Salinity in the Colorado River Basin

Scott L. Morford

Abstract: Salinity in the Colorado River has increased two-fold due to anthropogenic activity in the Basin. The increased salt load constitutes a threat to wildlife (e.g. selenium) and imposes substantial economic cost to public and private sectors. Concurrent with anthropogenic salt load, future precipitation regimes may contribute to increases in river salinity that will exceed established regulatory thresholds. Here I discuss the problems, sources, and mitigation/management of salinity from a basin-wide perspective, and investigate the future flow/salinity scenarios. Currently, more than $30 million a year is spent on salinity mitigation in the basin, with an estimated $350 million in damages. Under future drought conditions, salinity mitigation expenditures may exceed $80 million, with damages approaching $1 billion annually. Even under drought conditions, salinity is not expected to pose a danger to wildlife in the river main-stem, but may threaten habitat in tributaries with significant point-source salinity inputs.

Introduction and scope:

The water quality challenges the Colorado River and its tributaries face are diverse and location-dependent. The Basin covers roughly 640,000 km$^2$ between seven western states and northern Mexico. Industrial, mining, agricultural, and municipal activities all contribute to local-to-regional impairment of water quality (Spahr et al. 2000, Bureau of Reclamation 2013) for human use and ecological services. This paper will investigate salinity as an integrator of water quality throughout the basin, and will discuss how mitigation of salinity influences river and basin management.

Salinity, also called total dissolved solids (TDS), is defined as the mass of dried ionic constituents that pass a 2µm filter, and is quantified in-river as either a concentration (mass · volume$^{-1}$) or as a load (mass · time$^{-1}$). Pursuant to the Federal Water Pollution Control Act Amendments of 1972 (Public Law 92-500), salinity numerical standards/thresholds were established throughout the basin and are monitored at large reservoirs. Because no large sink for salinity exists within the basin (with the exception of the Salton Sea), the numerical threshold standards increase downstream (Fig. 1) and range from 723 mg · L$^{-1}$ at Hoover Dam to 879 mg · L$^{-1}$ at the Imperial Dam near the Mexico boarder. The Salinity Control Act of 1974 (Public Law 93-320) also places numerical limitations on the salinity of water delivered to Mexico – ensuring that agriculturally derived hypersaline water does not spike salinity in the Colorado River below Imperial Dam.

While numerous other laws and amendments have been enacted to manage Colorado River Basin water quality, most of these regulations relate to management of the river to meet the numerical water quality standards imposed by the 1972 and 1974 legislations. Salinity control in the Colorado River Basin is performed by the Natural Resource Conservation Service (NRCS - USDA), Bureau of Reclamation (Dept. of Interior), and the Bureau of Land Management (BLM - Dept. of Interior), and state programs. These programs are overseen by state-federal Colorado River Basin salinity control forum in conjunction with the EPA.
Figure 1: Salinity in the Colorado River increases downstream due primarily to agricultural water use. Source: US Bureau of Reclamation – 2009.
**The problem of salinity:**

Economic models prepared by the Bureau of Reclamation in 2004 suggest that salinity contributes to more than $300 million dollars per year in economic damage across the Colorado basin, with roughly half occurring in agricultural sectors (Borda, 2004). Agriculture throughout the region is dependent on irrigation water, and many high-value crop species are sensitive to salinity concentrations and loading of particular elements such as sodium and boron (CRBSCF 2011). Salinity also contributes to corrosion of pipes in agricultural and municipal settings, contributing to an estimated $80M year loss for households utilizing high-salinity water.

Salinity also has a profound effect on municipal water quality. The EPA has set a (non-enforceable) salinity threshold of 500 mg • L$^{-1}$ for drinking water, which is exceeded by many municipalities in the lower Colorado River Basin. High salinity makes water less palatable to users, and is correlated with other constituents that can interfere with water treatment, particularly in reservoirs where most municipalities draw their water. For example, at Lake Mead (Las Vegas’s water supply) concentrations of bromine and total organic carbon (TOC) are positively correlated with salinity, and both contribute to potentially hazardous disinfection by-products compounds during water treatment (bromate and trihalomethanes, respectively). While these hazards can be mitigated in the treatment process, they contribute additional costs to municipalities that may intensify under conditions of higher salinity and lower flow/reservoir storage (Roefer et al 2005).

Salinity effects on stream biota are poorly resolved (Bishop & Porcella, 1980), particularly at concentrations representative of current and future conditions in the lower Colorado Basin. In the few studies conducted, it appears that that Colorado River fish (Colorado Squawfish, Humpback Chub, and Bonytail) select for water salinity values less than 4000 mg L (Pimentel & Bulkley 1983), with acute toxicity occurring only in concentrations greater than 10,000 mg • L$^{-1}$ (Nelson and Flickinger, 1992) – an order of magnitude higher than salinity levels currently found in the river. Furthermore, salinity within the main stem of the Colorado River historically fluctuated dramatically by season before the introduction of large dams that regulated and integrated the flows. So while salinity may be rise and fall in response to climate and anthropogenic forcings at timescales of years to decades under a regulated flow regime, any change is likely to be contained within the seasonal peak-to-peak amplitude of salinity concentration in a pre-dam flow regime (Fig. 2). No information has been found on how the attenuation of salinity peaks has influence river biota.

So while direct salinity effects seem to have negligible effects on fish species, some of the dissolved metal constituents can be toxic to fish, birds, and mammals. For example, selenium inhibits reproduction and recruitment of fish, and is commonly found at concentrations greater than 5 µg • L$^{-1}$ (EPA guideline for aquatic life) – in some cases exceeding the guidelines by more than two orders magnitude (Spahr et al 2000) in some parts of the upper Colorado River. EPA standards for domestic and agricultural water use is 50 µg • L$^{-1}$. Monitoring by the National Contaminant Biomonitoring Program has found high concentrations of selenium in fish tissue at 13 of 16 sites sampled within the Colorado River Basin (Schmitt and Bunck, 1995). Moreover, because some fish use high-salinity agricultural drains as habitat (Frankenberger and Engberg 1998), exposure to selenium can be high, even when main stem selenium concentrations are within regulatory thresholds.
Salinity loads and sources in the Colorado River Basin.

The Colorado River transports between 7 and 9 million tons of salt annually to the Gulf of California depending on climatic control and salt mitigation practices within the basin. In 2011 the average annual salinity at Imperial Dam (just north of the Mexico border) was a flow weighted 680 mg $\cdot$ L$^{-1}$, more than double the natural salinity concentration (334 mg $\cdot$ L$^{-1}$) estimated by the EPA. Irrigation, reservoirs, and mining and industry are the primary anthropogenic sources of salinity, contributing 37%, 12%, and 4% of the total salinity load to the Colorado river, respectively (Bureau of Reclamation, 2013).

Natural sources of salinity include saline springs and weathering of rock within the basin. Roughly 17% of the total salinity load can be attributed to point-source saline springs (36% of the natural load). While the Colorado River basin hosts a wide variety of geologies, marine sedimentary rocks and their alluvium are the dominant surface lithology throughout the region. These rocks not only host relatively high amounts of native salinity given their origin, but are often poorly consolidated, which contributes to increased rates of erosion, surface area, and reactivity. For example, more than half of the salinity generated in the upper Colorado River basin is attributable to landscapes dominated by Mancos Shale, a marine mudrock from the Upper Cretaceous (100 – 66 MYA). These formations are also the primary source of selenium throughout the basin (Spahr et al. 2000).

Irrigation consumes nearly 13 million acre-feet of Colorado River water annually, using roughly 70% of the total flow (Cohen et al, 2003), and contributes to salinity via two primary
mechanisms. First, evapotranspiration effectively concentrates salts in drainage water that is returned to the river. Salts applied in irrigation water cannot be left to accumulate within the soil if the land is to remain arable. To prevent accumulation, water in excess of evapotranspiration demand must be applied so that drainage water can carry the applied salinity to drains, thus preventing salinity & sodicity from building within the rooting zone.

Second, the excess drainage water interacts with already saline soil and regolith in the vadose zone, dissolving and transporting additional salts to the Colorado River. Irrigated agriculture occupies 13,000 km² within the basin (Cohen et al 2013), and the salts that would naturally accumulate and remain within these soils and regolith in the absence of irrigated agriculture are being added to the river. As a result, a relatively small area contributes the majority of anthropogenic salinity load in the Colorado River – with many of the largest contributors occurring in the upper basin where saline lithology is dominant. For example, the Grand Valley Irrigation District (Grand Junction, Colorado) comprises ~ 2% of the irrigated area, but contributes ~ 13% of the anthropogenic salinity load within the whole basin. Most of soils in the irrigation district are developing on Mancos shale, suggesting that naturally saline soils and regolith can contribute to amplifying anthropogenic salt loads in the Colorado (Bureau of Reclamation 2013).

Water use by municipal, household, and industrial users in the basin also contribute to increases in Colorado River salinity, though at a much smaller scale than agricultural use. Similar to agriculture, consumptive use is the primary mechanism contributing the salinity, but households can also be a source of salt through use of water softening salts or municipal application of road salts (Bureau of Reclamation, 2013). Expansion of energy development throughout the region is also speculated as a potential source of salinity to the Colorado River, but it is not yet clear how these practices will impact interaction between ground- and surface-waters, and whether saline and polluted water utilized in drilling can be effectively mitigated by deep injection or impoundment (EPA 2012). Given the contentious nature of energy development, peer-reviewed data and analysis is needed to assess its impact on Colorado River salinity, but it likely will be small relative to other natural and agricultural sources from a basin-wide perspective.

**Mitigation and Management of Salinity**

BLM, NRCS, and the Bureau of Reclamation spend $32M annually to prevent 1.3 million tons of salts from entering the Colorado River (Bureau of Reclamation, 2013). The primary strategies include implementation of best management practices in irrigation districts, erosion control on public lands, and reduction in point source inputs from natural geologic sources. Salinity control is also achieved on river by regulating salinity discharge at large dams. From a regulatory perspective, salinity control is divided into Title I (below Imperial Dam) and Title II (above Imperial Dam) programs, with the former responsible for maintaining treaty obligations with Mexico (Public Law 93-320).

The NRCS administers salinity control programs in 12 irrigation districts across the upper Colorado River Basin, improving salinity control on an estimated 250,000 hectares. Their program reduces salinity inputs to the Colorado river by 600,000 tons annually at an average annual cost of $13 million (amortized cost; $47 ton⁻¹, Bureau of Reclamation, 2013). On-farm,
irrigation efficiency is improved by installing pressurized irrigation pipelines in combination with sprinklers to replace flood irrigation practices. Off-farm mitigation includes upgrading earthen irrigation canals through lining, or replacing canals with pipeline to minimize seepage. Together, these controls reduce water usage and reduce deep percolation by more than 90% in agricultural areas, reducing the total salt load be delivered/returned to the river.

In addition to operating the large dams on the Colorado River, the Bureau of Reclamation also manages water delivery to irrigation districts and performs point-source remediation of salinity. By partnering with the NRCS and state agencies, the Bureau funds the improvement or replacement of inefficient irrigation canals. Additionally, the Bureau operates pumping facilities in the Paradox Valley of west-central Colorado, limiting interaction between a collapsed salt-dome and the Delores River, a tributary of the Colorado. The salinity at the site has been measured at more than 250,000 mg · L⁻¹, an order of magnitude more saline than the global ocean, and contributes an estimated 205,000 tons year⁻¹ of salinity to the Colorado River. By lowering the groundwater level adjacent to the Dolores River, the Bureau can effectively cut salinity inputs in half at the site. The excess brine is then pumped into underlying geologic layers, more than 4300 m below the earth surface. However, the long-term viability of the project has been called into question due to the increasing pressure required to inject the brine. Without mitigation at the Paradox Valley unit, salinity is expected to increase by 10 mg · L⁻¹ throughout the entire Colorado River system (Bureau of Reclamation, 2013).

The BLM is the largest landholder within the Colorado River Basin, managing roughly a third of the land area within the Colorado River Basin. Although the agency claims salt retention of 126,000 tons year⁻¹, 90% is attributed to nonpoint source control without rigorous accounting. It appears that primary mechanism by which the BLM contributes to salinity control is through erosion control in previously adopted best management practices, but it’s not clear what efforts the agency has directly implemented to improve salinity control.

Large dam operations on the Colorado river regulate salinity via two methods. First, water impounded behind dams mixes and attenuates the peak-to-peak amplitude (Fig. 2) of salinity concentrations that result from yearly high and low flow periods. Prior to river regulation, salinity below Glen Canyon Dam often exceeded 1100 mg · L⁻¹ during the late summer, but following impoundment salinity values are closer to 600 mg · L⁻¹ year round. More directly, dam operators can control salinity by pumping from different depths. Like in the ocean, large reservoirs can host vertical haloclines, with higher salinity found in bottom waters. Deeper water intakes can mix the deeper high salinity water with shallow low salinity waters to achieve desired salinity concentrations (Bureau of Reclamation, 2005).

The management and mitigation strategies discussed above fall under Title II of the Salinity Control Act, and are implemented based upon economics, with costs generally between $40 – $60 per ton of salt removed (Bureau of Reclamation, 2013, PL 93–320). In contrast, the programs implemented under Title I are designed to ensure treaty obligations to Mexico and include a number of large, expensive projects – including desalinization, Protective and Regulatory Pumping, and lining of large irrigation canals to Coachilla. Additionally, Title I projects also fund agricultural improvements in the Wellton-Mohawk Irrigation District similar to other Title II programs.
The Yuma desalting plant was constructed to reduce the salinity of Colorado River water being delivered to Mexico if other management strategies fell short. The plant currently stands in ready reserve if other salinity mitigation fail to meet treaty obligations. At full capacity the plant can produce 80,000 acre-feet yr\(^{-1}\) of water within salinity thresholds, at a cost of $300 - $500 per acre-foot (up to $40 million yr\(^{-1}\) at full capacity), substantially more costly than mitigation efforts under Title II programs (Bureau of Reclamation, 2007). Protective and Regulatory Pumping is designed to recover groundwater that would otherwise transit the international border underground near the Yuma Mesa in Arizona. The pumping field covers roughly 170 km\(^2\), and is comprised of 22 wells and laterals with a total pumping capacity of 125,000 acre-feet per year. The pumped water is delivered to Mexico as a component of the 1.5 million acre-feet water guaranteed under treaty. There is no direct data on the salinity content of this water, but it likely well below treaty thresholds (Bureau of Reclamation, 2005).

**Salinity under future climate uncertainty**

Predicting future salinity scenarios in the Colorado River system is difficult due to the complexity of estimating inputs and uncertainty over future precipitation trends. The Bureau of Reclamation uses the Colorado River Simulation System (Mueller and Osen, 1988) to estimate future salinity trends, but the model has historically overestimated agricultural salt inputs. Recent improvements in the model, including a broader set of climate scenarios suggests that probability of exceeding regulatory salinity limits are between 14%– 25% through 2025, depending on the continuation of salinity mitigation programs by the Bureau of Reclamation and the NRCS (Prairie et al, 2005). The Bureau of Reclamation has set a goal for increasing annual salinity control by 40% (~ 500,000 tons yr\(^{-1}\)) before 2030, but it is unclear if these goals can be met with irrigation improvements alone.

Even under prolonged drought, it appears that salinity of Colorado main stem will not reach thresholds that would endanger biological communities. Small tributaries may see increases in salinity that threaten wildlife, particularly where point-source contribution are independent of flow (e.g. Paradox Springs). The primary damage of prolonged drought, lower flow, and higher salinity within the Colorado River mains steam will be economic, with economic costs topping $1 billion annually (Borda, 2004). Damages to agricultural and household users will rise substantially, as some land will need to be fallowed and water treatment costs will rise. In particular, climate driven changes in river salinity may force utilization of the Yuma desalting plant, which could double costs for managing salinity in the basin.

![Figure 3: Salinity projections (Y-axis) for 2005 – 2025 (X-axis), including 10\(^{th}\), 50\(^{th}\), and 90\(^{th}\) percentiles. (USBR 2013).](image-url)
References.


Cohen, M., Christian-Smith, J., Berggren, J. 2013. Water to supply the land: Irrigated agriculture in the Colorado River Basin. Pacific Institute, Oakland CA.


