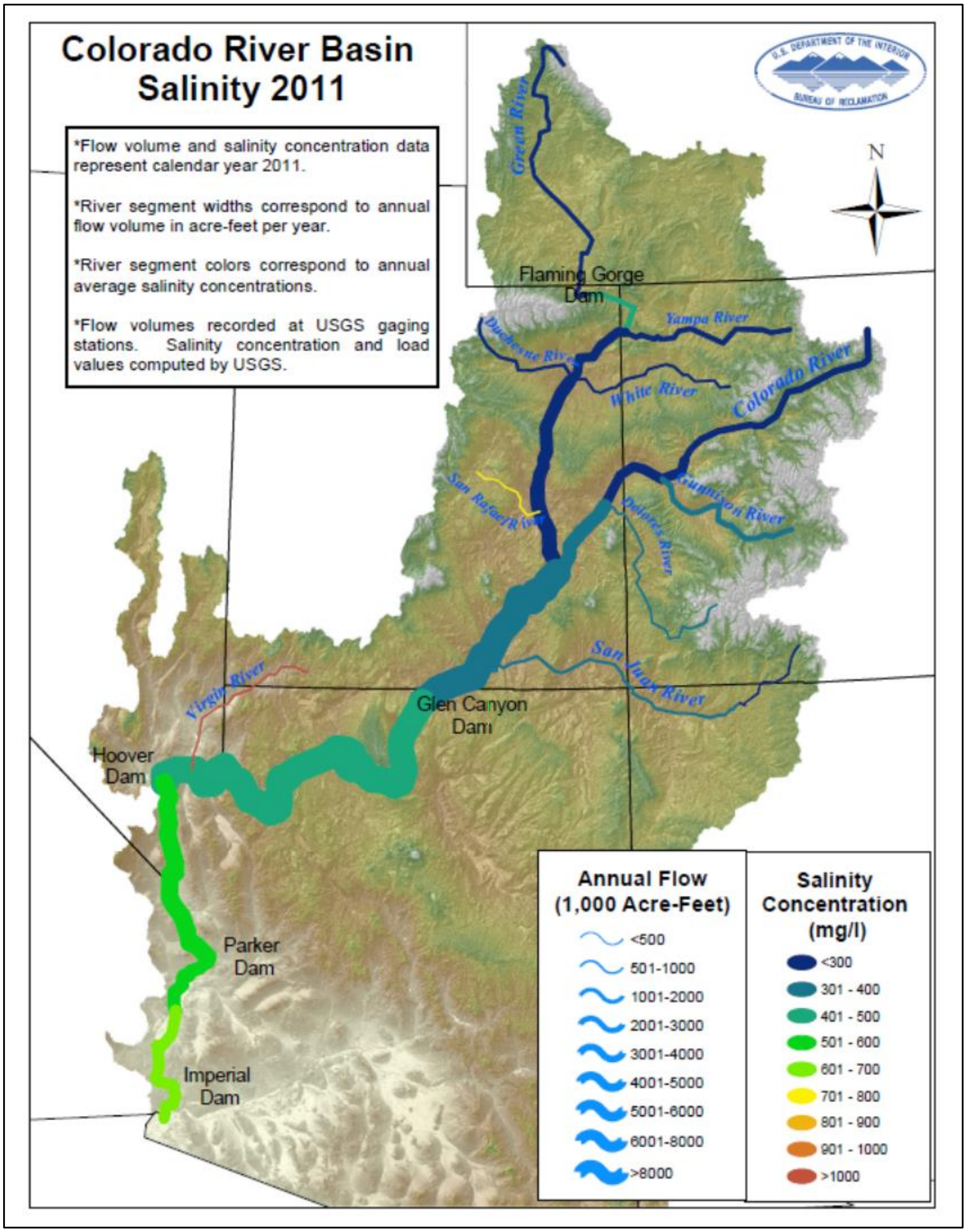

Figure 1: Salinity of the Colorado River (From CRBSCF, 2014)

Natural sources of salinity and the geology of the Colorado River Basin

Salinity is the concentration of dissolved salts in a water body. Many salts are soluble, and the most common ions contributing to groundwater and surface water salinity are calcium, magnesium, sodium, potassium, chloride, sulfate, and bicarbonate (Tuttle and Grauch, 2009). Major sources of salinity include atmospheric deposition or meteoric salts (not discussed here), salts derived from weathering or dissolution of geologic formations, salts derived from groundwater entrapped during formation of the basin, and anthropogenic sources, which will be discussed in detail later (Vengosh, 2014). For the Colorado River Basin, rock-water (or soil-water) interactions in geologic formations constitutes the most important natural source of salinity. Although the geology of the Colorado River Basin is varied, including igneous, metamorphic, and sedimentary rocks, sedimentary rock deposited in shallow marine environments is present throughout most of the basin; these can include bedded deposits of gypsum (calcium sulfate) and halite (sodium chloride), as well as sodium and magnesium-rich shales (U.S. Bureau of Reclamation, 2003). Other geologic sources of salinity can include carbonate rocks like dolomite and limestone, which release calcium, magnesium, and bicarbonate (Tuttle and Grauch, 2009). The Mancos Shale, for example, was deposited in the Cretaceous period (66–145 million years ago) and is distributed throughout much of the Upper Colorado River Basin in Colorado and Utah; groundwater movement through the intact formation (despite its low permeability) and water movement through soils derived from weathered Mancos Shale are major sources of salinity to the Upper Colorado River (Tuttle et al., 2014; Gardner and Young, 1988). Elsewhere in Colorado and Utah, there are significant beds of halite (sodium chloride) formed as evaporates during the Pennsylvanian sub-period of the Carboniferous period; these salt beds are generally impermeable, but dissolve into the groundwater along the upper surface (Shope and Gerner, 2014). Groundwater may eventually find its way to the Colorado River via saline springs, and soils formed from weathered salt-containing geologic formations may contribute to salinity through erosion (salts are carried on suspended soil particles) or runoff from the soils (U.S. Bureau of Reclamation, 2003). Saline springs are generally considered point sources whereas runoff and erosion are usually thought of as non-point sources of salinity; non-point sources are generally more difficult to quantify and trace. In contrast, point sources like saline springs may be well known – an example of this is the Glenwood-Dotsero Springs Unit, which is responsible for 440,000 tons of salt loading (U.S. Bureau of Reclamation, 2003).

Since the major natural sources of salinity in the Colorado River Basin are salt-containing geologic formations and saline soils derived from these parent materials, the amount of water that flows through the soil has a major effect on river salinity. Although higher flows generally lower salinity due to dilution (U.S. Bureau of Reclamation, 2013), research conducted on the Green River, McElmo Creek, the Price River, and the San Rafael River has shown that increases in river salinity and especially salt loading can be observed during significant thunderstorms and periods of snowmelt (Figure 2; U.S. Bureau of Reclamation, 2003). In addition to increasing water flow through salt-laden soils and geologic formations, these events also increase erosion; studies conducted on the Mancos Shale have shown that salt loading to the river and sediment loss from the landscape are positively correlated (Schumm and Gregory, 1986). While it is generally assumed that these are natural contributions to salinity, the fact that many "natural" landscapes are actually managed public lands makes it important to consider the potential for increased erosion from certain management practices. For this reason, the Bureau of Land Management of the U.S. Department of the Interior primarily tries to reduce salt loading to the

Colorado River by reducing erosion through changes in land use and management (CRBSCF, 2014).

Source	Type of Source	Salt Loading (tons per year)
Paradox Springs	Springs / point	205,000 [1]
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 [1]
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 [1]
McElmo Creek	Irrigation / non-point	119,000
Price-San Rafael	Irrigation / non-point	258,000 [1]
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 [1]
Other, non regulated areas	Various	5,200,000
Total		8,724,000

Figure 2: Natural sources of salt loading to the Colorado River (From U.S. Bureau of Reclamation, 2013).

Anthropogenic contributions to salinity

While it is undisputable that there is a high amount of natural salt loading to the Colorado River, human activities certainly play an important role as well. The natural salinity of the Colorado River at Imperial Dam is estimated to be 334 mg L^{-1} (prior to the construction of the dams and before significant irrigation withdrawals and agricultural return flows), but the water salinity above Imperial Dam is now approximately double that at 680 mg L^{-1} (U.S. Bureau of Reclamation, 2013). Natural salinity sources have been estimated at 47% of the total salt loading to the Colorado River, with irrigation accounting for 37% (predominately agricultural), reservoir evaporation making up 12%, and municipal and industrial sources comprising a mere 4% of the salt loading (U.S. Bureau of Reclamation, 2013).

Agriculture

Colorado River water is essential to agriculture both inside the Colorado River Basin and outside the basin due to water exports. More than 90% of cropland and pasture in the basin receives supplemental irrigation to make it viable for production, and about 60% of all this irrigated land is for either forage production (alfalfa alone covers 25% of the irrigated land) or grazing land (Cohen et al., 2013; Figure 3).

Acres (1000s)											
Crop	AZ	CA	CO	NV	NM	UT	WY	US Total	Mexico	CRB Total	% total
Total Forage	307	289	332	17	37	124	208	1,315	79[a]	1,394[a]	41%
Alfalfa hay	257	181	157	-	29	104	55	783	79	863	26%
Other tame hay	28	97	119	-	0.2	10	21	285	-	275	8%
Pasture	53	2	263	8	15	153	131	628	23	651	19%
Wheat	86	43	41	-	-	0.1	-	169	250	420	12%
Vegetables[b]	138	96	4	-	11	0.1	-	250	30	280	8%
Cotton	171	22	-	-	-	-	-	193	60	253	8%
subtotal	754	452	641	25	64	277	339	2,555	443	3,077	89%
Total Irrigated	876	504	697	25	99	322	342	2,868	499	3,367	

Figure 3: Irrigated acreage by crop for the Colorado River Basin (From Cohen et al., 2013)

On a per-acre basis, the Lower Colorado River Basin uses four times as much water as the Upper Colorado River Basin due to the cooler climate, smaller capacity for water storage, and shorter growing season in the latter (Cohen et al., 2013). Although agriculture is far and away the largest user of Colorado River water (accounting for 70% of water withdrawals), the majority (53%) of the salinity damages also fall on agriculture (Cohen et al., 2013; U.S. Bureau of Reclamation, 2013). Salinity can cause declines in crop yield once a certain threshold is reached (the maximum soil salinity that causes no yield decline in a specific crop), as it becomes more difficult and eventually impossible for plants to extract water in the soil (Grattan, 2002).

Salinity problems in agriculture occur due to naturally saline soils, evaporative concentration of salts in irrigation water, or capillary rise of a shallow groundwater table and subsequent evaporative concentration (Provin and Pitt, 2017). The build-up of salts in the root zone can be prevented by artificial drainage (especially in clay-rich soils), reducing evaporation through mulches or reducing excess water application (more on this later), and leaching salts from the root zone by irrigating slightly in excess of crop requirements (Provin and Pitt, 2017). The first and last of these solutions have been widely employed: tile drains or perforated pipes are installed in fields below the root zone to move water from shallow groundwater tables or irrigation to drainage ditches. However, salts from the groundwater, salts picked up as irrigation water moves through the saline soils, and salts concentrated from the irrigation water by preferential crop uptake and evaporation can all move through the tile drains and into the drainage ditches. The water in these drainage ditches was historically allowed to re-enter the river as "return flow", providing a major source of salinity.

Other anthropogenic sources

Municipal water use impacts salt loading by concentration of salts through consumptive use of water, much in the same way that agriculture concentrates salts. Discharge of treated wastewater can often represent an important source of salinity, though this is not a major source for the Colorado River (U.S. Bureau of Reclamation, 2013). Development of energy resources in the Colorado River Basin represents another potential source of salt loading to the basin. The Mancos Shale discussed earlier was recently estimated by the U.S. Geological Survey to contain

66 trillion cubic feet of natural gas, 45 million barrels of liquid natural gas, and 74 million barrels of shale oil (U.S. Geological Survey, 2016). One potential concern with increased drilling for shale oil and gas is the mobilization of saline groundwater that was previously contained by shale aquicludes; this groundwater has been static and has very high sulfate and sodium chloride levels from interaction with the marine-deposited shale aquicludes (U.S. Bureau of Reclamation, 2013). Drilling may provide a new flow path that allows this groundwater to reach the surface (U.S. Bureau of Reclamation, 2013). Oil and gas drilling may also impact salinity by increasing the vulnerability of land to surface runoff and erosion, by the generation of large quantities of saline wastewater, and by consumptive use of low salinity water; oil and gas production in Colorado produces 25 million barrels of saline water per month, which must be concentrated in evaporation ponds, injected into deep low-quality aquifers, or disposed of to surface water (U.S. Bureau of Reclamation, 2013).

Moving forward – Efforts to decrease salinity

The salt loading of the Colorado River has already been reduced by 1.2 million tons per year, but more improvements are needed to meet a goal of reducing salinity by 1.9 million tons per year before 2030 (U.S. Bureau of Reclamation, 2011). Changes that have reduced salt loading to date include taking areas with poor drainage and stored salts out of production, more efficient irrigation systems, and the lining of water delivery canals (U.S. Bureau of Reclamation, 2013). Farmland with adequate natural drainage allow salts to be leached further into the soil profile rather than collected and returned to the river as agricultural drainage water; however, these salts may eventually end up increasing the groundwater salinity and that of connected surface waters. Improvements in irrigation efficiency and the efficiency of water delivery systems can theoretically reduce water withdrawals from the river and limit the amount of water that percolates through salt-laden soils and returns to the river. For example, the Coachella Canal was lined with concrete, which reduced seepage losses from the canal from 141,000 acre-feet per year to 9,000 acre-feet per year (U.S. Bureau of Reclamation, 2013). One major consequence of such canal lining projects is a reduction in groundwater recharge. The lining of the All-American Canal was completed in 2010, but because of the hydrologic connection between seepage losses from the canal and aquifers in the Mexicali Valley, groundwater inflows to the valley are expected to decrease by up to 80%, creating a major problem for agriculture in the area and an international conflict (Cortez Lara, 2014). Nonetheless, the U.S. Bureau of Reclamation has a competitive grant process to help irrigation districts and water agencies improve the efficiency of water conveyance systems (CRBSCF, 2014). Another way in which the U.S. has sought to reduce salt loading and meet its treaty obligations with Mexico is by constructing networks of wells to pump groundwater to add to surface water deliveries; according to the U.S. Bureau of Reclamation (2003), increased pumping in Mexico caused increase groundwater flow from the U.S. to Mexico, and well fields were constructed as a result to capture this groundwater in the U.S. and make sure that it was included as part of the U.S. contractual obligations.

Irrigation efficiency improvements, like lining canals, can reduce the amount of water moving through soils derived from marine-deposited sedimentary rock (especially in the Upper Basin) and thus the salt loading of agricultural drainage water that returns to the Colorado River. The U.S. Department of Agriculture supports irrigation efficiency improvements through programs like the Environmental Quality Incentives Program (EQIP) of the Natural Resources Conservation Service (NRCS); $19.8 million was allocated to the program in 2004 to control salinity in the Colorado River Basin (Harrison and Rainford, 2004). The EQIP program for the

Colorado River was funded by the 1996 Farm Bill and more recently re-authorized by the 2014 Farm Bill (CRBSCF, 2014). Irrigation efficiency can be improved by replacing flood or furrow irrigation, in which free water moves down the field due to a gentle slope, with targeted water-delivery systems such as central pivot sprinklers, micro-sprinklers, or drip irrigation (Figure 4). In Colorado for example, improved irrigation systems have been adopted on over 120,00 acres, though the majority have been improved surface irrigation systems with smaller amounts of sprinkler and drip irrigation installation (NRCS, 2013).

TYPE OF IRRIGATION SYSTEM	% OF MONITORED EFFICIENCY
Open ditch	35%
Open ditch w/ siphon tubes	40%
Concrete ditch w/siphon tubes	50%
Gated pipe	50%
Underground pipe & Gated pipe	50%
Underground pipe/Gated pipe/Surge	55%
Center Pivot Sprinkler	90%
Big Gun Sprinkler	70%
Side roll Sprinkler	75%
Micro spray	90%
Drip Irrigation	95%

Figure 4: Efficiency of different irrigation system types (From NRCS, 2013)

Although improvements in irrigation efficiency have reduced agricultural drainage water and thus salt loading, some excess water will always be required to leach salts applied in irrigation water from the root zone. The capture and treatment of saline drainage water can be another important tool in efforts to reduce salt loading to the Colorado River. The Yuma Desalting Plant, for example, was designed to treat irrigation drainage water from the Wellton-Mohawk Irrigation and Drainage District using reverse osmosis; the treated water is then mixed with untreated water (to increase return flows while maintaining acceptable water quality) and returned to the Colorado River (U.S. Bureau of Reclamation, 2003). Unfortunately, the high operational cost of the plant makes it less competitive with other options to reduce salt loading, and the plant has not been operated since 1993, apart from a pilot run to test the ability of the plant to mitigate the effects of severe drought (U.S. Bureau of Reclamation, 2011).

Summary and conclusions

Salinity is a major problem for the Colorado River and the associated economic damages are significant. Approximately half of the salt loading to the Colorado River is natural due to the high salt content of the geologic formations composed of sedimentary rock deposited in marine environments. However, the salinity of the Colorado River is approximately double the natural salinity, largely due to effects of irrigated agriculture. Consumptive use of water on irrigated landscapes concentrates salts in the remaining water, which is often discharged to the Colorado River or connected surface water. Furthermore, increased water flow through soils derived from salt-containing geologic formations mobilizes more salts than would otherwise be removed from the soil in this arid region. The salt loading of the Colorado River has decreased in recent years due to efforts to reduce water demand and diversions from the Colorado River, reductions in saline irrigation drainage water from increased irrigation efficiency, and treatment of irrigation drainage water in some cases. However, more improvements need to be made to reach salinity reduction targets and increasing demand for Colorado River water is likely to exacerbate challenges of reducing the salinity of the Colorado River.

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