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Water Quality

Changing Water Depth, Salinity and Oxygen Availability in the Salton Sea

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HIGHLIGHTS

- **Toxic trace metals and harmful pesticides have accumulated in bottom sediments beneath oxygen-poor waters of the Salton Sea. As the lake recedes, these metals and organic compounds will likely remobilize to surface waters and be released as volatile gases or transported into ambient air as dust from the dried playa.**
- **Detailed research and real-time monitoring of the biogeochemistry of the waters and sediments in the Salton Sea has been lacking in recent years due to difficulty in accessing the lake with receding shorelines.**
- **Restoration efforts, ecological assessments, and water policies must consider expected changes in levels of oxygen and hydrogen sulfide in the lake and their relationships to toxic metals in muds that will ultimately end up in dust.**

River waters from the vast surrounding agricultural regions of the Coachella and Imperial Valleys have been draining into the Salton Sea for more than a century. These waters are rich in chemical contaminants such as trace metals sourced from the Colorado River and contributions related to human activities, including fertilizers and pesticides. The Salton Sea, at a maximum depth of 40 feet, is currently losing water at a rate of 1 foot/year as monitored by the U.S. Geological Survey. This rapid rate of water loss is due largely to new irrigation practices and water policies that reduce the inflow against a backdrop of constant evaporation under the desert sun. Because there is no other surface outflow of water from the Sea, the increasingly saline and oxygen-depleted basin becomes a trap for the inflowing metals, fertilizers, and pesticides.

SUNSET across the shrinking Salton Sea, which now has more than twice the salinity of the Pacific Ocean. Caroline Hung

As the Sea continues to shrink over the coming years, increasingly large areas of dry lakebed, also known as playa, will be exposed to the winds, producing large volumes of dust rich in harmful metals and pesticides (Frie et al., 2017). This wind-blown dust will spread to nearby and possibly more distant communities and pose significant health threats. Current literature includes evidence for impacts already felt in surrounding communities (Buck, 2020; Cohen, 2014; Frie et al., 2019). For example, 20% of Imperial County's pediatric population has been diagnosed with pediatric asthma compared to 8% nationwide (Marshall, 2017; Chapter 6). Tracing the sources and sinks of contaminants as well as their links to fluxes of total dust is key to identifying the threat of exposed lakebeds to public health (Chapter 4). In addtion, deleterious impacts to local ecological habitats and food webs result from seasonal oxygen loss. This condition will likely be exacerbated with higher temperatures and increasing salinity in the face of warming climate and progressive evaporation (Chapter 5).

Here, we highlight potential consequences of changing volume of the Sea in terms of the cycling of elements in the lake; the ecological impacts; and related relationships to past, present, and future compositions of dust sources. We develop research questions with the understanding that the behaviors of toxic trace metals, including remobilization from sediments back into the water above, are influenced by the changing biogeochemistry of the water itself—that is, the evolving interplay of living organisms and the chemistry of the waters and the sediments of the lake bottom. These dynamic changes relate to decreasing water volume and are expressed in parameters such as dissolved oxygen, salinity, and accumulation and release of hydrogen sulfide, a toxic gas created in oxygen-poor environments. Due to these ongoing changes in water and sediment chemistry, it is highly likely that dust composition will continue to change as the lake shallows—in ways that could become increasingly harmful to surrounding communities. In other words, with declining lake volume we can expect more dust, and that dust will be more contaminated.

Any future possibility for the Salton Sea will be influenced by the distribution of toxic metals in oxygen-free (anoxic) bottom sediments and their relationships to changing lake conditions. There is a high risk that these toxic metals will be released from the sediments and enriched in lake waters with changing oxygen levels. Negative impacts for public health and livestock will also be associated with transport of selenium and molybdenum as dust from the dry lakebed. Lastly, critical remaining questions are defined that should determine future research and offer possible remediation strategies.

Dead Zones

A MAJOR CONSEQUENCE of the shrinking Salton Sea in the last few decades is oxygen loss. This loss is due mainly to eutrophication (pollution from excess fertilizer loading) resulting from human activities as well as to decreased oxygen solubility with increasing salinity. The process of eutrophication starts with the introduction of vast amounts of fertilizer in runoff (nitrogen and phosphorus) that become concentrated as the waters evaporate. Nutrient overload leads to excessive blooms of primary producers such as algae, which affect oxygen levels in the lake. These changes in surface lake chemistry can negatively impact the entire ecosystem (Chapter 5).

Specifically, excessive nutrient input in agricultural runoff linked to fertilizers can lead to extensive blooms of photosynthetic algae in surface waters such that dissolved oxygen levels can become highly elevated relative to the concentrations expected in equilibrium with overlying oxygen-rich air (Figure 3.1). However, oxygen concentrations decline quickly below the surface to levels much lower than those predicted from exchange with air. When these photosynthetic microorganisms die, they settle to the bottom of the lake, and associated decay of their organic remains leads to the formation of “Dead Zones” (the lower percentages of dissolved oxygen seen in Figure 3.1). Further, when surface waters become warmer in the summer months, mixing of oxygen-rich surface waters to the deeper, cooler, more dense waters are inhibited due to density layering, which leads to oxygen loss (anoxia in the extreme) in the deep waters. This condition is most persistent and widespread during the summer (Figure 3.1). On days in the late summer when intensified winds result in mixing anoxic waters into the surface, oxygen-deficiencies can spread, resulting in catastrophic ecological impacts. These effects are not unlike the infamous dead zone that plagues the Gulf of Mexico each summer and many coastal regions and lakes throughout the world. The historical record of these human impacts in the Salton Sea is reflected in the organic matter and metal contents of sediment, which show the upper 20 centimeters to be rich in organic remains of primary producers tracking more than a century of agriculture in the region (Schroeder et al., 2002; Vogl and Henry, 2002). Those sediments in the deepest parts of the lake are also rich in metals, because the cycling of these ele-

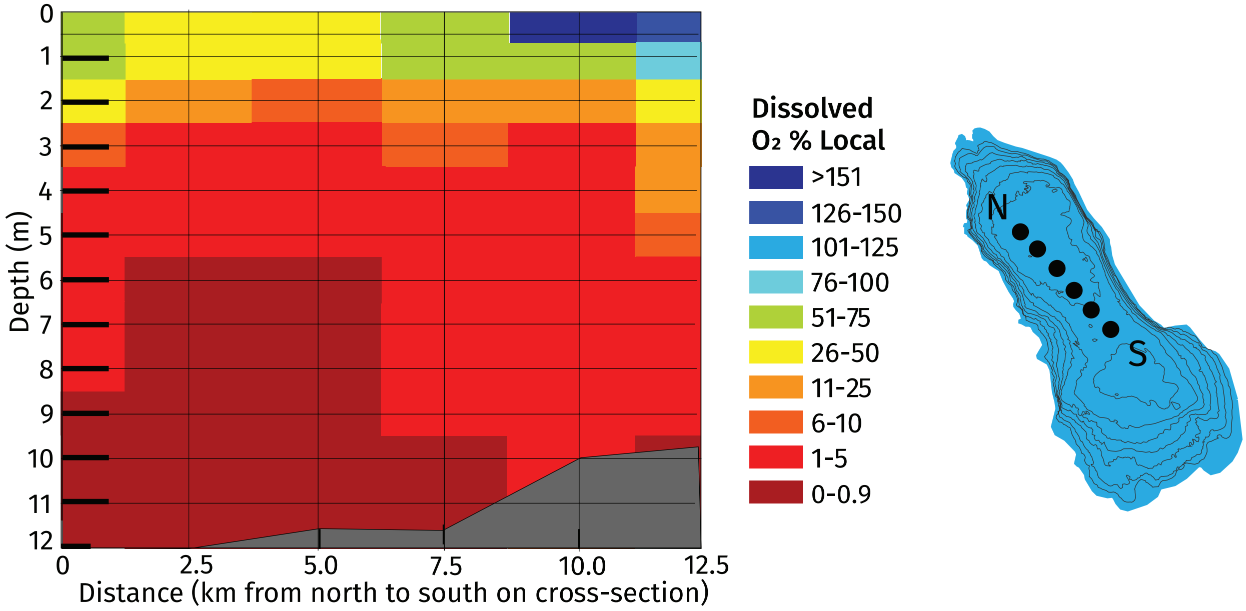


Figure 3.1 Dissolved oxygen sampled at horizontal transects in the northern portion of the lake during an upwelling event in August 2020. The general trend shows that oxygen (O_2) decreases with depth and anoxia—defined as less than 1% dissolved O_2—is persistent in the deepest waters. Credit: Caroline Hung.

ments is also tied intimately to the oxygen history of the overlying lake waters.

Persistent loss of dissolved oxygen in the deep lake waters also changes the chemistry of the Salton Sea in other ways. Because anoxic bottom waters are no longer favorable to oxygen-loving microorganisms, anaerobic bacteria that reduce sulfate (SO_4^{2-}) in the absence of oxygen take over and produce hydrogen sulfide as an end-product of their metabolism. The sequence of oxygen loss and subsequent production of hydrogen sulfide via bacterial degradation of organic material produced in the nutrient-rich waters can be generalized as follows:

$$\text{organic matter} + O_2 \rightarrow CO_2 + H_2O$$

In the subsequent absence of O_2, microbes use sulfate as one of several alternatives to oxygen in the following reaction:

$$\text{organic matter} + SO4_2- \rightarrow H_2S + 2HCO_3^-$$

Under the hot temperatures of the summer months, these microbial processes are accelerated, and hydrogen sulfide builds up in the bottom waters. On windy days, hydrogen sulfide is released to the surface waters and the air above the lake (Figure 3.2). There are important consequences for lake ecology and the quality of life and related health issues in surrounding communities when this happens. Critically, low oxygen waters rich in hydrogen sulfide are toxic to much of the life in the lake, including the fish as witnessed by massive fish-kill events—with many “downstream” consequences, such as food availability for waterfowl.

Further, release of foul-smelling hydrogen sulfide as monitored by the South Coast Air Quality Management District (SCAQMD) results in levels that exceed state safety standards (30 parts per billion/hour) (Figure 3.2; Reese et al. 2008; Reese et al. 2009), which can cause temporary headaches in addition to more severe health effects such as inflammation and irritation of the respiratory system. The effects of these release events during the summer are known to extend to great distances, including westward as far as coastal communities. Critical remaining questions in this regard include: Will anoxic, hydrogen sulfide events become more common in the coming years with rising salinity and temperatures? How will these events now and in the future disrupt lake ecology and human wellbeing? Might the long-range atmospheric transport of this hydrogen sulfide highlight the possibility of similar tranport of fine-grained toxic dust to distant populated areas (see Chapter 4)?

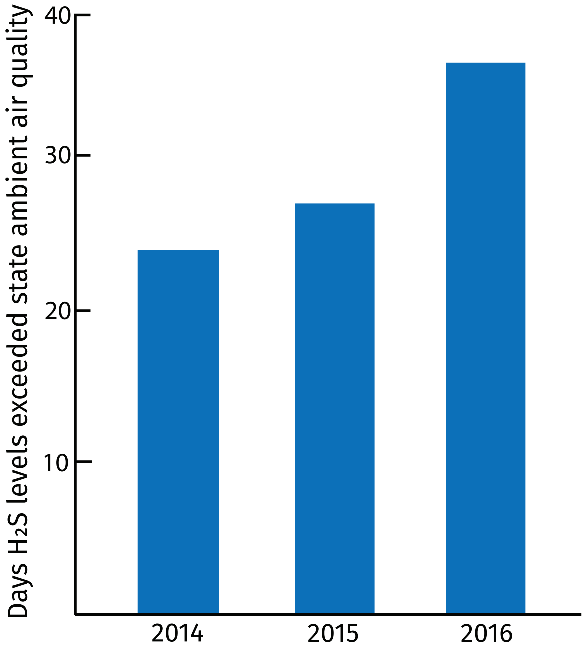


Figure 3.2 The number of days when hydrogen sulfide (H_2S) levels surpassed state ambient air quality standard of 30 parts per billion per hour at the Near-Shore Air Quality Monitoring Station. Credit: Caroline Hung. Source: South Coast Air Quality Management District.

For these immediate health reasons and others discussed below, the hydrogen sulfide system in the lake is a canary in the coal mine when it comes to assessing the potential hazard of Salton Sea water conditions and related impacts on near and distant communities. The very small dataset in Figure 3.2 suggests that the problem is growing, demanding a more thorough investigation of the patterns, consequences, and possible solutions.

During the late summer, strong winds from the south resulting from Santa Ana cyclones, monsoons, and surges from the Gulf of California induce mixing in the lake. Upon mixing with oxygen in the surface waters, the abundant hydrogen sulfide can react with oxygen to form sulfate and stimulate production of the mineral gypsum (calcium and sulfate combined), forming tiny crystals averaging 25 microns in the surface lake waters (Tiffany et al., 2007). These “gypsum blooms” can be detected from space using NASA MODIS satellites (Ma et al., 2020; Figure 3.3). The daily satellite images with records going back to the year 2000 give us an historical window to hydrogen sulfide mixing and release events, including the frequency, duration, and magnitude, as well as a way to monitor this phenomenon going forward. Levels of gypsum precipitation may be sufficiently high to ex-

SALT CRUST caps exposed playa and extends beneath the water line along many stretches of the receding shoreline. Caroline Hung

plain the formation of a gypsum crust on shorelines of the Salton Sea, but the mechanism of formation of these crusts is currently unknown. We do know that the salty crusts have formed recently and rapidly, as they often form around beverage cans and other objects from the last few decades. These crusts offer both negative and positive possibilities for lake chemistry and ecology and dust impacts on surrounding communities but have not been studied.

Toxic Metals

TRACE METALS AND OTHER CHEMICALS (e.g., pesticides) enter the Salton Sea via drainage into the lake, primarily via agricultural runoff. Selenium, for example, is found in cattle manure and fertilizers. Importantly, once brought into the lake, metal distributions and patterns of remobilization and related impacts on lake ecology, wildlife, and human populations in the region are intimately tied to spatial and temporal patterns of oxygen and hydrogen sulfide concentrations.

As discussed above, each summer anoxic waters are able to enrich the underlying sediment in metals far beyond the concentrations observed on the lake margin. While beneficial at low levels, these metals can become health hazards when elevated. Dissolved metals enter the lake via rivers at nontoxic levels, where they are enriched through evaporation and distributed in relation to spatially varying oxygen levels. Importantly, the metals are ultimately deposited with the sediments on the lake bottom and accumulate in a bullseye pattern, with the strongest enrichments in the oxygen-poor, hydrogen sulfide-rich central portions of the Sea (Figure 3.5). The net result is that the metals flow into the Salton Sea, but there is no path out other than by dust once the bottom sediments are exposed. A critical and under appreciated concern is that metals are most enriched in sediments in the central portions of the basin, making the dust increasingly toxic as the shoreline recedes.

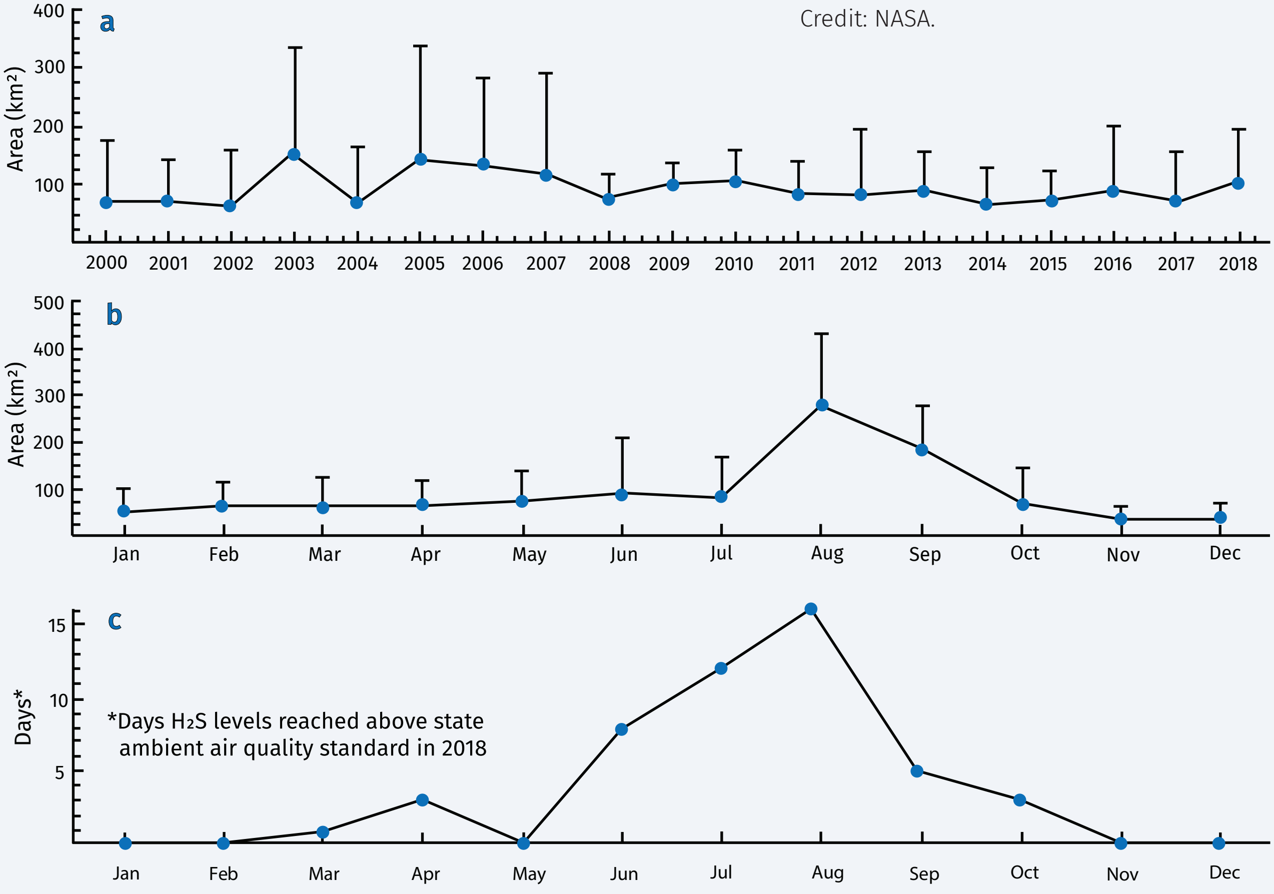
The metal- and pesticide-enriched sediments have been accumulating on the bottom for many decades. (Holdren and Montano, 2002; Moreau et al., 2007; Schroeder et al., 2002; Vogl and Henry, 2002). According to a comprehensive study by Vogl and Henry (2002), a number of metals and metalloids (i.e., cadmium, copper, molybdenum, nickel, zinc, and most notably selenium) are found at elevated concentrations of potential ecological concern in muddy sediments underlying the waters of the Salton Sea. Critically, these sediments and their metals would be exposed to the atmosphere following the projected dramatic reduction of lake level and would be widely distributed as dust throughout the region, including transport to nearby communities (Chapter 6). Im-

Hydrogen Sulfide and Gypsum Blooms

BOX 3A

OXYGEN-LEAN WATERS reach the surface of the lake on days with seasonally intensified winds and associated mixing—along with hydrogen sulfide formed under anoxic conditions—as the chemical and temperature layering or stratification of the lake breaks down. These events are linked to hydrogen sulfide production in the lake and regional wind patterns and result in widely distributed "rotten egg" odors during the summer. Upon mixing with oxygen in the surface waters, the abundant hydrogen sulfide can react with oxygen to form sulfate and stimulate production of the mineral gypsum, forming tiny crystals visible from space as blooms. This gypsum then precipitates out of the water column forms a salt crust around the margin of the Sea.

Figure 3.3 **NASA MODIS satellite view of a widely distributed gypsum bloom on August 17, 2019.** Credit: NASA.



*Days H_2S levels reached above state ambient air quality standard in 2018

Figure 3.4 **Gypsum bloom area in the Salton Sea from 2000 to 2018 presented as annual (a) and monthly (b) averages (Adapted from Ma et al., 2020). The monthly trend for days when H_2S concentration exceeds state ambient air quality standards (>30 ppb) at the Near-Shore site is shown in (c). Data for (c) are from SCAQMD public records for 2018 and show peaks in the late summer months of August and September.** CREDIT: Caroline Hung portantly, with further drops in lake level, the sediments with the highest toxic trace metal concentrations (Figure 3.5) will be exposed and picked up by winds and transported as dust. However, regardless of whether the center, deepest regions with the most metal-enriched muds are exposed (Chapter 2), vast areas of the lake bottom depicted in Figure 3.5 already have molybdenum and selenium concentrations higher than levels acceptable for daily human intake (Vyskočil and Viau, 1999; Wilber, 1980). Therefore, the associated flux of dust transport leads to the delivery of toxic trace metals at higher than acceptable doses (Guerzoni et al., 1999; Mosher and Duce, 1987). The high concentrations are important, but it is the combination of elevated concentrations and high rates of delivery as dust that raises concern.

An important implication of this relationship is that delivery of metals can happen even without exposure of the most metal enriched sediments in the basin center. Metal enrichments are significant even in many shallower regions (Figure 3.5), which could be exposed relatively soon with only moderate lake-level decline. Signatures of lakebed sediments are already observed in ambient dust in adjacent regions and will likely increase dramatically as the shoreline continues to recede (Frei et al., 2017). Again, if the current water policy continues, there will be more dust, and that dust will be more toxic.

Historically, selenium has been the primary metal of interest in studies of the Salton Sea. Currently, high concentration of selenium in exposed muds pose a threat to the migratory birds populations who frequent the Sonny Bono Salton Sea National Wildlife Refuge at the southern shore. Selenium is widely distributed in minute amounts in virtually all materials of the Earth's crust, having an average abundance of about 0.09 milligrams per kilogram (mg/kg) of rock (Rudnick and Holland, 2005). The natural selenium content of most soils lies between 0.1 and 2 mg/kg. However, much of the mud beneath the Salton Sea shows much higher concentrations. The U.S. Geological Survey sampled selected irrigation inflows to the Salton Sea in 2007 and 2008 and found that the average total selenium concentration in waters for both sampling periods ranged from 0.00097 to 0.0645 mg/kg (May et al., 2009). This constant influx of selenium to the lake has made its way into the sediments, thus elevating their concentrations, and into the biota of the Salton Sea (e.g., algae, plankton, fish). Similarly, Schroeder et al. (2002) suggested that virtually all of the selenium discharged to the Sea resides within its anoxic bottom sediments—the materials that will become dust upon exposure.

The water chemistry of the Salton Sea will change dynamically in time and space as salinity increases due to future reductions in water level and temperature increases through climate change. One expected outcome is more frequent, widespread, and persistent episodes of oxygen loss in the water column (including the surface 0–3 meters) and thus hydrogen sulfide release events, resulting in immediate deleterious effects on the Sea's ecosystem. As the lake shallows, deeper water that is episodically or persistently oxygen depleted will mix with oxygenated surface waters. In contact with bottom sediments, this freshly oxygenated water will remobilize substantial amounts of metal, including selenium, to the overlying water. Then, with further lake drop, we predict a two-step ecological impact: dramatic release of metals to the waters followed by emission to and transport in the atmosphere. Because of these predicted but little studied changes, modeling efforts informed by newly collected field data with frequent monitoring are essential to any decision tree as the lake's future is determined—particularly as related to Salton Sea's ecology and the generation of toxic dust.

Health Impacts

TOXIC METALS REMOBILIZED from the bottom sediments of the Salton Sea when the lake margin recedes can re-enter the ecosystem and ultimately be transported to surrounding communities through windblown dust. Key toxic metals of interest are molybdenum and selenium, among others (Box 3B). These metals have been cited in multiple studies over the last decades (e.g., Vogl and Henry, 2002; Hamilton, 2004; Frei et al., 2017) and have potential health impacts as they spread to the Coachella and Imperial valleys and the Torres-Martinez reservation.

A recent study published by UC Riverside environmental scientists surveyed the toxic metal content of dust derived from dry lakebed (i.e., playa dust) at five sites around the Salton Sea from 2017-18 (Frie et al., 2019). Selenium stood out as the most enriched trace metal, which is not surprising given its elevated levels in the muddy bottom sediments of the lake. Although trace amounts of selenium are necessary for cellular function in many organisms, including humans, it is toxic to humans even in minute amounts above 0.055 mg/kg/day (Aldosary et al., 2012). Chronic exposure can trigger lung

BOX 3B

Toxic Metal Enrichment in Deep Water

METAL ENRICHMENTS are most prominent in the deepest, central parts of the basin and relate to persistent, seasonal episodes of oxygen deficiency and hydrogen sulfide availability. These sediments, if exposed and picked up as dust, pose a health threat to nearby communities. If the water above these sediments shallows and becomes oxygenated, these metals will be remobilized into the overlying water and potentially emitted to the atmosphere.

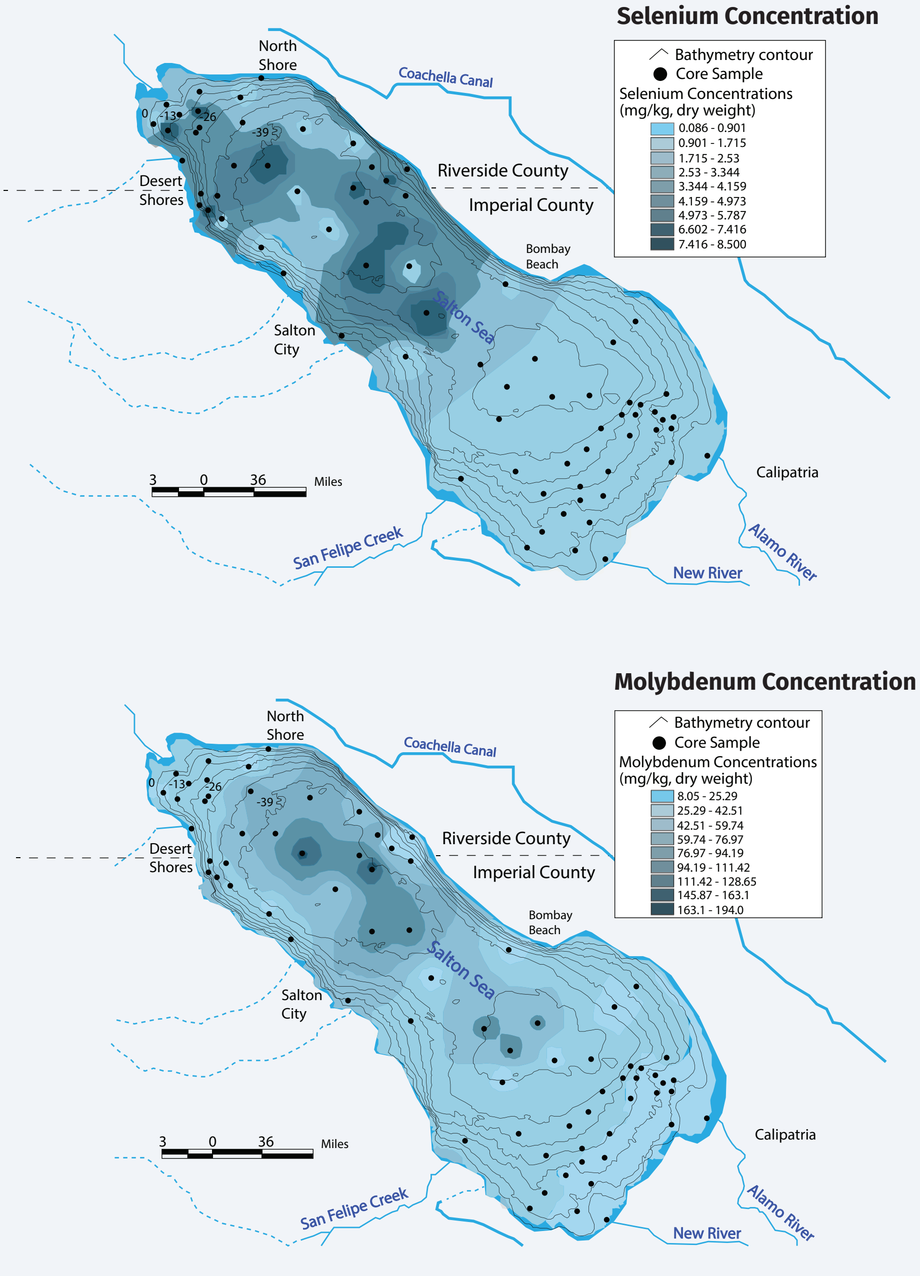


Figure 3.5 Bullseye pattern for selenium concentration (top) and molybdenum concentration (bottom) in bottom sediments of the Salton Sea. Darker areas, which are sediments most highly enriched in selenium, tend to be in the deepest portions of the basin. Credit: Caroline Hung. Sources: Bathymetry with two-meter intervals, Watts et al. (2001); molybdenum data, Vogl and Henry (2002).

malfunction (i.e., dyspnea, asthma, and cough) and various other disorders (Jaishankar et al., 2014). Critically, the rate of dust delivery—not only the concentration of metals in the dust—is critical.

In addition to concerns for public health through high selenium content in ambient dust, toxic levels in the water column and bottom sediments of the Salton Sea may have already caused an ecological crisis in the aquatic food chain (Hamilton, 2004). In 1996, a severe Type-C botulism outbreak killed more than 15,000 pelicans and associated fish-eating birds. Elevated levels of selenium and other trace metals in avian tissues suppress their immune system responses to diseases (Bruehler and Peyster, 1999). The harmful effects of selenium toxicity on the ecology of the Salton Sea will continue to influence the economies of surrounding communities. Recreational activities such as fishing, boating and camping have mostly ceased. Selenium introduced as dust and volatile gases is a threat to the most vulnerable residents of the Coachella and Imperial Valleys (Buck, 2020).

Molybdenum in excess can cause copper deficiency in humans and animals. The bottom sediments in the central regions of the lake are highly enriched in this metal (Figure 3.5). Although beneficial in ecosystems (e.g., molybdenum is in the enzyme that fixes nitrogen into soils), high molybdenum content transported through dust can harm surrounding livestock and agriculture. Of particular concern, excess molybdenum intake causes fatal copper deficiency diseases in grazing animals (Boyne and Arthur, 1986). Their rumen is the site of high hydrogen sulfide generation, and reactions between molybdenum and sulfur can result in interactions with copper, thus inhibiting its role in essential copper-dependent enzymes (Miltimore and Mason, 1971). Although toxicity of molybdenum compounds appears to be relatively low in humans, excessive exposure—perhaps through consumption of livestock and crops—could cause gout-like symptoms due to high levels of uric acid (Vyskočil and Viau, 1999).

In addition to concerns about selenium and molybdenum, related literature cites the potential toxicity of other trace metals accumulating in the bottom sediments of the Salton Sea, including arsenic (Bowell et al., 2014; Moreau et al., 2007) and lead, along with harmful DDT pesticides and PCBs as found in sediments and fish (Sapozhnikova et al., 2004).

Potential Outcomes

THE CYCLING OF ELEMENTS in the Salton Sea will continue to change as the lake shallows. A key research goal going forward is to gather information needed to predict how the salinity and the chemistry of the sediments and water column will evolve as lake water management practices evolve. If lake water levels continue to decline—which is almost certain to happen for at least the next ten years—salinity will increase, leading to more widespread and persistent anoxia and related ecological die-off. In the extreme case, the lake will drop to a level that will expose the sediments from the lake center with the highest concentration of toxic metals. This possibility is a major concern that has not been addressed adequately.

Intentionally diverting water to the lake will be necessary to keep the center of the lake immersed. Constructing wetland buffer zones around the edge of the shrinking lake could reduce fertilizer and metal transport into the lake itself, slowing further toxic enrichment of bottom sediments and frequency of harmful algal blooms. Excessive nutrient levels in the lake due to agricultural runoff are at the root of the many of the lake's problems and must be addressed. Research is needed to determine the optimal design of buffer zones and the lake level that would most effectively mitigate against dust production from the most contaminated bottom sediments. Importing a significant amount of water from the ocean or local freshwater sources could be the most effective means of restoring the Salton Sea ecosystem and minimizing release of toxic dust, although it might be the most difficult in terms of expense and water rights.

Research Needs

MODELS MUST BE DEVELOPED to predict water column evolution, including salinity change and related effects on oxygen levels and metal mobilization and mineral stability. It remains unclear how the importation of seawater versus freshwater would impact trace metal remobilization in sediments and oxygen distribution in the water column, but such difference could and should be studied. Preliminary model results predict that the addition of substantial freshwater and saltwater would lead to dissolution of the gypsum salt crust that covers much of the basin margin, which could result in exposure and remobilization of toxic metals within essential wetland habitats. While basin flooding would minimize the release of dust from the lakebed, each possible remediation effort must be assessed through the lenses of all related chemical and biological processes and consequences.

Action is required immediately to fully assess current

Tackling the Consequences of Water Quality Degradation

BOX 3C

Evolution of water column and sediment chemistry:

- **Model and measure the salinity and ionic composition effects on oxygen solubility and physical properties (e.g., density and temperature) of the Sea's waters to predict the consequences of water management policy.**
- **Monitor oxygen and hydrogen sulfide (H_2S) levels over all water depths, seasons, and regions of the Sea, including chemical analyses of the sediments and mineral precipitates to understand elemental cycling and sensitivity to changing water levels.**
- **Characterize metal enrichments in the sediments of the central Sea. Track potential for selenium remobilization using specialized natural tracers (e.g., selenium isotopes; Johnson et al. 1999; Stüeken 2017).**
- **Study nutrient and pesticide inputs to the Sea and cycling within those waters. Consider strategies to reduce fertilizer and pesticide inputs.**

Airborne release of hydrogen sulfide and transport of toxic dust:

- **Monitor airborne H_2S levels in surrounding communities and work with atmospheric circulation modelers to predict regional propagation of frequent H_2S in air masses.**
- **Assess health and life-quality risks to surrounding communities linked to more frequent, persistent, and likely more concentrated H_2S release from the Sea.**
- **Work with air quality researchers and atmospheric circulation and climate specialists to introduce H_2S detection in Salton Sea's waters and surrounding regions to forecast H_2S emission from the Salton Sea. Test further the relationships between these events and late summer gypsum blooms, given the historical record of those blooms and their immediate detectability from space.**

Health impacts to nearby people, livestock, and communities:

- **Assess potential impacts of metal inputs to surrounding livestock and farming regions.**
- **Work with the medical community and other researchers to evaluate health hazards.**

and predicted risks to Salton Sea water quality, including oxygen loss and resulting dust production. These efforts will require funds for measuring and modeling and are certain to play a key role in lake management and impact decisions. In other words, these results are needed up front as mitigation and remediation choices are being made. With current plans, anoxic conditions are likely to become increasingly prevalent in the water column, which will affect the overall ecology of the system and specifically the cycling of toxic metals. The areal and vertical extents of dissolved oxygen and toxic metal concentrations in the water column and bottom sediments of the Salton Sea have not been evaluated in sufficient detail in full consideration of recent changes and future management plans for the region. Essential new data must be integrated into first-of-their-kind quantitative models to help us predict the outcome of any potential remediation scenarios. Specific research goals focus on three topics: (1) evolution of water column and sediment chemistry, (2) airborne release of hydrogen sulfide and transport of toxic dust, and (3) health impacts to nearby communities (Box 3C).

Despite vast amounts of past research in the Salton Sea, there is little understanding of the primary controls on oxygen, sulfide, and metal distributions and how changing lake levels might exacerbate current problems. Those problems include release of dust to surrounding communities and perturbations to fish stocks and waterfowl feeding habits as controlled by upward mixing of bottom waters low in oxygen and rich in hydrogen sulfide and potential exposure of metal-laden sediment. These are among the most critical concerns linked to current and future management choices—in terms of water quality and volume—yet they remain largely neglected in conversations about the Salton Sea's future.

CHAPTER THREE - REFERENCES

Aldosary, B. M., Sutter, M. E., Schwartz, M., & Morgan, B. W. (2012). Case Series of Selenium Toxicity from A Nutritional Supplement. *Clinical Toxicology*, *50*(1), 57–64. https://doi.org/10.3109/15563650.2011.641560

Bowell, R. J., Alpers, C. N., Jamieson, H. E., Nordstrom, D. K., & Majzlan, J. (2014). The Environmental Geochemistry of Arsenic—An Overview—. *Reviews in Mineralogy and Geochemistry*, *79*(1), 1–16. https://doi.org/10.2138/rmg.2014.79.1

Boyne, R., Arthur, J. R. (1986). Effects of molybdenum or iron induced copper deficiency on the viability and function of neutrophils from cattle. *Research in Veterinary Science, 41*(3), 417–419. https://doi.org/10.1016/S0034-5288(18)30643-X

Bruehler, G., & de Peyster, A. (1999). Selenium and Other Trace Metals in Pelicans Dying at the Salton Sea. *Bulletin of Environmental Contamination and Toxicology*, *63*(5), 590–597. https://doi.org/10.1007/s001289901021

Buck, H. J. (2020). Understanding inaction in confronting ecosystem collapse: community perspectives from California's Salton Sea. *Ecology and Society*, *25*(1), art27. https://doi.org/10.5751/ES-11443-250127

Cohen, M. J. (2014). *Hazard's Toll: The Costs of Inaction at the Salton Sea*. Pacific Institute. https://pacinst.org/wp-content/uploads/2014/09/PacInst_HazardsToll-1.pdf

Frie, A. L., Dingle, J. H., Ying, S. C., & Bahreini, R. (2017). The Effect of a Receding Saline Lake (The Salton Sea) on Airborne Particulate Matter Composition. *Environmental Science & Technology*, *51*(15), 8283–8292. https://doi.org/10.1021/acs.est.7b01773

Frie, A. L., Garrison, A. C., Schaefer, M. V, Bates, S. M., Botthoff, J., Maltz, M., Ying, S. C., Lyons, T., Allen, M. F., Aronson, E., & Bahreini, R. (2019). Dust Sources in the Salton Sea Basin: A Clear Case of an Anthropogenically Impacted Dust Budget. *Environmental Science & Technology*, *53*(16), 9378–9388. https://doi.org/10.1021/acs.est.9b02137

Guerzoni, S., Molinaroli, E., Rossini, P., Rampazzo, G., Quarantotto, G., De Falco, G. and Cristini, S. (1999). Role of desert aerosol in metal fluxes in the Mediterranean area. *Chemosphere*, *39*(2), 229–246. https://doi.org/10.1016/S0045-6535(99)00105-8

Hamilton, S. J. (2004). Review of selenium toxicity in the aquatic food chain. *Science of The Total Environment*, *326*(1), 1–31. https://doi.org/10.1016/j.scitotenv.2004.01.019

Holdren, G. C., & Montaño, A. (2002). Chemical and physical characteristics of the Salton Sea, California. *Hydrobiologia*, *473*(1), 1–21. https://doi.org/10.1023/A:1016582128235

Jaishankar, M., Tseten, T., Anbalagan, N., Mathew, B. B., & Beeregowda, K. N. (2014). Toxicity, mechanism and health effects of some heavy metals. *Interdisciplinary Toxicology*, *7*(2), 60–72. https://doi.org/10.2478/intox-2014-0009

Johnson, T. M., Herbel, M. J., Bullen, T. D., & Zawislanski, P. T. (1999). Selenium isotope ratios as indicators of selenium sources and oxyanion reduction. *Geochimica et Cosmochimica Acta*, *63*(18), 2775–2783. https://doi.org/10.1016/S0016-7037(99)00279-3

Ma, J., Duan, H., He, L., Tiffany, M., Cao, Z., Qi, T., Shen, M., Biggs, T., & Xu, X. (2020). Spatiotemporal pattern of gypsum blooms in the Salton Sea, California, during 2000–2018. *International Journal of Applied Earth Observation and Geoinformation*, *89*, 102090. https://doi.org/10.1016/j.jag.2020.102090

Marshall, J. R. (2017). Why emergency physicians should care about the Salton Sea [Editorial]. *Western Journal of Emergency Medicine*, *18*(6), 1008. DOI: 10.5811/westjem.2017.8.36034

May, T. W., Walther, M. J., Saiki, M. K., & Brumbaugh, W. G. (2009*). Total Selenium and Selenium Species in Irrigation Drain Inflows to the Salton Sea, California, October 2008 and January 2009* [Open-File Report 2009-1123]. U. S. Geological Survey. https://doi.org/10.3133/ofr20091123

Miltimore, J. E., & Mason, J. L. (1971). Copper to molybdenum ratio and molybdenum and copper concentrations in ruminant feeds. *Canadian Journal of Animal Science*, *51*(1), 193–200. https://doi.org/10.4141/cjas71-026

Moreau, M. F., Surico-Bennett, J., Vicario-Fisher, M., Gerads, R., Gersberg, R. M., & Hurlbert, S. H. (2007). Selenium, arsenic, DDT and other contaminants in four fish species in the Salton Sea, California, their temporal trends, and their potential impact on human consumers and wildlife. *Lake and Reservoir Management*, *23*(5), 536–569. https://doi.org/10.1080/07438140709354037

Mosher, B. W., & Duce, R. A. (1987). A global atmospheric selenium budget. *Journal of Geophysical Research: Atmospheres*, *92*(D11), 13289–13298. https://doi.org/10.1029/JD092iD11p13289

Reese, B. K., Anderson, M. A., & Amrhein, C. (2008). Hydrogen sulfide production and volatilization in a polymictic eutrophic saline lake, Salton Sea, California. *Science of the Total Environment*, *406*(1–2), 205–218. DOI: 10.1016/j.scitotenv.2008.07.021

Reese, B. K., & Anderson. M. A. (2009). Dimethyl sulfide production in a saline eutrophic lake, Salton Sea, California. *Limnology and Oceanography*, *54*, 250–261. https://doi.org/10.4319/lo.2009.54.1.0250

Rudnick, R. L. (Ed.). (2005). *Treatise on Geochemistry, Volume 3: The Crust*. Elsevier.

Sapozhnikova, Y., Bawardi, O., & Schlenk, D. (2004). Pesticides and PCBs in sediments and fish from the Salton Sea, California, USA. *Chemosphere*, *55*(6), 797–809. https://doi.org/10.1016/j.chemosphere.2003.12.009

Schroeder, R. A., Orem, W. H., & Kharaka, Y. K. (2002). Chemical evolution of the Salton Sea, California: nutrient and selenium dynamics. *Hydrobiologia*, *473*, 23–45. https://doi.org/10.1023/A:1016557012305

Stüeken, E. E. (2017). Selenium isotopes as a biogeochemical proxy in deep time. *Reviews in Mineralogy and Geochemistry*, *82*(1), 657–682. https://doi.org/10.2138/rmg.2017.82.15

Tiffany, M. A., Ustin, S. L., & Hurlbert, S. H. (2007). Sulfide irruptions and gypsum blooms in the Salton Sea as detected by satellite imagery, 1979–2006. *Lake and Reservoir Management*, *23*(5), 637–652. https://doi.org/10.1080/07438140709354043

Vogl, R. A., & Henry, R. N. (2002). Characteristics and contaminants of the Salton Sea sediments. *Hydrobiologia*, *473*(1), 47–54. https://doi.org/10.1023/A:1016509113214

Vyskočil, A., & Viau, C. (1999). Assessment of molybdenum toxicity in humans. *Journal of Applied Toxicology*, *19*(3), 185–192. https://doi.org/10.1002/(SICI)1099-1263(199905/06)19:3<185::AID-JAT555>3.0.CO;2-Z

Watts, J. M., Swan, B. K., Tiffany, M. A., & Hurlbert, S. H. (2001). Thermal, mixing, and oxygen regimes of the Salton Sea, California, 1997–1999. In *Saline Lakes* (pp. 159–176). Springer.

Wilber, C. G. (1980). Toxicology of Selenium: A review. *Clinical Toxicology*, *17*(2), 171–230. DOI: 10.3109/15563658008985076