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Born from a Flood: The Salton Sea and Its Story of Survival

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ABSTRACT: The Salton Sea is a terminal lake located in the deepest point of the topographically closed Salton Trough in southeastern California. It is currently the largest lake in area in the state. It was created by a flooding event along the Colorado River in 1905–1907, similar to the way historical floods over past centuries created ephemeral incarnations of ancient Lake Cahuilla in the same location. Its position at the center of today's Imperial Valley, a hot and arid locale home to some of the most productive irrigated agricultural lands in the United States, has ensured its ongoing survival through a delicate balance between agricultural runoff, its principal form of input, and vast evaporation losses. Nevertheless, its parallel role as a recreational resource and important wildlife habitat, established over its first century of existence, is threatened by increasing salinity decreasing water quality, and reduced water allocations from the Colorado River that feeds the valley's agriculture. The Salton Sea faces an increasingly uncertain future that will be influenced by reduced water imports from the Colorado River, demands for additional water sources to support farming and energy industries in the valley, and needs to stabilize the lake salinity, maintain recreational resources, and preserve what have become important ecosystems and wildlife habitats.
KEY WORDS: Salton Sea, flood, terminal lake, water, agriculture, salinity, wildlife habitat.

0 INTRODUCTION: PHYSICAL AND GEOLOGIC SETTING

The Salton Sea is the largest lake in area in the state of California. It is a terminal lake located in Riverside and Imperial counties in the southeastern part of the state (Fig. 1). It occupies the lowest portion of the Salton Trough, a deep sediment-filled structural and topographic basin that extends linearly from the Gulf of California to the northwest through the Mexicali Valley in Mexico, and in the United States, the Imperial Valley south of the Salton Sea and the Coachella Valley north of the Salton Sea (Fig. 1). The lake itself is 36 miles long, 15 miles wide, 51 ft. deep, 376 sq. miles in area, and contains approximately 7.35 million acre feet (af) of water. Its surface water elevation is approximately 227 ft. below sea level, and much of the land surrounding the sea is also below sea level (Fig. 1).

The closed basin surrounding the Salton Sea is bounded by the Santa Rosa Mountain range to the northwest, the Orocopia Mountain range to the northeast, the Chocolate Mountain range to the east, and the peninsular mountain ranges of southern and Baja California to the southwest, and the Colorado River Delta to the south. It experiences an arid, low-rainfall desert climate, with summer temperatures often exceeding 100 °F. Precipitation in the central parts of the basin is very low, typically averaging 2.5 in. per year, although higher amounts occur in the surrounding mountains to the west and northwest.

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The Salton Trough overlies a deeper underground basin extending to depths of 20 000 ft. or more in some locations (Fig. 2). The upper portion of the basin is composed of interbedded alluvial and lakebed deposits, at most a few thousand feet thick. More consolidated deposits and a fractured rock "basement complex" (including volcanic rock and portions of the Brawley, Borrego, Palm Spring, and Imperial formations) underlie these materials and extend to deeper bedrock. Groundwater is present throughout the basin. Although estimates of 1.1 to 3 billion af have been made for the total volume of groundwater in storage in the basin (Imperial County, 1997), much of it is not considered recoverable because of high salinity, high temperature, or general economic inaccessibility because of depth. Historically, the shallower basin fill deposits, especially near the basin perimeter where hydraulic conditions are unconfined, have been considered the best water-bearing materials in the basin. Confined and lower permeability conditions exist in the shallow materials in the central basin owing to the greater abundance of lakebed clays, making groundwater less available.

Historically, the Salton Trough has been a zone of heavy tectonic activity and frequent earthquakes and was created by the relative motion of the North American and Pacific plates over the last 4–5 million years (see e.g., Loeltz et al., 1975; Babcock, 1974; Dutcher et al., 1972). It represents a region of transition from the divergent plate boundary of the East Pacific Rise to the transform boundary of the San Andreas fault system. At the present time, the plate motion in the Salton Trough is primarily horizontal (strike-slip) along major faults such as the San Jacinto and Imperial faults. Locally, geothermal hot spots are created by magmatic intrusions in the pull-apart regions (Newmark et al., 1988). The Salton Sea, Cerro Prieto and

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Figure 1. Map of the greater Salton Sea area in southern California and Baja California Norte showing the regional watershed basin (darker shaded area) and the sea level elevation contour within the basin (dashed line circling the sea). The Colorado, Alamo, and New rivers are shown along with the All American and Coachella water import canals.

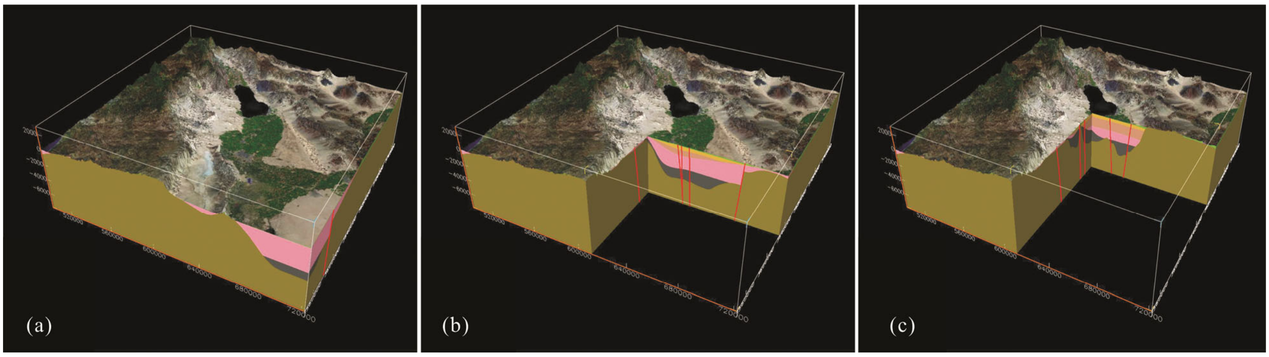

Figure 2. Three-dimensional geologic models of the Salton Sea Basin, looking north, showing, from bottom to top, the underlying basement materials, the overlying Imperial, Palm Spring, Borrego, and Brawley formations that comprise a "basement complex", and the post-Brawley (delta sediment and alluvial) deposits that extend to the present day surface. The cut out (west to east) cross-section shown in the second figure corresponds, approximately, to the US-Mexico border. The vertical red lines correspond (west to east) to the Elsinore, San Yacinto, Imperial, and San Andreas fault systems.

Brawley geothermal fields are located at these hot spots, where water temperatures at depths of 8 000 ft. may typically exceed 680 °F (360 °C). While several geothermally active faults penetrate to the surface, most of the tectonically induced faults are located at depth, well below the shallow strata in which most low temperature groundwater is found. Nevertheless, numerous hot wells, hot springs and "mud pots" can be found in the vicinity of surface fault expressions surrounding the inactive Rock Hill, Mullet Island, Obsidian Butte, and Red Island volcanoes near the southern boundary of the sea (e.g., Redlands Institute, 2002, p. 68 therein).

1 BIRTH OF TODAY'S SALTON SEA

The Salton Sea that we know today is intimately tied to agriculture. It was created between 1905 and 1907 by a Colorado River flood that breached the improperly designed headworks of an early irrigation canal built to support a nascent agricultural industry in the Imperial and, later, Coachella valleys (Tobin, 2001, Chapter 2 therein). Floodwaters flowed through an uncontrolled canal opening to the north, significantly eroding and broadening it, and filled the topographically low center of the basin. It took multiple attempts and well over a year to redirect the river flow back to its traditional discharge into the Gulf of California, albeit only insecurely. Future flood related ruptures would only be averted, reliably, through the construction of dams and reservoirs upstream along the Colorado River later in the 20th century.

Despite its arid climate, the Salton Sea Basin is now home to some of the most productive agricultural lands in the United States. These include approximately 100 000 acres of irrigated cropland in the Coachella Valley north of the sea and 525 000 acres in the Imperial Valley, south of the sea. In addition, there are also extensively irrigated lands in the Mexicali Valley to the far south of the sea (Fig. 3). The Colorado River provides most of the water used for agricultural purposes in the basin. As of 2003, over 3.2 million af of water are imported from the Colorado River on an average annual basis through the All American Canal and distributed to croplands through the Coachella Canal, East Highline Canal, and a number of other feeder channels (Figs. 1, 3; Redlands Institute, 2002). Over 90% of the total is used in the Imperial Valley, with the remaining amount routed to the Coachella Valley through the Coachella Canal. Colorado River water is also used to support agriculture south of the US and Mexico border in the Mexicali Valley (Fig. 3).

As a terminal lake, the continued existence of the Salton Sea over the past century has been due to the agriculture infrastructure set up over the same period and the lake's use as an irrigation discharge reservoir. In this sense, the lake receives irrigation runoff and related forms of agricultural wastewaters as its only inputs, which are then offset by evaporative losses from the lake's surface. To some, this constitutes the lake as an artificial water body, different from a dammed reservoir, and unsustainable in the long term under natural, non-agricultural conditions. Over its first few years, the lake elevation fluctuated as it adjusted to evolving balances between its initial flooded volume (at a lake level of -195 ft.), growing agricultural inputs, and evaporation outputs. Currently, water inflows occur primarily from the Alamo, New, and Whitewater rivers, irrigation drains, surface runoff from rainfall, and some groundwater inflows (Figs. 1, 4; Table 1), approximately 10% to 15% of which originate in Mexico (SSA, 1997). Water losses from the lake proper occurring from evaporation amount to approximately 1.35 million af per year and roughly equivalent to annual water inputs between 1950 and 2000 (Fig. 4).

At the time of its formation, the Salton Sea was a freshwater lake, but soon acquired a salinity level equal to that of seawater (33 parts per thousand; ppt) through dissolution of

Table 1 Water inflows to the Salton Sea for 1999 (after Weghorst, 2001)

Source	Subtotal (af/y[1])	Total (af)
Alamo River (total)		643 426
Alamo River (Mexico)	1 668	
Alamo River (IID[2])	641 758	
New River (total)		465 779
New River (Mexico)	176 447	
New River (IID)	289 332	
IID (total)		94 414
CVWD[3] (surface)		81 765
CVWD (aquifer)		-366
Other unmeasured (precipitation, surface, aquifer)		68 400
Total		1 353 418

[1]. One acre-foot (af)=1 233.5 m^3 or 1 km^3=810 701 af; [2]. IID=Imperial Irrigation District; [3]. CVWD=Coachella Valley Water District.

Figure 3. Orbital photo of the Salton Trough (June 6, 2013) showing the Salton Sea, irrigated agricultural regions in the Coachella (north of sea), Imperial and Mexicali valleys (south of sea). Dotted loop indicates approximate groundwater mound underneath All American Canal. Inset shows algal bloom observed on October 10, 2003. Photos are courtesy of the NASA Earth Observatory (http://earthobservatory.nasa.gov).

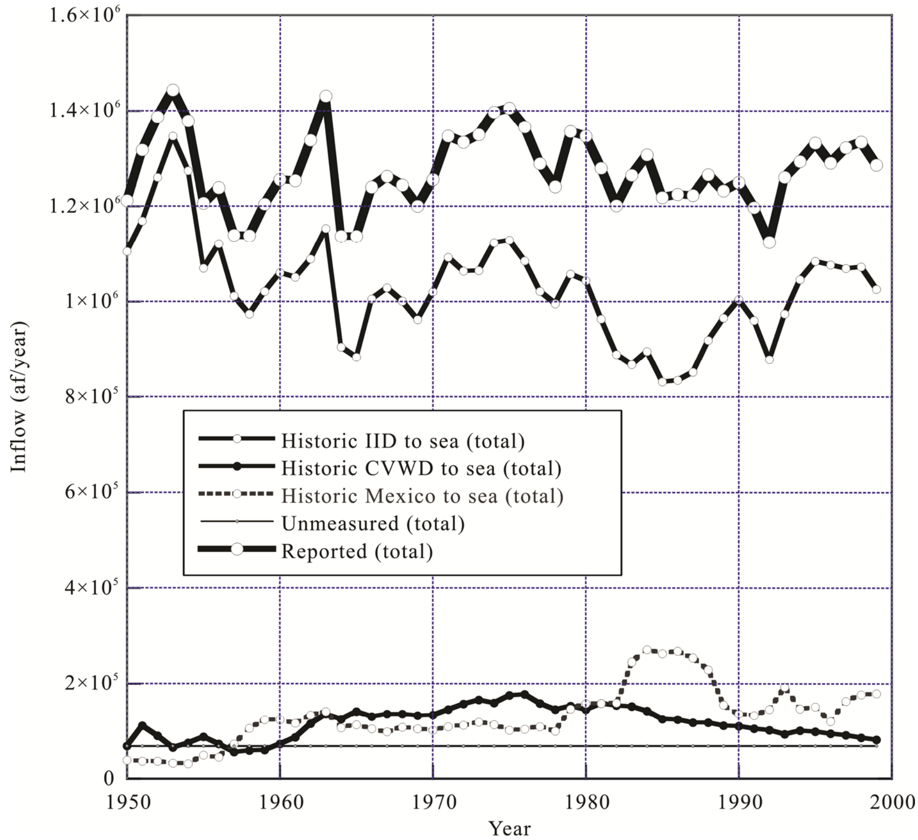

Figure 4. Past water inflows to the Salton Sea, after Weghorst (2001), in af/y; historic IID includes measured flows from the Alamo River, New River, including both US and Mexican contributions, and direct irrigation drainage from Imperial Irrigation District agriculture; historic Mexico includes the subset of Alamo and New River flows originating in Mexico; historic CVWD includes direct irrigation drainage and aquifer underflows derived from the Coachella Valley Water District agriculture; unmeasured represents a calibrated residual (other surface, aquifer or precipitation inputs) developed from the accounting model of Weghorst (2001).

natural (marine) salts covering the basin floor prior to the flood. The salinity has since increased to over 44 ppt from dissolved salts contained in agricultural runoff (Hart et al., 1998), and it continues to increase unabated today. These salts are leached from natural minerals in the irrigated soil columns (such as selenium) or derived externally from fertilizers applied to the fields. Additional wastewaters and other contaminants (such as pesticides) are also common in the lake inputs (Fig. 5), further complicating the deteriorating water quality conditions in the lake and contaminant accumulation along the lakebed (e.g., Schroeder et al., 2002; Setmire, 1979).

In the years after its formation, the Salton Sea has also generated interest in aquatic and lakeside recreational opportunities in the southern California desert, commercial development ensued. The lake was naturally populated by fish derived from the original Colorado floods as well as other artificially introduced species. It has become one of the most important wetland habitats along the Pacific Flyway, providing a stopping point now for hundreds of migratory bird species that previously stopped at Tulare Lake in California's San Joaquin Valley (Barnum and Johnson, 2004; DWR, 2004). Tulare Lake was once the largest body of freshwater in west of the Mississippi River but is now dried as a result of agricultural water diversions.

2 BEFORE THE SALTON SEA: PACIFIC OCEAN AND LAKE CAHUILLA

Although some may consider the Salton Sea as an accident attributable to the flooding in 1905–1907, it is worth noting that the basin has previously been the home to numerous bodies of water and other floods of one sort or another.

Millions of years ago, the Pacific Ocean and the Gulf of California extended much further inland, north through the Salton Trough and close to the present day Indio (Fig. 6a). It occupied much of the area within the sea level contour shown in Fig. 1. The Colorado River emptied into the gulf at a point close to present day Yuma, Arizona. Notably, any groundwater occupying the deeper formations underlying the extended gulf at this time was essentially seawater (Downs and Woodward, 1961).

The Colorado River carried large volumes of silts and sediments accrued from its journey through what is now the American West. As depicted in Fig. 6b, these sediments were deposited to form a large delta as the river discharged into the gulf. Over thousands of years, the size of the delta and its amassed sediments grew so large that the northern part of the gulf became physically separated from the present day gulf to the south, and the meandering Colorado River veered towards its present day discharge point in Mexico (Figs. 6c, 6d). Once this occurred, the residual of the gulf on the north side of the delta began to evaporate, for lack of any substantive inflows,

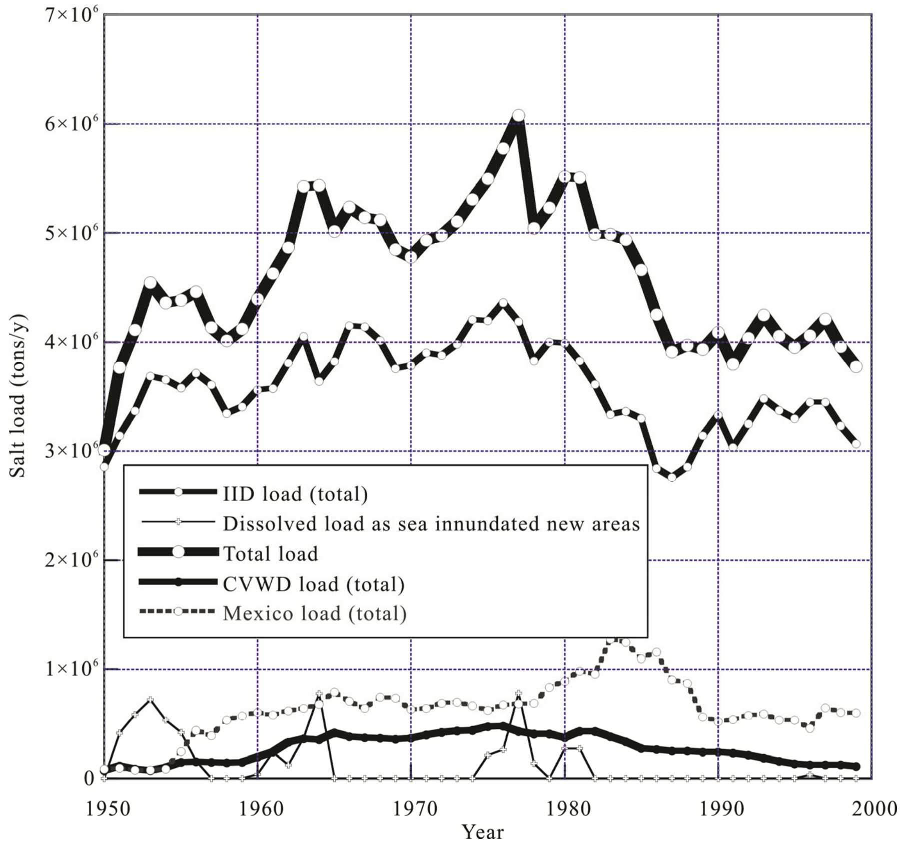

Figure 5. Past salt inputs to the Salton Sea, after Weghorst (2001), in tons/y; historic IID includes measured inputs from the Imperial Irrigation District agriculture, including both US and Mexican contributions; historic Mexico includes the subset of IID inputs originating in Mexico; historic CVWD includes measured inputs from the Coachella Valley Water District agriculture; Inundated component represents an estimate of inputs derived from newly covered lands during periods of sea growth.

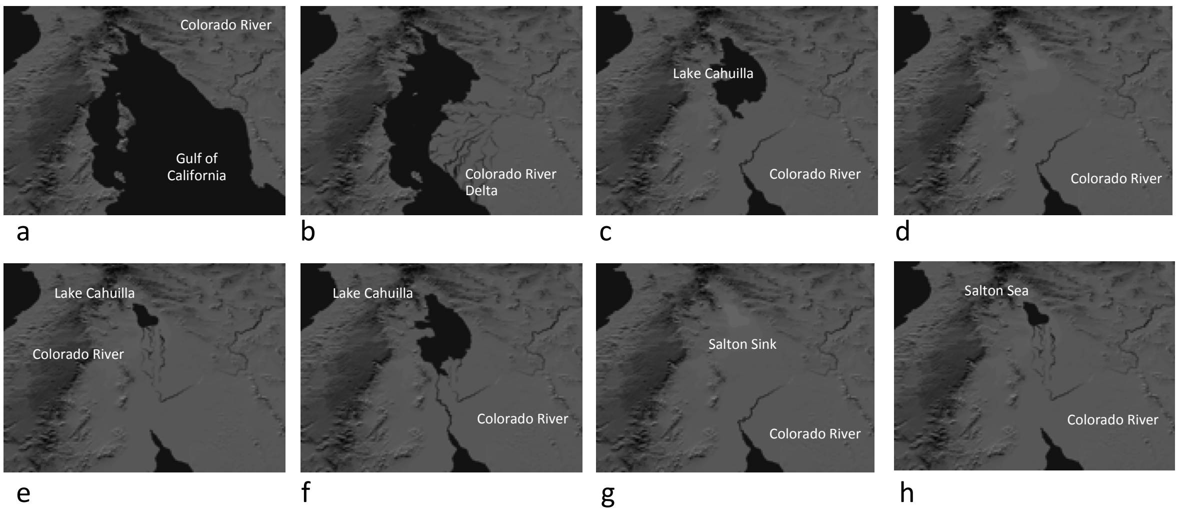

Figure 6. Processes leading to the formation of Lake Cahuilla and the Salton Sea. (a) The Gulf of California 12 million years ago; (b) sediments from the Colorado River and Delta fill in the gulf; (c) Salton Basin is cut off from the gulf; (d) a period when the basin was dry; (e) historically, the Colorado River would periodically shift course; (f) ancient Lake Cahuilla; (g) the Salton Trough ad Salton Sink, circa 1900; and (h) formation of contemporary Salton Sea in 1905.

and became increasingly more saline. These waters were able to percolate into the subsurface or evaporate further to form marine halite deposits at the center of the current day lakebed.

Over time, the meandering Colorado would occasionally flood to the north of the delta (Figs. 6e, 6f), fill the emptied basin, and create a new, essentially fresh water lake, much in the same way today's lake was formed (Figs. 6g, 6h). The new lake would re-dissolve marine salt deposits left from the previous evaporative periods. Then, in the same way, the flooding would cease and the river would meander back to a southern discharge point in the gulf, isolating the lake and allowing the evaporation processes to begin anew. Occasionally, the lake would drain to the gulf directly while also being filled by the Colorado.

These flooding episodes repeated irregularly over a long period of time, often generating lakes much larger than present day Salton Sea. The most recent incarnations of this lake occurred between 1600 and 1700 AD (Redlands Institute, 2002; Waters, 1983), when it has been called Lake Cahuilla. The rim of Lake Cahuilla (at +12 ft. above sea level, just above the seal level contour in Fig. 1) is visible in geologic outcrops and surface topography (Buckles et al., 2002; Waters, 1983), shellfish records, and Native American cultural artifacts (Wilke, 1978). Halite deposits left over after the most recent evaporation of Lake Cahuilla were sites of salt mines in the 19th and early 20th centuries, and, of course, contributed to the initial salinity of the Salton Sea.

3 THE SALTON SEA IN THE 20TH CENTURY: ECOLOGY

Since the 1920s, the primary economic benefits of the Salton Sea—namely (1) a repository for agricultural and related wastewater discharges, and (2) a fishery, wildlife, recreational resource—have progressively evolved to be at odds with one another. Because of its use as an agricultural sump, the lake has increasingly suffered from toxic algal blooms (Fig. 3), periodic fish die-offs, and avian deaths in a complicated chain reaction involving high salinity and wastewater content, hot temperatures, and wind-driven lake water circulation. These effects conspire to spread and consume salts and wastewater nutrients over the water column, generate organic wastes and anoxic waters along the lakebed, and turn over contaminated and anoxic waters from the lakebed for further exposure to fish and other wildlife. This scenario is analogous to other ecological disasters associated with agricultural drainage (e.g., at the Kesterson Reservoir in northern California; Wu et al., 1995), and left unabated, will only lead to a collective worsening of the ecosystem as a whole (Friend, 2002).

This declining ecosystem is in obvious conflict with the fishery, wildlife, recreational benefits of the lake, and has led to a significant and, at times, adversarial and politically delicate efforts to develop a restoration program for the lake (e.g., USBR, 2007a, b; SSSS, 2000; http://saltonsea.ca.gov). The primary goals of revitalization include efforts to stabilize lake water salinity and elevations, restore ecosystem and wildlife habitats, protect human health, and maintain the agricultural and recreational economies built around the lake.

One of the more recent concepts involves splitting the lake across its midpoint with a dam or a dike as a means to create a saline marsh on the south and fresher-water lake on the north (USBR, 2007a, b). These objectives would presumably allow for the continuity of agricultural drainage in the southern portion while promoting more sustainable recreational and wildlife habitat uses in the northern portion. The plan has not been implemented and has been criticized for its costs, especially as they relate to the seismic stability of the proposed mid-lake dam, as well as for incomplete plans for dealing with accumulating solids in the southern basin.

4 THE SALTON SEA IN THE 21ST CENTURY: WATER, ENERGY, AND ECOLOGY

Most of the water entering the Salton Sea (Table 1) is indirectly derived from the Colorado River, from which, on average, over 5 million af of water per year have been imported into California prior to 2003. These imports have largely been used to satisfy the dominant demands of agriculture in the Salton Sea Basin (~3.5 million af) and urban uses in San Diego. They have grown to exceed historical federal water allocations for California from the Colorado River.

As a result, a federally mandated re-apportionment of Colorado River water in California has been developed and implemented under the so-called Quantification Settlement Agreement (QSA; SDCWA, 2014; IID et al., 2003). This agreement stipulates an aggregate import reduction to 4.4 million af per year for California and provides for increased transfers from agriculture (Salton Sea Basin) to urban (San Diego) uses under the new allocation. The call for the QSA is fundamentally rooted in a need for better national management of Colorado River water in light of growing water demands and drought across the American southwest and because of poor allocation decisions made for the entire river in the early 20th century. However, its need has been highly shaped by the swelling demands for water in just southern California alone.

Interestingly, the role of water in maintaining the ecological and economic vitality of the Salton Sea was not seen as a direct "beneficial use" within the calculus of the QSA re-apportionment. As a result, collateral impacts to the lake, and to the Salton Sea Basin in general, from the required import reductions and transfers were not carefully considered (LLNL, 2002; Weghorst, 2001). These impacts include, potentially: (1) newly fallowed agriculture, leading to reduced water inputs to the lake; (2) altered water and salt balances in the lake, leading to lower lake levels, openly exposed shorelines, and higher rates of lake water salinization and water quality degradation; (3) accelerated detrimental impacts on fisheries, wildlife, and recreation; and (4) wind driven re-suspension of dried lake sediments (including accumulated solid wastes) that may appear on newly exposed shorelines.

These have collectively promoted a renewed focus for additional sources of water in the basin, such as groundwater, both to offset imported water reductions (e.g., IID, 2012; Tompson et al., 2008) as well as satisfy new and expanding demands for water in the basin tied to lake restoration or renewable energy development. New energy developments in the basin include, for example, expanded geothermal exploration (e.g., Bjornstad et al., 2011, 2006; Tiedeman et al., 2011) and solar energy production (e.g., Greer et al., 2013).

The concept of using groundwater in the Salton Sea Basin as an additional source for agricultural or domestic needs, energy production, or Salton Sea restoration efforts goes back, in part, to several studies that have indicated a potential for substantial, usable amounts of groundwater in some portions of the Imperial Valley (e.g., Loeltz and Leake, 1979; Loeltz et al., 1975; Dutcher et al., 1972). Fundamentally, groundwater availability in the basin will be tied to the (a) volume and capacity of the basin; (b) overall producibility of groundwater; (c) quality of groundwater; and (d) renewability and recharge opportunities for groundwater.

As a whole, groundwater storage in the basin is larger than the 1.1 to 3 billion af cited earlier (Imperial County, 1997), potentially as high as 4.5 to 6.5 billion af in newly updated estimates (Tompson et al., 2008). However, much of this is confined to greater depths where quality is poor (high salinity), producibility is low (poor permeability and accessibility) and natural recharge, required for sustained use as a supply, is not well demonstrated from available data (e.g., Tompson et al., 2008; Imperial County, 1997).

Historically producible groundwater in the basin has been confined to a "shallow" system, extending to no more than 2 000 ft. deep in most areas, and which is typically considered to be isolated from a "deeper" system that can extend to as much as 20 000 ft. in depth. Producibility can vary from very poor (as in Colorado River delta deposits) to very good (basin perimeter and Coachella Valley). Groundwater quality can also vary widely, and often show high salinities derived from irrigation waters or mineralogic and ancient seawater sources. Groundwater renewability, as realized through groundwater recharge, is dominated by irrigation (of Colorado River water) in the agricultural areas, localized canal leakage along the All American and Coachella Canals, or from the Colorado River itself along the southern basin boundary in Mexico. Precipitation-based recharge is very low over much of the basin, but is most prominent along mountain front regions in the Coachella Valley.

Interest in new conjunctive-use groundwater development in the Imperial Valley, following existing projects in the Coachella Valley (Table 2), is growing (Greer et al., 2013; IID, 2012; Tompson et al., 2008; URS, 2000; Montgomery Watson, 2000; LeRoy Crandall and Associates, 1983, 1981; Mallory et al., 1980). This potential has long been acknowledged in the East Mesa area (Figs. 1, 3), for example, in which a large, artificial groundwater mound has accumulated from 60+ years of leakage under the unlined All American Canal (AAC).

Canal flow rate data tabulated by USBR (1994, 1993) indicate aggregate losses of 4.9 million af from the unlined All American Canal (AAC) between 1948 and 1988 (or approximately 123 000 af/y on average), as well as 4.8 million af from the unlined Coachella Canal (CC) between 1948 and 1979, when it was reconstructed as a lined canal (or 155 000 af/y on average). The apparent losses for the canals gradually declined between the early and later years, a process deemed typical for unlined impoundments where seepage is controlled by percolation into unsaturated sediments.

Reanalysis of the loss rates in the AAC and the remaining unlined portions of the CC in 1988 were developed by Reclamation (USBR, 1994, 1993) and showed adjusted losses of 94 206 af/y for the AAC and 26 000 af/y for the CC (Table 2). Another source of groundwater recharge occurs along the lower reaches of the New River, near Calexico. Montgomery Watson (1996) has estimated losses of 7 000 af/y from the river, although this water is very poor in quality.

Canal leakage has led to groundwater mounding underneath both the Coachella and All American Canals. The mound under the Coachella Canal led to groundwater discharges into the East Highline Canal (4 000 af/y, Tetra Tech Inc., 1999; USBR, 1989) that were later reduced as a result of the canal being lined in 1979.

Table 2 Selected recharge rates to groundwater in the Salton Sea Basin circa 1988 (approximate, after Tompson et al., 2008)

Source	Subtotal (af/y[1])	Total (af/y)
Coachella Valley irrigation[2]		314 000
Coachella Valley ASAR[2,3]		228 520
Whitewater River	165 554	
Dike 4	3 968	
Mission Creek	24 723	
Martinez Canyon	775	
Coachella Valley aquifer underflow[4]		366
Imperial Valley irrigation[5]		0 to 250 000
Imperial Valley river and canal leakage[6]		127 206
All American Canal leakage	94 206	
Coachella Canal	26 000	
New River	7 000	
Precipitation over all groundwater basins[7]		75 000
Overall total		995 092

[1]. One acre-foot (af)=1 233.5 m^3 or 1 km^3=810 701 af; [2]. CVWD (2006) data; [3]. ASAR=aquifer storage and recovery; [4]. Table 1, after Weghorst (2001); [5]. see discussions about evapotranspiration and the range of these values in and about Table 2.5 of Tompson et al. (2008); [6]. see related discussions in Tompson et al. (2008); [7]. Tompson et al. (2008; Table 2.3 and Appendix A therein); Precipitation refers to basin areas in US only (excluding Mexico).

The mound under the All American Canal in the East Mesa area extends across both sides of the US-Mexico border (Fig. 3) and appears to have reached a steady state in terms the associated increase in groundwater storage. Estimates of accrued increases groundwater in storage under the canal lay between 0.7 and 1.5 million af (Tetra Tech Inc., 1999; USBR, 1994, 1993).

Quantification of this difference and the mechanisms that contribute to it (e.g., steady losses to evapotranspiration, discharges into agricultural drains and canals, or into the lake directly) will be critical to the feasibility, efficacy and design criteria for any conjunctive-use project in this particular area (Tompson et al., 2008). Since the All American Canal has recently been reconstructed as a lined canal to eliminate future leakage, sustainable sources of new water (excess Colorado River flows, recycled water) will also need to be carefully considered in the evolving calculus of Colorado River allocations in southern California overall, changing appropriations of Colorado River water to agriculture in the Salton Sea Basin, consideration of lake level and water quality impacts, and availability of nominally new or potentially reclaimed groundwater resources (IID, 2012; Tompson et al., 2008).

5 SUMMARY: AN UNCERTAIN FUTURE

Despite its origins in an uncontrolled flood in 1905, the Salton Sea is now, effectively, an artificial terminal lake in decline owing to increasing salinity, potential reductions in agricultural water inputs, and collateral impacts to its fishery, wildlife, and recreational resources. Its continued life after the flood and its complex decline today are due to varied, intertwined, human-induced impacts of agriculture, water diversions, and public perceptions of its beneficial uses. Future flooding events are essentially impossible because of the controlled flows of Colorado River today. This may be contrasted with the multiple, occurrences and declines in its predecessor, Lake Cahuilla, whose comings and goings over past centuries and millennia were naturally induced by sporadic flooding events and subsequent desiccation processes.

Today's Salton Sea is a member of a growing club of terminal lakes across the globe whose disappearance or deterioration are closely related to water diversions and correlated water quality impacts. Locally in California, these include the aforementioned Tulare Lake and Kesterson Reservoir, as well as Mono Lake and Owens Lake (e.g., Negrini et al., 2006; DWR, 2004; Jellison et al., 1998; Wu et al., 1995), and, globally, many others, such as the Dead Sea, the Aral Sea (Zavialov, 2007), and Lake Urmia (Erdbrinkjan, 2014).

The Salton Sea faces an increasingly uncertain future. Its continued existence as a water body will be directly tied to the continued existence of agriculture in the basin. Yet its continued survival as an ecological and recreational resource will be directly tied to our ability to implement technically based solutions able to stabilize its salinity and restore ecosystem and wildlife habitats established over the past century.

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REFERENCES CITED

Babcock, E. A., 1974. Geology of the Northeast Margin of the Salton Trough, Salton Sea, California. *Geological Society of America Bulletin*, 85(3): 321. doi:10.1130/0016-7606(1974)85<321:gotnmo>2.0.co;2

Barnum, D. A., Johnson, S., 2004. The Salton Sea as Important Waterfowl Habitat in the Pacific Flyway. *Studies in Avian Biology*, 27: 100–105

Bjornstad, S., Hall, B., Unruh, J., et al., 2006. Geothermal Resource Exploration, NAF El Centro—Superstition Mountain Area, Imperial Valley, California. Geothermal Resources Council Transactions, Volume 30, Geothermal Resources Council Annual Meeting, September 10–13, San Diego CA

Bjornstad, S., Alm1, S., Huang, W.-C., et al., 2011. An Update on Geothermal Energy Resource Investigations, Chocolate Mountains Aerial Gunnery Range, Imperial Valley, California. Geothermal Resources Council Transactions, Volume 35, Geothermal Resources Council Annual Meeting, October 23–26, San Diego CA

Buckles, J. E., Kashiwase, K., Krantz, T., 2002. Reconstruction of Prehistoric Lake Cahuilla in the Salton Sea Basin Using GIS and GPS. *The Salton Sea*, 632: 55–57. doi:10.1007/978-94-017-3459-2_4

CVWD, 2006. 2005–2006 Annual Review and Water Quality Report. Coachella Valley Water District, Coachella, California

Downs, T., Woodward, G. D., 1961. Middle Pleistocene Extension of the Gulf of California into the Imperial Valley. *Geological Society of America*, *Abstracts with Programs*, 68(12): 21

Dutcher, L. C., Hardt, W. F., Moyle, W. R. Jr., 1972. Preliminary Appraisal of Ground Water Storage with Reference to Geothermal Resources in the Imperial Valley Area, California. Geological Survey Circular 649, Prepared in Cooperation with the U. S. Bureau of Reclamation, U. S. Geological Survey, Washington D.C.

DWR, 2004. The Importance of the Salton Sea and Other Terminal Lakes in Supporting Birds of the Pacific Flyway, California Department of Water Resources, Sacramento CA [2015-12-14]. http://www.water.ca.gov/saltonsea/historicalcalendar/docs/TerminalLakes.pdf

Erdbrinkjan, T., 2014. Its Great Lake Shriveled, Iran Confronts Crisis of Water Supply. The New York Times, 2014-1-30

Friend, M., 2002. Preface. *Hydrobiologica*, 473: vii–xii

Greer, C. B., Quinn, J. J., O'Connor, B. L., et al., 2013. A Groundwater Model to Assess Water Resource Impacts at the Imperial East Solar Zone, Environmental Science Division. Argonne National Laboratory, Argonne, IL (ANL/EVS/R-13/10)

Hart, C. M., Gonzales, M. R., Simpson, E. P., et al., 1998. Salinity and Fish Effects on Salton Sea Microecosystems, Zooplankton and Nekton. *Hydrobiologica*, 381: 129–152

Imperial County, 1997. Imperial County General Plan. July 23

IID, 2012. Appendix B, Desalination/Groundwater Development Feasibility Study, in Final Imperial Integrated Regional Water Management Plan (IRWMP), Imperial Irrigation District, Imperial, CA [2015-12-14]. http://imperialirwmp.org/2013%20Updates/finalirwmp.html

IID, MWD, CWD, 2003. Quantification Settlement Agreement by and Among Imperial Irrigation District (IID), a California Irrigation District; The Metropolitan Water District of Southern California (MWD), a Metropolitan Water District and Coachella Water District (CWD), a California County District, October 10, 2003

Jellison, R., Romero, J., Melack, J. M., 1998. The Onset of Meromixis during Restoration of Mono Lake, California: Unintended Consequences of Reducing Water Diversions. *Limnology and Oceanography*, 43(4): 706–711. doi:10.4319/lo.1998.43.4.0706

LLNL, 2002. Facilitate the California 4.4 Plan: New Water, Interim Mitigation, Salton Sea Reclamation, Energy and Environmental Directorate. Lawrence Livermore National Laboratory, University of California, Livermore, CA

LeRoy Crandall and Associates, 1981. Report of Phase II Investigation, Feasibility of Storing Colorado River Water in Desert Groundwater Basins. Prepared for Metropolitan Water District of Southern California, Los Angeles, CA

LeRoy Crandall and Associates, 1983. Phase I Hydrogeologic

Investigation, Feasibility of Recovering Ground Water in the East Mesa area, Imperial County, California

Loeltz, O. J., Irelan, B., Robison, J. H., et al., 1975. Geohydrologic Reconnaissance of the Imperial Valley. California, Geological Survey Professional Paper 486-K. U. S. Geological Survey, Washington D.C.

Loeltz, O. J., Leake, S. A., 1979. Relation Between Proposed Developments of Water Resources and Seepage from the All-American Canal, Eastern Imperial County, California. Open File Report 79-744, Prepared in Cooperation with the U. S. Bureau of Reclamation U. S. Geological Survey, Tucson, AZ

Mallory, M. J., Swain, L. A., Tyley, S. J., 1980. Potential for Using the Upper Coachella Valley Ground-Water Basin, California, for Storage of Artificially Recharged Water. U.S. Geological Survey, Open File Report 80-599. U.S. Geological Survey, Menlo Park, CA

Montgomery Watson, 1996. County of Imperial, Imperial County Groundwater Study. Prepared by Montgomery Watson Inc.

Montgomery Watson, 2000. Groundwater and Surface Water in Southern California: A Guide to Conjunctive Use. Association of Ground Water Agencies, Azusa, CA

Negrini, R. M., Wigand, P. E., Draucker, S., et al., 2006. The Rambla Highstand Shoreline and the Holocene Lake-Level History of Tulare Lake, California, USA. *Quaternary Science Reviews*, 25(13/14): 1599–1618. doi:10.1016/j.quascirev.2005.11.014

Newmark, R. L., Kasameyer, P. W., Younker, L. W., 1988. Preliminary Report on Shallow Research Drilling in the Salton Sea Region, Lawrence Livermore National Laboratory, Livermore, CA (UCID-21484)

Redlands Institute, 2002. Salton Sea Atlas. University of Redlands, ESRI Press, Redlands, CA

San Diego County Water Authority (SDCWA), 2014. Quantification Settlement Agreement. San Diego County Water Authority, San Diego, CA [2015-12-14]. http://www.sdcwa.org/quantification-settlement-agreement

Schroeder, R. A., Orem, W. H., Kharaka, Y. K., 2002. Chemical Evolution of the Salton Sea, California: Nutrient and Selenium Dynamics. *Hydrobiologica*, 473: 23–45

Setmire, J. G., 1979. Water-Quality Conditions in the New River, Imperial County, California. U.S. Geological Survey Water-Resources Investigations 79-86, 63. U.S. Geological Survey, Washington DC

Salton Sea Authority (SSA), 1997. The Salton Sea: A Brief Description of its Current Conditions, and Potential Remediation Projects [2015-12-14]. http://www.sci.sdsu.edu/salton/Salton%20Sea%20Description.html

Salton Sea Science Subcommittee (SSSS), 2000. Strategic Science Plan, Salton Sea Restoration Project. U.S. Geological Survey, Reston, VA. 107

Tetra Tech Inc., 1999. Final Report: A Study on Seepage and Subsurface Inflows to Salton Sea and Adjacent Wetlands. Tetra Tech, Inc., San Bernardino, CA

Tiedeman, A., Bjornstad, S., Alm, S., et al., 2011. Intermediate Depth Drilling and Geophysical Logging Results at Superstition Mountain, Naval Air Facility El Centro, California, Geothermal Resources Council Transactions, Volume 35, Geothermal Resources Council Annual Meeting, October 23–26, San Diego CA

Tobin, J., 2001. Great Projects: The Epic Story of the Building of America, from the Taming of the Mississippi to the Invention of the Internet. The Free Press, New York, NY. 336

Tompson, A. F. B., Demir, Z., Moran, J., et al., 2008. Groundwater Availability within the Salton Sea Basin: Final Report, Lawrence Livermore National Laboratory, Livermore, CA (LLNL-TR-400426)

URS, 2000. Feasibility Assessment Hayfield Lake/Chuckwalla Valley Groundwater Conjunctive-Use Project. URS Corporation, Prepared for Metropolitan Water District of Southern California, Volumes I–III. Los Angeles, CA

USBR, 1989. East Highline Canal Seepage and System Improvement Study, Special Technical Report, US Department of the Interior, Bureau of Reclamation and the Imperial Irrigation District, Imperial County, CA

USBR, 1993. Coachella Canal Lining Project, Final Environmental Impact Statement; Draft Environmental Impact Statement, Environmental Impact Report, Geohydrology Appendix, US Department of the Interior, Bureau of Reclamation and the Coachella Valley Water District, Riverside and Imperial Counties, CA

USBR, 1994. All-American Canal Lining Project, Final Environmental Impact Statement; Final Environmental Impact Report, Geohydrology Appendix. US Department of the Interior, Bureau of Reclamation and the Imperial Irrigation District, Imperial County, CA

USBR, 2007a. Restoration of the Salton Sea Summary Report. U.S. Department of the Interior, Bureau of Reclamation, Lower Colorado Region, September. U.S. Department of the Interior, Bureau of Reclamation, Lower Colorado Region, Boulder City, NV

USBR, 2007b. Restoration of the Salton Sea. U.S. Department of the Interior, Bureau of Reclamation, Lower Colorado Region. U.S. Department of the Interior, Bureau of Reclamation, Lower Colorado Region, Boulder City, NV

Waters, M. R., 1983. Late Holocene Lacustrine Chronology and Archaeology of Ancient Lake Cahuilla, California. *Quaternary Research*, 19(3): 373–387. doi:10.1016/0033-5894(83)90042-x

Weghorst, P., 2001. Salton Sea Accounting Model, U. S. Bureau of Reclamation, Lower Colorado Region. U.S. Department of the Interior, Bureau of Reclamation, Lower Colorado Region, Boulder City, NV

Wilke, J. P., 1978. Late Prehistoric Human Ecology at Lake Cahuilla, Coachella Valley, California. Contributions of the University of California Archaeological Research Facility, Berkeley, California. 38

Wu, L., Chen, J. G., Tanji, K. K., et al., 1995. Distribution and Biomagnification of Selenium in a Restored Upland Grassland Contaminated by Selenium from Agricultural Drain Water. *Environmental Toxicology and Chemistry*, 14(4): 733–742. doi:10.1002/etc.5620140422

Zavialov, P. O., 2007. Physical Oceanography of the Dying Aral Sea. Springer Praxis Publishing, Chichester, UK