

CRISIS AT THE SALTON SEA

The Vital Role of Science



A special report prepared for policymakers and stakeholders by the

**UNIVERSITY OF CALIFORNIA RIVERSIDE
SALTON SEA TASK FORCE**

JULY 2021

Sponsored by the **EDGE Institute** and the **Center for Science to Policy** at **UC RIVERSIDE**

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SNOW GEESE in flight above the Sonny Bono Salton Sea National Wildlife Refuge. Jonathan Nye

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SHOREBIRDS FORAGING near North Shore Yacht Club. Jonathan Nye

EXECUTIVE SUMMARY

The Vital Role of Science in a Successful Salton Sea Policy

The Salton Sea—a hypersaline, terminal lake in southern California—is in crisis. A combination of mismanagement and competition among federal, state and local agencies has hindered efforts to address declining lake levels and unstable water chemistry. This delay has heightened the public health threat to regional communities as retreating shorelines expose dry lakebed—a source of potentially toxic dust—while aquatic ecosystems face collapse due to rising salinity and oxygen loss. Although state agencies are making efforts to mitigate the problems, the scientific assumptions informing current management practices are outdated or lacking entirely, making outcomes unpredictable at best.

THE ABSENCE OF AN ADAPTIVE, SCIENCE-BASED approach to addressing the environmental and human health challenges at the Salton Sea prompted UC Riverside's Environmental Dynamics and GeoEcology (EDGE) Institute and Science to Policy Center to launch an independent Salton Sea Task Force to identify critical scientific research necessary to guide policymakers in making decisions about the region's future. As an interdisciplinary group of scientists, engineers, medical experts, and economists, we considered three potential, realistic scenarios facing the Salton Sea over the coming decade: (1) ongoing

decline, where lake levels continue to decrease without intervention, (2) stabilization, where enough water is directed to the Sea to slow the decline and potentially stabilize the lake at a level lower than it is today, and (3) recovery, where enough water is brought in from the ocean or local freshwater sources to stabilize, and possibly increase, lake levels.

Based on our expertise and first-hand research at the Salton Sea, we identified substantial challenges and opportunities in seven interconnected areas: water policy, watershed hydrology, water quality, air quality,



AIR QUALITY MONITORING EQUIPMENT: dust sticks to the marbles and can be analyzed later in the lab. Emma Aronson

ecology, human health, and geothermal resources. This report devotes a chapter to each of these areas of concern and provides specific suggestions for research tasks that would provide the necessary clarity to evaluate outcomes of current Salton Sea management policies and help make necessary adjustments moving forward.

Urgency

PRAGMATIC URGENCY drives the research outlined in this report. We are keenly aware of the limited funding currently allocated for mitigation efforts at the Salton Sea, and we duly focused our scientific curiosity about this dynamic region through the lens of the two primary goals the state of California identifies in its current Salton Sea management plan: (1) improve air quality for the communities surrounding the Salton Sea and (2) provide critical environmental habitat for birds along the Pacific Flyway. Furthermore, we evaluated these goals using four criteria used commonly to determine the success or failure of a policy: *effectiveness*, *efficiency*, *equity*, and *sustainability*.

Effectiveness

FIRST CONSIDER EFFECTIVENESS, which measures how successfully a plan achieves its desired results. We can set a lower bound for the effectiveness of current Salton Sea policies by asking two questions: Will air quality improve? Will there be critical habitat for birds and fish?

The Salton Sea Management Program, led by a consortium of state agencies, aims to achieve its desired outcomes by constructing 30,000 acres of bird habitat and dust suppression projects by 2028. Progress has been slow, however, with only 755 acres completed by the end of 2020 (SSMP, 2021). Potential outcomes of these efforts are highly uncertain. Plans to limit air pollution rely largely on limiting acreage of exposed lakebed, or playa. Yet the acreage of exposed playa will depend on the Sea's volume, which in turn depends on regional water policy (Chapter 1) and complex interactions between surface water and groundwater, a factor that has been overlooked until recently (Chapter 2). Air quality, too, is a function not only of water availability but also of the chemistry and biology of the lake itself, which is changing rapidly as water volume diminishes (Chapters 3, 4, 5).

The degree to which restoration efforts will produce viable bird habitats is similarly uncertain (Chapter 5). The characteristics of restored wetland habitat will depend on the intersection of water quantity, water quality, and other inputs, such as food sources for birds. Yet, as this report demonstrates, we are proceeding with a lack of understanding of the Sea's water quantity (Chapters 1 and 2) and water quality (Chapter 3) dynamics. In short, whether planned wetland projects will provide the minimum range of ecosystem functions required to support specific bird species depends on variety of factors that require further scientific research (Chapter 5).

Efficiency

CURRENT STATE POLICIES are even more concerning from an efficiency perspective. Within the economic lexicon, efficiency is an outcome for which net benefits—total benefits less total costs—are maximized. The lack of understanding of the outcomes associated with current mitigation efforts to reduce air pollution or restore critical habitat coupled with uncertainty surrounding the drivers of pulmonary illness associated with changing Salton Sea characteristics (Chapter 6) make any quantifiable measure of the benefits indeterminate. Reasonable discussions about efficiency are premature until we

garner a better understanding of the science. Indeed, expecting efficiency from Salton Sea management policies may be unrealistic. A less demanding criterion would be to seek a solution that is merely cost-effective, defined as the minimum cost to achieving a particular outcome.

Even a less demanding, cost-effective criterion will be difficult to achieve without an understanding of the science and issues identified in this report. Because of the uncertainty surrounding the drivers of pulmonary illness associated with changing Salton Sea characteristics (Chapter 6) and the likely outcomes associated with current mitigation efforts to restore critical habitat or reduce air pollution (Chapters 3, 4, 5), any quantifiable measure of benefits is indeterminate. Without a firmer grasp on probable outcomes for proposed mitigation strategies, assessments of the cost-effectiveness of current policies are also premature.

Put another way, the rate of return on current investments in mitigation as measured by current management targets are highly uncertain and not guaranteed to be positive over time, due largely to the issues identified in this report. Furthermore, as economics is about trade-offs, the consequences of a receding Sea on the state's intended outcomes of reducing air pollution and improving critical habitat should be considered alongside economic opportunities—namely, what can be gained from further development and investment in the Sea's geothermal and lithium resources (Chapter 7).

Equity

RECENTLY CALIFORNIA has increased its efforts to incorporate local community concerns and insight into its Salton Sea management plan. Considering input from local stakeholders is a commendable pivot relative to the state's earlier efforts, which were focused more on trying to identify cost-effective solutions than on how different communities would bear those distributions of costs and benefits. Despite this progress, equity issues are still largely unresolved because of the uncertain outcomes associated with air pollution (Chapter 4), how that pollution impacts local communities surrounding the Salton Sea (Chapter 6), and what rents associated with geothermal and lithium development can be funneled back into the local communities in terms of employment and income opportunities (Chapter 7).

It is critical to note that significant health disparities in this region are likely to amplify the impacts of expected environmental hazards (Chapter 6). The communities



surrounding the Salton Sea are characterized relative to state averages by low income, poor health, and low access to health care. As such, knowing how the benefits and costs of different management plans will affect these communities is paramount to understanding the degree to which such plans are equitable; because of the uncertainty surrounding the effectiveness of the management plans—and until an understanding of the issues raised in this report is achieved—the degree to which such plans are equitable is unclear.

Sustainability

FINALLY, THIS REPORT clarifies the need for more scientific research to understand how the Salton Sea system will evolve over time. Getting a better handle on the Sea's future volume, chemistry and probable generation and transport of dust and other air pollutants is critical to



LAUNCHING WATERCRAFT for field work is difficult. Shorelines have receded far from existing boat ramps. Charlie Diamond

the restoration and sustainability of critical habitat for birds and clean air for local communities. Both a better understanding of the science and continual monitoring and assessment of the consequences of mitigation will be required to gauge the effectiveness and return on the state's efforts. The same kinds of science are crucial for recognizing when ongoing investments in a particular strategy need to be reimagined and reconfigured.

Action

A COMMON REFRAIN in discussions about how to manage the Salton Sea crisis is 'enough science has been done—what we need now is action.' This report makes clear that we need both science and action. Without significant

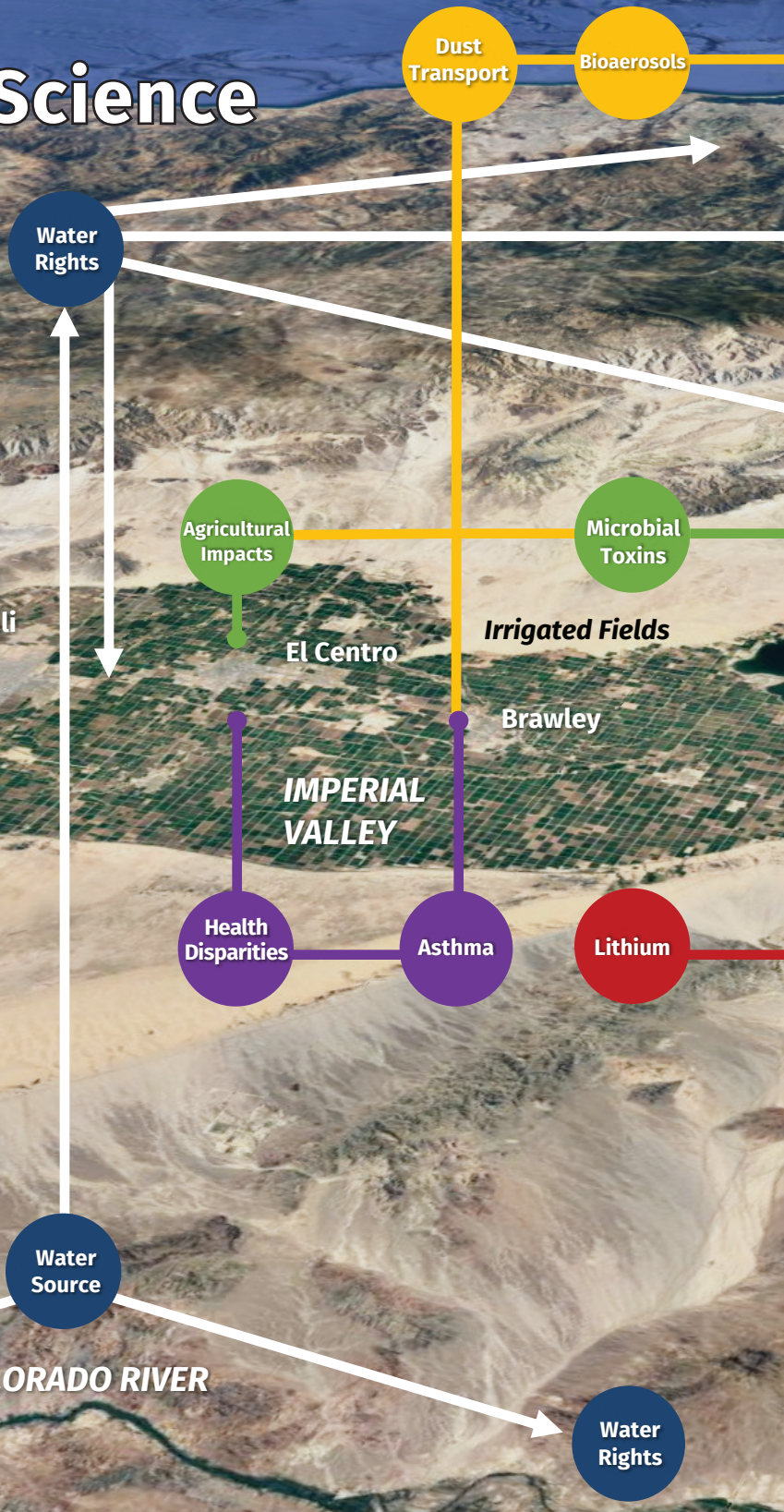
consideration of the issues presented in this report, the ability of the Salton Sea Management Program to achieve the desired outcomes of its mitigation efforts will be difficult, if not impossible. We therefore recommend that the Salton Sea Management Program set aside a portion of the funding allocated to mitigation efforts for a competitive research program open to researchers from universities, non-profits, and other state agencies so that action may be informed by ongoing and complementary scientific monitoring and inquiry. Moreover, we recommend that the federal government, which owns roughly 40% of lands at the Salton Sea, partner with California to invest in economic and mitigation efforts in the region, also setting aside a portion of funding for the necessary scientific research to make effective investments.

CRISIS AT THE SALTON SEA

The Vital Role of Science

BASED ON DIVERSE EXPERTISE and first-hand experience in the region, the UC Riverside Salton Sea Task Force identified seven interconnected areas of concern that require immediate scientific research and monitoring investments to ensure the success of planned mitigation activities:

- 1 WATER POLICY
- 2 WATERSHED HYDROLOGY
- 3 WATER QUALITY
- 4 AIR QUALITY
- 5 ECOLOGY
- 6 HUMAN HEALTH
- 7 GEOTHERMAL RESOURCES



MEXICALI VALLEY

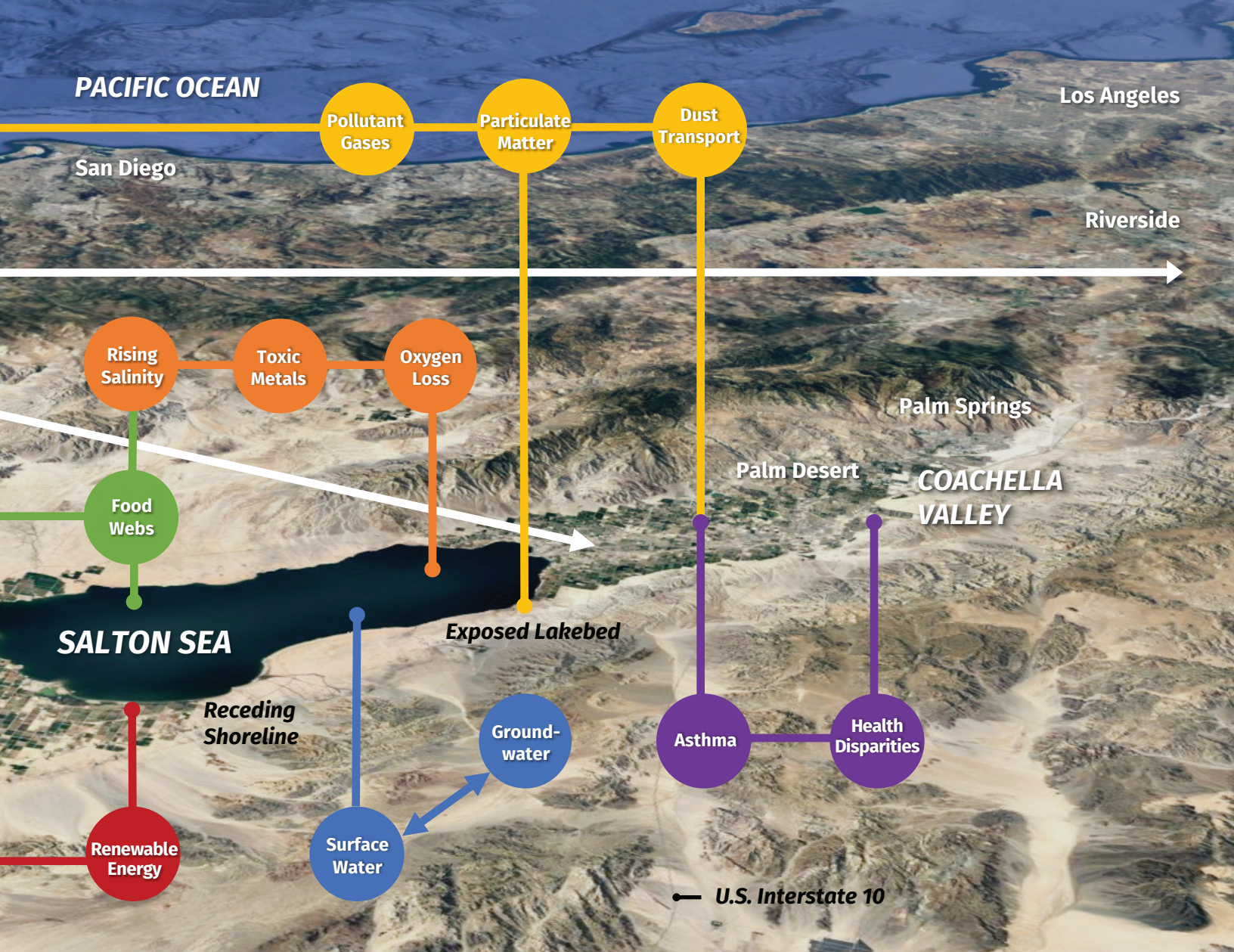
U.S. Interstate 8

Yuma

COLORADO RIVER

LOOKING WEST across the Salton Basin toward the Pacific Ocean. Credit: Sarah Simpson; BASE MAP: Google Earth





Water Policy

1

A key science need is to determine the optimal lake water level to reduce lakebed dust, maintain wildlife habitat, and improve livelihoods in the region.

The problems facing the Salton Sea are multi-faceted and complex, spanning from ecological and medical concerns to health disparities and economic opportunities. Continued shrinking of the sea exposes dry lakebed that exacerbates windblown dust as aquatic ecosystems crash or disappear. Managing lake levels is challenging in large part because urban water districts in San Diego and Los Angeles compete

with agricultural irrigation and natural ecosystems for the same inflows from the Colorado River, which are projected to decline. As the construction of wetland restoration and dust mitigation projects ramps up on the northern and southern shores of the lake in the coming years, it will become increasingly imperative that scientific research and monitoring guides these activities.

2 Watershed Hydrology

A comprehensive assessment of lake-groundwater interactions is needed to explain the underlying causes of significant reductions in Salton Sea volume since 1995.

The Salton Sea watershed is one of the most productive agricultural regions in the United States. With an area of 8,417.4 square miles, this watershed's hydrology is coupled tightly to water imported from the Colorado River, which provided about 1.1 million acre feet per year of water to the lake via irrigated agricultural runoff and subsurface drainage from 1980 to 2018. Despite no substantial decrease in agricultural inflows, lake levels declined significantly from -227.06 feet in 1995 to -236.4 feet in 2018. One possible explanation for this unexpected drop is poorly understood connections among the lake, local groundwater aquifers and subsurface water flows, which have never been evaluated adequately.

The water volume of the Salton Sea is a straightforward difference between inflows and outflows. The Sea's only surface outflow is via well-understood rates of evaporation; inflow is estimated from measured flow rates near the mouths of various rivers. The unknown factor is the dynamics of subsurface water. The model that the Salton Sea Management Program has used to predict lake levels for current management plans assumes constant net groundwater flows into the lake, but it does not consider the possibility that the lake may discharge to groundwater. Accurate predictions of future lake levels require new research to properly quantify all lake-groundwater interactions.



AGRICULTURAL DRAINS (left) entering the Alamo River near its terminus at the Salton Sea. Jonathan Nye

Water Quality **3**

Shrinking of the Salton Sea will exacerbate water quality issues as dead zone episodes last longer and the receding shoreline exposes mud that is more highly concentrated in toxic metals and pesticides.



GREEN TIDE from precipitation of gypsum in the warm waters of the Salton Sea in August 2020. Caroline Hung

Changing water chemistry at the Salton Sea is already causing serious perturbations to fish stocks and waterfowl feeding habits. It also makes windblown dust from the dry lakebed increasingly toxic as the Sea recedes. Each summer the deeper waters lose oxygen and accumulate hydrogen sulfide through the activities of algae and bacteria. These dead zone waters mix with the surface layers on windy days, resulting in fish kills and airborne accumulation of foul-smelling hydrogen sulfide. It is likely that these conditions will become longer-lived and more frequent as lake volume decreases. Concentrated in the

central portions of the basin, these waters also tend to enrich the underlying sediment in metals far beyond concentrations observed on the lake margin. Molybdenum and selenium, for example, are beneficial at low levels but become health hazards when elevated. Along with pesticides, these metals will likely remobilize to surface waters as the sea recedes and be transported into ambient air as dust from the dried lakebed. It is imperative to monitor the dynamic biogeochemistry of the lake water for patterns of oxygen loss and toxic metal remobilization under different water management strategies.

4 Air Quality

Airborne dust fluxes at sites close to the Salton Sea are already in the high range of values observed at Owens Lake, California, before mitigation began; dust control there has already cost more than \$2 billion.

Despite uncertainties in quantifying the impact of the shrinking Salton Sea on local air pollution, measurement and modeling studies suggest that ongoing declines in lake volume will contribute to lower air quality for residents throughout the basin and beyond. A large fraction of the coarse particulate matter captured at sites closest to the shore of the Salton Sea is associated with emissions from the lakebed and sea spray. Pungent and reactive gases are regularly produced in the Sea and emitted to the atmosphere, contributing to noxious odors and formation of fine particulate matter. As the shoreline recedes, harmful

algal blooms will likely become more frequent, producing microbial toxins that may become airborne, and newly exposed fumaroles will emit greenhouse gases and ammonia directly to the atmosphere. Worsening air quality will further burden local residents already dealing with disproportionately high levels of ambient particulate matter and related respiratory issues. More research is necessary to fully understand the transport, composition, and health impacts of air pollutants originating from the Salton Sea and its exposed lakebed, and to inform and guide mitigation efforts aimed at improving the health and well-being of local communities.



GYPSUM-LADEN SALT CRUST on the exposed lakebed near Desert Shores. Caroline Hung

Ecology 5

Without significant freshwater introduction to the Salton Sea, the lake ecosystem faces collapse due to excessive nutrients, rising salinity, and declining water levels.



WETLANDS in Unit 2 of the Sonny Bono Salton Sea National Wildlife Refuge. Jonathan Nye

The dynamic and unstable Salton Sea region historically has supported abundant wildlife, ranging from a diverse array of microorganisms to endangered species of fish and birds. Terrestrial desert ecosystems give way to agricultural fields, riparian zones, natural and managed wetlands, and the aquatic ecosystems of the lake itself, which are supported by water and nutrients derived largely from agricultural run-off. Excessive nutrient flows into the Sea result in harmful algal blooms and dead zones, threatening wildlife and humans. Declining lake levels disrupt migration patterns for fish-eating

birds and isolate populations of endangered desert pupfish inhabiting the Sea's margins, putting them at increased risk of extinction. The salinity of the Sea—already at 74 parts per thousand, more than double that of the Pacific Ocean—will continue to rise as the Sea shrinks, leading to a catastrophic collapse of the aquatic food web if the current trend is not halted. Planned construction of wetland habitats may benefit certain species of non-fish-eating birds; however, there are currently no official plans to maintain or restore a fully functioning lake ecosystem.

6 Human Health

Respiratory illness and other consequences of the environmental hazards in and around the Salton Sea will likely amplify the region's significant social and economic disparities.

The ongoing crisis at the Salton Sea presents multiple consequences for the region's human residents. In communities already subject to disparities in social and economic status, the environmental hazards of life in the region—particularly increases in windblown dust that are expected as the shrinking sea exposes more dry lakebed—are evident from the epidemiology of diseases, especially pulmonary diseases such as asthma. Comorbid factors including the high incidence of obesity,

poverty, poor access to health care, and chemical exposures from agriculture work further degrade the quality of life, driving additional impacts on mental health in the community. Continued environmental degradation at the Salton Sea accompanied by increased production of dust and other air pollutants has already impaired the economic and social fabric of the region. Health disparities and costs to the community will likely increase unless steps are taken to address the issues raised here.



NORTH SHORE YACHT CLUB, originally built along the shoreline, is now high and dry. Jonathan Nye

Geothermal Resources

7

Economic opportunities for developing non-traditional mineral and energy resources at the Salton Sea could help offset expected environmental and human health costs.



GEOHERMAL POWER PLANT on the southeastern shore operating in the early morning. Jonathan Nye

The existing renewable electrical generation industry at the Salton Sea Geothermal Field has tremendous potential to become a world-class producer of lithium and other critical metals, which can be extracted from geothermal brines. The industry could also generate nontraditional geothermal energy via production of electricity from pumped storage and by producing hydrogen via electrolysis, thereby boosting California's ability to meet legal mandates to produce more renewable energy while lowering greenhouse gas emissions.

Development of these nontraditional resources together could make expanded geothermal power production at the Salton Sea more competitive with solar and wind power. These efforts would lead to substantial local job creation and increased tax revenues. Multiple benefits would be maximized by coordinating the expansion of geothermal resources with reclamation plans for the Sea, as the receding shoreline opens up new land suitable for construction of both artificial wetlands and new geothermal infrastructure.

1

Water Policy

Framing the Crisis Unfolding at the Salton Sea

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HIGHLIGHTS

- **Diverse environmental problems at the Salton Sea are severe and require immediate action in the short term and science-based planning for the intermediate and long term.**
- **Regional water policy decisions will have the greatest impact on the fate of the Salton Sea, as urban water districts, agricultural irrigation and natural ecosystems all compete for California's allotment of water from the Colorado River.**
- **Management plans that are enacted without a better understanding of the natural, physical, biological, chemical, and ecological systems in and around the Salton Sea—and how those systems interact with local communities—will be uninformed at best.**
- **A competitive, interdisciplinary research program open to researchers at universities and non-profits is needed to guide policymakers, government scientists, and contractors.**

The Salton Sea is shrinking, and salinity is rising—leading to the demise of once abundant fish and invertebrate populations and the loss of a vital feeding, resting, and nesting site for millions of birds migrating along the Pacific Flyway (Figure 1.1). The rapid shrinkage of the Sea is generating toxic gases and micron-sized particulate dust (Cohen et al., 2006; Buck et al., 2011; Frie et al., 2019) that threatens the health of hun-

dreds of thousands of Californians, many of whom live in disadvantaged and vulnerable low-income communities. Beginning in January 2018, some of the water flowing into the Sea was diverted to urban water districts, accelerating the decline to -236.4 feet by the end of 2020 (SSMP, 2021). Despite vast investments of time and an ample planning horizon, adequate solutions addressing the full range of problems have failed to materialize in implementation or



BLACK-NECKED STILTS foraging along the receding shoreline near North Shore Yacht Club. Jonathan Nye

concept. Indeed, more than two decades have transpired since the introduction of the water transfer between the Imperial Irrigation District and the San Diego County Water Authority that would become the 2003 Quantitative Settlement Agreement (Littleworth and Garner, 2019), yet little has been accomplished.

More recently, funds have been appropriated to design and implement a 10-year interim Salton Sea Management Plan (SSMP, 2018). The passage of California's \$7.5-billion Proposition 1 bond in 2014 allocated slightly over \$80 million for the Salton Sea—funding primarily for the design and documentation of the interim plan with some allocations for construction projects. In 2018 California voters passed Proposition 68, with \$200 million earmarked for mitigation of dust and other environmental problems emanating from the Salton Sea. In total, with the enactment of the 2020–2021 state budget, California has appropriated \$345.3 million for Salton Sea-related activities; the federal government has appropriated \$14 million (SSMP, 2021). These legislative actions provide

funding for mitigation and restoration—but not research.

Including some additional, smaller appropriations towards Salton Sea restoration activities, the funding to date has focused almost exclusively on design-and-build projects for dust mitigation and habitat restoration in and around the Salton Sea. Although such efforts are necessary, little funding has been available for basic research based on the evolving environmental conditions at the Sea over that same period. Barnum et al. (2017) summarized research gaps based on a study conducted in 2014. Many of the concerns in that study are still pertinent today and underscore the urgent need for an adaptive, science-based approach to management. The UC Riverside (UCR) Salton Sea Task Force was created to address this omission and provide guidance to policy makers on what we still need to know to solve the growing environmental and human health crisis. Although support for increased funding to manage the Salton Sea is gaining traction, we caution that policies and strategies not supported by up-to-date, evidence-based

science may lead to ineffective, costly, and unsustainable outcomes—in effect, poor investments.

Water Rights

THE SALTON SEA is shrinking primarily because regional water policy—indirectly—is providing it a significantly smaller share of water from the Colorado River (Box 1A). The Salton Sea’s main water source has always been the Colorado River, which flows through some of the driest portions of the United States. Water released from upstream dams on the Colorado River in Colorado, Utah, and Arizona is earmarked for use by seven states and a myriad of water districts. California holds senior water rights on much of this water, most of which in turn is allocated to the Imperial Irrigation District, which supports the agricultural production of the Imperial Valley to the south of the Salton Sea. Much smaller portions of California’s share go to other irrigation and municipal water districts in the region (Thrash and Hanlon, 2019). Colorado River water makes its way to the Salton Sea as irrigation run-off from the agricultural fields of the Imperial

Valley. That reliable water source was curtailed after a protracted legal battle finalized the 2003 Quantification Settlement Agreement (QSA), which allowed Imperial Irrigation District to sell a sizeable amount of its Colorado River water allocation to San Diego County Water Authority (Figure 1.2).

To generate the water for transfer and sale, Imperial Irrigation District engaged in several activities to reduce the amount of water used for irrigation, including the fallowing of agricultural lands in the Imperial Valley early in the program, to be followed up later by improved irrigation efficiency. Both water-saving approaches conveyed the known side effect of drastically reducing inflows to the Salton Sea. To mitigate the certain impact on Salton Sea volume and provide time for a solution, the QSA stipulated that a total of 800,000 acre-feet of “mitigation” water to be sent to the Salton Sea from 2003 through 2017. Although inflows to the Salton Sea remained somewhat constant during that period, Salton Sea water elevation declined (Chapter 2). The decline accelerated at the beginning of 2018, due to the cessation of this mitigation water.

The QSA served several purposes, including mandating a reduction in California’s overall Colorado River water use from 5.2 million acre-feet annually to its legal cap of 4.4 million acre-feet. The agreement also provided San Diego a reliable water source—even though it had the lowest priority water rights for Colorado River water. However, the potential costs associated with these transfers and the consequent effects on the Salton Sea and surrounding communities are exorbitant (Cohen, 2014).

In an effort to avert potentially substantial externalities to both environmental and human health, the Salton Sea Authority created a 10-year management plan. Numerous governments, non-governmental organizations, and local stakeholders prepared this plan, which relies on a mixture of new wetland construction and water quality control (Forney, 2018). Wetlands naturally grow as the shoreline recedes. These vegetated wetlands are supplied primarily by surface water inflows from the New and Alamo rivers and expected to support invertebrates, rails, and migrating geese. Intentional construction of estuarine wetlands or impoundments are being developed on the northern and southern shorelines with freshwater combined with the Sea’s already salty water in the hope of supporting fish and fish-eating birds. In the future, more extreme measures may be taken to control salinity and water quality. Desalination plants could be



FIGURE 1.1 Viewing the Salton Sea in its western North America regional context reveals its critical position for water birds migrating lake-to-lake along the Pacific Flyway as well as the vastness of irrigated agricultural lands to the south.

Credit: Sarah Simpson. Source: Google Earth.

BOX 1A

California's Share of the Colorado River

NO WATER IS DIRECTED INTENTIONALLY TO THE SALTON SEA, yet its existence depends on unintended water transfers from the Colorado River (yellow box). In the federal tiered system of water rights, Palo Verde Irrigation District and the U.S. Bureau of Reclamation have first dibs on California's annual allotment of the Colorado River, which is 4.4 million acre-feet. Next in line is Imperial Irrigation District (IID), which provides water to about 500,000 acres of farmland in the Imperial Valley. Irrigation run-off and drainage from the Imperial Valley provides more than 90 percent of the Sea's annual inflow. A regional water policy called the 2003 Quantification Settlement Agreement authorizes IID to transfer some of its water to urban users in San Diego County and other parts of southern California, limiting water available to the Sea.

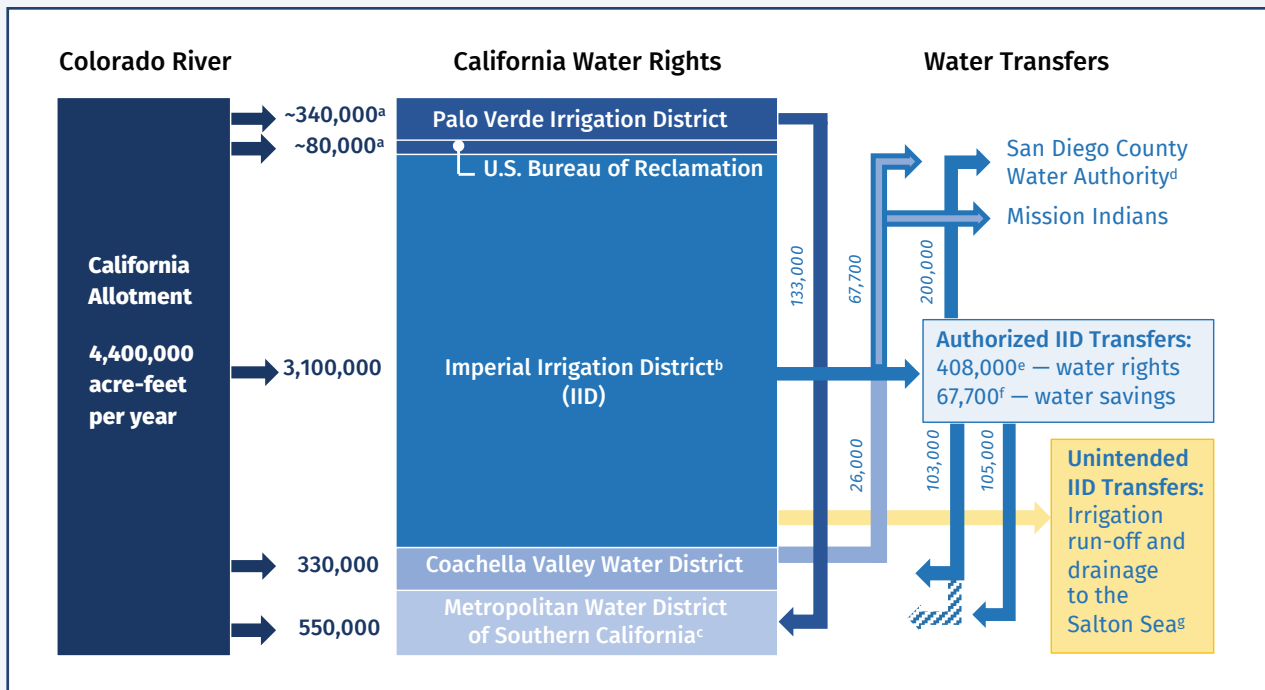


FIGURE 1.2 Annual Colorado River water allotments.

- a** Estimates are based on Palo Verde Irrigation District's right to irrigate 104,500 acres and the Bureau of Reclamation's right to irrigate 25,000 acres for its Yuma Project; agreements do not specify quantity of water or crop type.
- b** The 2003 Quantification Settlement Agreement (QSA) requires Imperial Irrigation District (IID) to stay within its limit of 3.1 million acre-feet per year and authorizes the agency to transfer a specified amount of its water rights and water savings to other agencies. The QSA also set 330,000 acre-feet per year as the maximum allotment for Coachella Valley Water District (CVWD).
- c** If Colorado River inflows to California drop below 4.4 million acre-feet, Metropolitan Water District (MWD) will be the first agency required to reduce usage.
- d** San Diego County Water Authority, which had no rights to California's 4.4-million-acre-feet limit before 2003, is now guaranteed water ahead of MWD.

- e** The QSA authorizes IID to transfer up to 408,000 acre-feet of its water rights to other users, including 103,000 acre-feet to CVWD; if unused, that amount can be transferred instead to MWD (striped arrow).
- f** IID and CVWD achieved annual water savings of 93,700 acre-feet by lining their two main canals to prevent leakage. The QSA stipulates that the water conserved by these projects be passed on to San Diego County Water District and several bands of Mission Indians in San Diego County. IID's All American Canal generates annual water savings of about 67,700 acre-feet; CVWD's Coachella Canal generates annual savings of about 26,000 acre-feet.
- g** The QSA required IID to direct an average of 53,000 acre-feet of mitigation water to the Salton Sea each year from 2003 to 2017, when mitigation transfers ceased.

Credit: Sarah Simpson. Sources: Littleworth and Garner, 2019; San Diego County Water Authority, 2020; Water Education Foundation, 2021.



GREAT EGRETS and other birds foraging in the Imperial Valley south of the Salton Sea. Jonathan Nye

constructed, or freshwater flows could be diverted to the shoreline while allowing the central basins to increase in salinity. Proposals for pumping in fresh water or desalinated water from elsewhere—even possibly from the Gulf of California—are currently under consideration with the Salton Sea Management Program.

People who live in the region initially wanted to preserve the Sea’s shorelines as they were in 2006, or even earlier. The initial, ambitious plan proposed by the Salton Sea Authority included developing the northern half of the Sea as a recreational fishing and boating destination. California deemed that plan too expensive and then took another decade to produce the current Salton Sea management plan, introducing a significantly scaled-back effort limited primarily to the north and south shorelines along with dust mitigation in targeted areas (2020a, b). The \$400 million estimated capital cost to implement the Phase I of the interim Salton Sea Management Plan pales in comparison to the estimated costs associated with declining air and water quality, the endangerment of certain species of fish and birds, and the health threats to those living around the Salton Sea (Cohen, 2014). To the extent state and/or federal governments may assume liability for such damages—either voluntarily or through lawsuits—the mitigation and restoration costs will likely seem insignificant.

Water Budget

COMPLEX MODELS for determining the interactions among the stakeholders of the region and the flows of waters into the Sea need more solid information to fully determine what the future will be for the Salton Sea and how policies should be developed to determine the best strategy for mitigation. Central to a model developed by Kjelland et al. (2019) are two factors: climate and local hydrology. Accordingly, the UCR Salton Sea Task Force has

synthesized outstanding research questions facing this critical region and how the Salton Sea’s changing environment might impact people living in the Imperial and Coachella Valley communities. This report will provide recommendations to managers at state and federal natural resource agencies to assist them in creating timely and relevant research agendas to complement the current management plan, and to California legislators, who will be developing and approving public policy.

California’s current Salton Sea management plan calls for wetland restoration and dust suppression projects across 30,000 acres of shoreline to be implemented by 2028. For example, 755 acres of dust suppression projects were completed in 2020, and construction began on the 4,110-acre Species Conservation Habitat in January 2021 (SSMP, 2021). The northern and southern shores will have diked ponds fed by gravity flow from the three rivers flowing into the Sea, and wetlands will be allowed to develop as the shoreline recedes. These wetlands are intended to have much lower salinity than the main body of the Sea, possibly allowing for the growth of fish populations to attract pelicans and other fish-eating birds; however, the engineering plans are not based on current scientific knowledge of the Sea’s ecosystem.

It is also important to note that current management plans do not call for any Colorado River allocations to be directed to the Sea, nor do they explicitly include any other new sources of water. Without intentional intervention, lake levels will continue to decline, even as wetlands are constructed on exposed lakebed. We are optimistic that this dropping-lake-level trend could be stabilized or partially reversed, however, if future decisions are made to direct water to the Sea. We therefore considered three plausible water budget scenarios facing the Salton Sea over the next two decades: (1) ongoing decline, (2) stabilization, and (3) recovery (Box 1B, Figure 1.3).

Hypothetical Future Scenarios for the Salton Sea

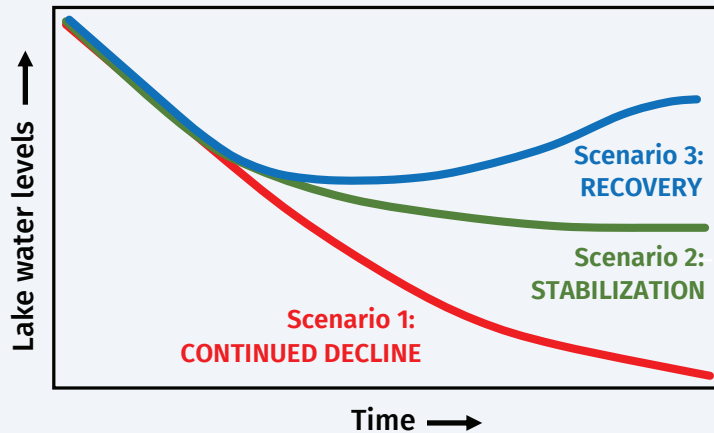


FIGURE 1.3 Three possible outcomes for future Salton Sea water levels: continued decline (red), stabilization (green), and recovery (blue). Credit: Sarah Simpson.

Source: UC Riverside Salton Sea Task Force.

Continued Decline

WITHOUT INTERVENTION, water levels will continue to decline, even as wetlands are constructed on exposed lakebed. The lake level measured on December 31, 2020, was -236.4 feet (SSMP, 2021)—a drop of 8.4 feet since 2003. Without a change in inflows, another five feet of decline is expected by the end of 2025 (SSMP, 2021).

The exposure of additional lakebed on the southern shore has accommodated the start of construction of the 4,110-acre Species Conservation Habitat project, which broke ground in January 2021 (SSMP, 2021). Newly exposed lakebed may also be appropriate for construction of new geothermal power plants and lithium extraction facilities (Chapter 7).

Even as wetlands are constructed along the lakeshore, the Sea will continue to decrease in volume, and the deeper portions will increase in salinity, metals, and pesticides. Dead zones will become more prevalent.

Stabilization

A CHANGE TO CURRENT water policy could intentionally direct a limited amount of Colorado River water to the Salton Sea, possibly by purchasing portions of river allocations currently devoted to agriculture (Levers et al., 2020). Such an effort could slow the decline, possibly stabilizing lake level at some point lower than it is today.

For this scenario to be effective, it would be critical to identify what specific lake level is necessary to avoid exposing the most toxic lakebed sediments, which concentrate in the deeper portions of the Sea (Chapter 3).

The Salton Sea Management Program projects the decline in lake levels will stabilize around -255 feet by 2030, but the computer model they use does not account for changing subsurface water flows, which may explain unexpected declines since 1995. Accurately projecting future water levels requires careful assessment of lake-groundwater interactions (Chapter 2).

Recovery

WITH LONG-RANGE PLANNING and significant capital investment, a significant new source of water could be pumped into the Salton Sea or adjacent historic wetlands from the Gulf of California or local groundwater sources. The Salton Sea Management Program is currently assessing water importation proposals to inform their long-term management plan, due for completion by the end of 2022 (SSMP, 2021). Another recovery option would be to negotiate significant Colorado River water purchases to direct to the Sea (Levers et al., 2020).

A goal of some stakeholders in the region is to increase Salton Sea water volume to the average historic water levels (1980–1995), which were stable at approximately -228 feet.

Recovery schemes that rely on imported water would take at least ten years to implement, so actions to mitigate human health hazards and ecological collapse must be made in the meantime.

Even if more water is directed to the Sea, there may be additional challenges to stabilizing lake water levels (Chapter 2). Overall Colorado River inflows may decline soon owing to lower snowpack and population growth upstream, for example. Higher evaporation rates are also expected as climate warms. There could also be unforeseen changes in subsurface water flow around the Sea, particularly if adjacent aquifers are pumped to supply water to the growing population expected in the Coachella Valley, to restore wetlands around the margins of the Sea, or to facilitate geothermal mineral extraction.

Motivations

THE MAJOR IMPETUS for promoting an active university research program at the Salton Sea is health problems due to the Sea's unstable ecology (Chapter 6). The population's average income is less than \$35,000 annually, with the demographics roughly 80% Hispanic, 13.7% White/Hispanic, and 10.5% Black Americans (Marshall, 2017). It is not difficult to surmise that health problems may increase as the Sea's shorelines widen. Declining water quantity and quality is promoting harmful algal blooms that can be toxic to wildlife and people. Southern California deserts are projected to face increased temperatures and lower rainfall. Directly north, Palm Desert, Palm Springs and the other desert cities are home to 350,000 residents who enjoy clean desert air. Potential future Salton Sea scenarios may jeopardize that outcome.

Dust always affects air quality in deserts; however, in the Salton Sea region the chemical composition of that dust could be contributing to the particularly high incidence of asthma in children. Asthma from inhalation of dust has negative impacts on children (20% are estimated to have asthma) in the area as well as adults. Because Colorado River water has higher than average concentra-

tions of metals such as selenium and molybdenum, dust originating from exposed shorelines could consist of higher, potentially toxic concentrations of metals (Buck et al., 2011; Frie et al., 2019; SSMP 2021). With lower lake levels, the unique salt crust that paves the bottom of the Sea will be revealed. Currently it is unknown whether this crust will be a stable surface or the degree to which it will contribute to particulate loads in the air. Wind patterns in the Salton Basin are variable and seasonal, resulting in dust composition that will be variable as well. The full complexity of atmospheric patterns and geochemistry of dust particles remains unknown (Chapter 4).

As the salinity increases, organisms living in the Salton Sea must adapt to living in extreme environments (Chapter 5). Tilapia—the major fish species remaining in the Sea—is struggling to survive as salinity has surpassed 74 parts per thousand, more than double the salinity of the Pacific Ocean (SSMP, 2021). The endangered desert pupfish will find its habitats increasingly isolated from one another. Bird populations that rely on these fish for food, such as brown and white pelicans, are declining, and migratory species from across North America are affected adversely (Lyons et al., 2018). Over the last 115 years since the current Salton Sea formed, migratory birds by the millions have made it an important stopover (Shuford et al., 2002). Some of the more than 400 bird species are on their way south along the Pacific Flyway, while others arriving from Canada and northern United States spend the winter months at the Salton Sea feeding on fish and invertebrates. Because wetlands have been destroyed over much of California, including Owens Lake, the Salton Sea has—now more than ever—become one of the most important habitats for these birds (Figure 1.1).

The Sea also experiences extremes in chemical inputs, particularly as nutrient-rich and pesticide-laden

How will the cultural connections of the Torres-Martinez Desert Cahuilla community be affected by changes to the Salton Sea?

Although the modern Salton Sea is the result of an “accident” caused by humans, the Salton Basin has been the location of an ephemeral body of water going back thousands of years. The Torres Martinez Desert Cahuilla Indians have a long history in the area. Their federal reserva-

tion, established in 1876, is now partly flooded by the current Salton Sea. Approximately 40% of their 24,024 acres of land lies under the northern portion of the Sea, near Mecca. The concerns of this group should be addressed as lakebed exposure and mitigation plans unfold.

runoff from the irrigated agricultural fields of the Imperial Valley is its primary source of inflows. Excess nutrients cause algal blooms with species known to contain toxic compounds from cyanobacteria and dinoflagellates. As the species die off, oxygen depletion in the shallow waters occurs, creating dead zones that will become longer and more frequent as water volume decreases (Chapter 3). These anoxic conditions, particularly in summer and early fall, promote the activity of microorganisms that produce unpleasant toxic gases—hydrogen sulfide, for example—that emanate from the lake during windy days. The lack of oxygen also causes changes in the chemical state of toxic metals, like selenium and molybdenum. As the lakeshore dries further, these metals could be incorporated into a toxic dust. Alternatively, aerosol droplets of surface water could form small particles spreading metals in a much wider pattern throughout the region.

As the costs for mitigation and restoration of the Sea begin to be realized, funding for these projects will come under scrutiny. The region holds two possibilities for enhancing funding: increased geothermal power generation and lithium extraction (Chapter 7). California's energy policy requires 100% renewable energy sources by 2045, yet solar and wind energy cannot provide a full solution to power the grid during night or low-wind conditions. Geothermal energy can be supplied on a continuous basis with excess energy converted to hydrogen to be stored until needed (Elders et al., 2019). Furthermore, geothermal brines contain economic concentrations of lithium, a metal required for batteries and other industrial uses (McKibben and Williams, 1989). The region's mineral and energy wealth could provide a stream of revenue needed for an economically feasible environmental outcome, but the idea needs further study, including an assessment of the potential environmental impacts from increased geothermal plants and mineral extraction.

Research Needs

FURTHER RESEARCH is needed to develop a deeper understanding of how the Salton Sea system functions now and in the future (Box 1C). More sustainable approaches for mitigating toxic dust risk are needed, as well as to ensure birds continue to have a home in the area. Creating a competitive, interdisciplinary research program open to researchers at universities, non-profits, and government agencies would provide critical guidance to policymakers, government scientists, and contractors.

Outstanding Concerns

BOX 1C

- What is needed to produce an accurate hydrological model that reflects the Salton Sea's status both today and in the future under different climate change scenarios and water supply and demand outcomes?
- Does the Salton Sea's playa or waters contribute more to the dust in one region relative to another? Which communities are most heavily impacted?
- How do the Salton Sea's shoreline crusts form? How stable are they, and what is their potential toxicity? Do they affect air quality in the region?
- How is the current Salton Sea ecosystem functioning today? What is its future?
- What will be the impact on biodiversity in the Sea and surrounding environments?
- How will the ecosystem in constructed marshlands relate to natural marshlands and adjacent nearshore communities?
- How has the metal (e.g., selenium) and nutrient cycling in Salton Sea's briny water habitats changed over the past 20 years? How will these biogeochemical cycles change with evolving lake levels?
- What will be the broad scale impacts if water is diverted back to the Salton Sea (e.g., development of San Diego, regional advantages, costs, and impacts of mitigation efforts to contain hydrogen sulfide releases)?
- What is the extent of the health problems in the region related to the Salton Sea?
- How does the Sea's unstable ecology affect human health?
- What is the connection between current health and past exposures to dust and noxious gases?
- How will the cultural connections of the Torres-Martinez Desert Cahuilla community be affected by changes to the Salton Sea?
- What is the potential for geothermal energy and mineral extraction (e.g., lithium) in this area? Are there other resources in this area that might improve the region's economy?
- What are the potential environmental impacts from increased geothermal plants and mineral extraction?

2

Watershed Hydrology

Hydrology and Water Resources in the Salton Sea Watershed

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HIGHLIGHTS

- The Salton Sea watershed in southern California and northern Mexico is one of the most productive agricultural regions in the United States.
- Salton Sea's water balance is controlled by complex interactions among agricultural water management practices, evaporation, and surface water-groundwater interactions.
- Survival of the Salton Sea is tied primarily to agricultural runoff and drainage from major agricultural regions in the basin— Imperial and Mexicali Valleys to the south and Coachella Valley to the north—and their associated water management decisions.
- No comprehensive assessment of lake-groundwater exchange has ever been performed. Consequently, efforts to make informed management decisions with an understanding of the consequences for lake water levels are severely limited.

The Salton Sea watershed is a closed (endorheic) basin with an area of 8417.4 mi² (21,801 km²), located in Southern California and the northern part of Mexicali Valley in Mexico (Figure 2.1). The watershed is one of the most productive agricultural regions in the United States and includes the Salton Sea, the largest inland terminal lake in California, with an area of 334 mi² (865 km²) (Yao et al., 2019). The watershed is

bounded by the Orocopia Mountain range in the northeast, the Santa Rosa Mountain range in the northwest, and the Chocolate Mountain range and the peninsular mountain ranges of southern and Baja California to the east and southwest, respectively (Tompson, 2016).

Nearly half of endorheic basins around the world, including the Salton Sea, are in water-stressed regions (Wada et al., 2011) where the lake storage is maintained

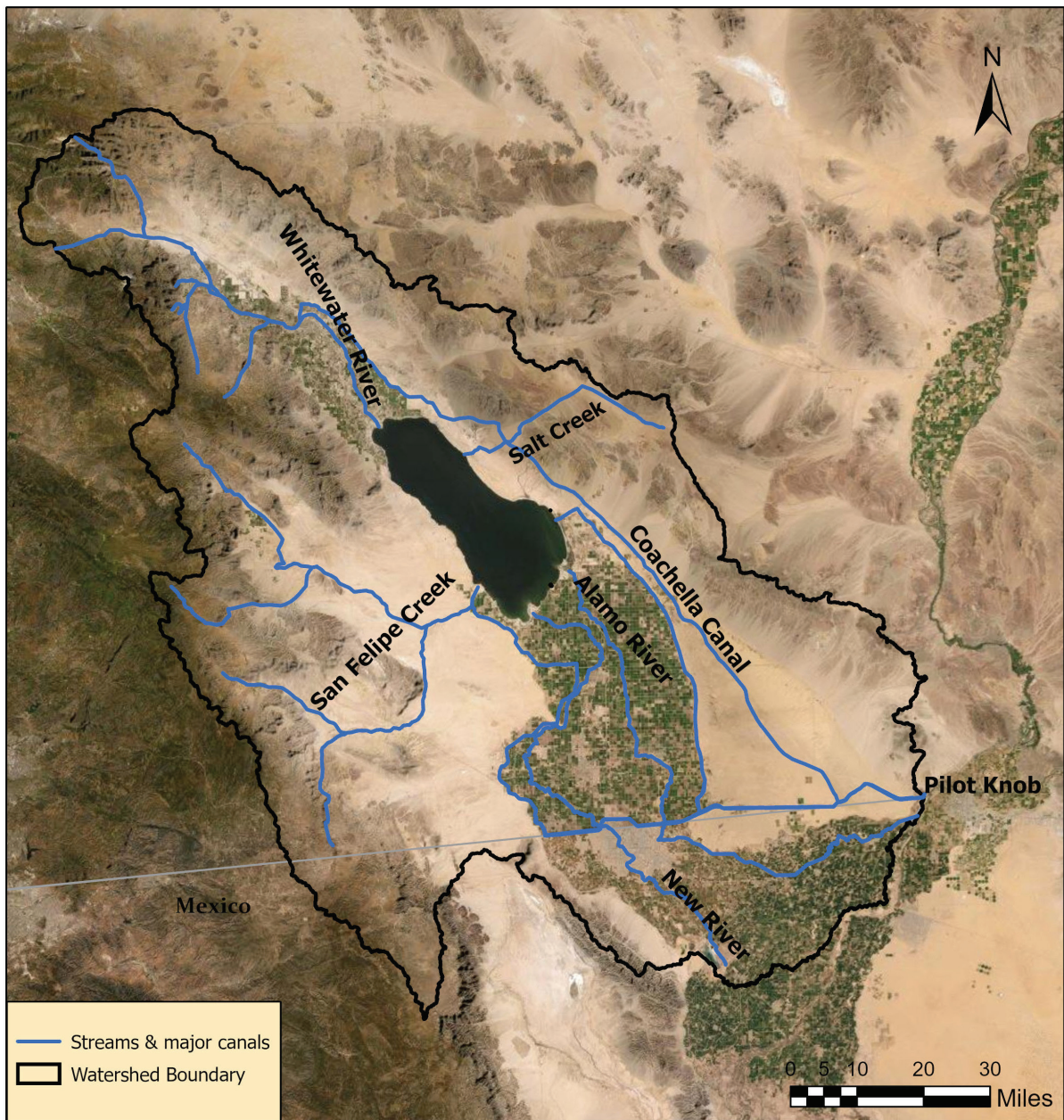


FIGURE 2.1 Location of the Salton Sea watershed and major streams and drainages. Credit: Hoori Ajami. Sources: USGS, ESRI.

by the balance between inflows (i.e., precipitation, surface runoff and groundwater inflow) and outflows (i.e., evaporation and discharge to groundwater). Recent analysis of remote sensing data and hydrologic modeling indicate a widespread water loss in endorheic basins globally during 2002–2016. The lakes’ storage losses are attributed to losses in groundwater, surface water, and soil moisture caused by climate variability and water management (Wang et al., 2018). The climate of the Salton Sea watershed is hot and arid with mean annual precipitation of less than 6 inches per year

(147.9 mm/yr), and high summer temperatures that can reach up to 115°F (49°C). Annual precipitation in the watershed during 1980–2018 indicates cycles of wet and dry periods relative to the long-term mean annual precipitation, which in recent decade since 2010 has been lower than the 39-year average (Figure 2.2).

Much of the concern about the Salton Sea in the 20th century was related to rising shorelines, but the lake trajectory is different today. During the period 1980–2018, average Colorado River inflows to the Salton Sea watershed at Pilot Knob Hydroelectric Plant were

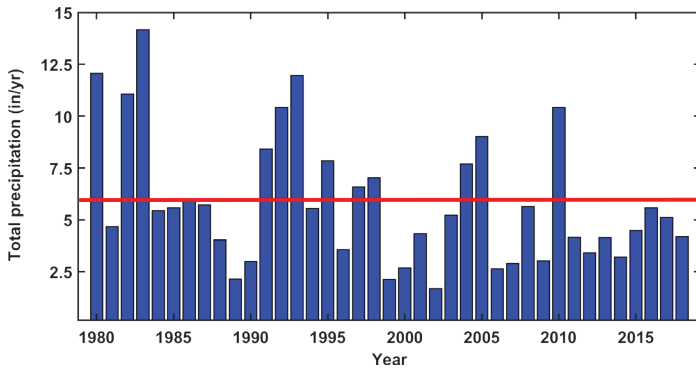


FIGURE 2.2 Annual precipitation in the Salton Sea watershed from a 4-kilometer resolution PRISM dataset. Annual precipitation in the most recent decade since 2010 has been lower than the 39-year average (red line). Credit: Hoori Ajami. Source: The Parameter-elevation Regressions on Independent Slopes Model (PRISM) Climate Group at Oregon State University.

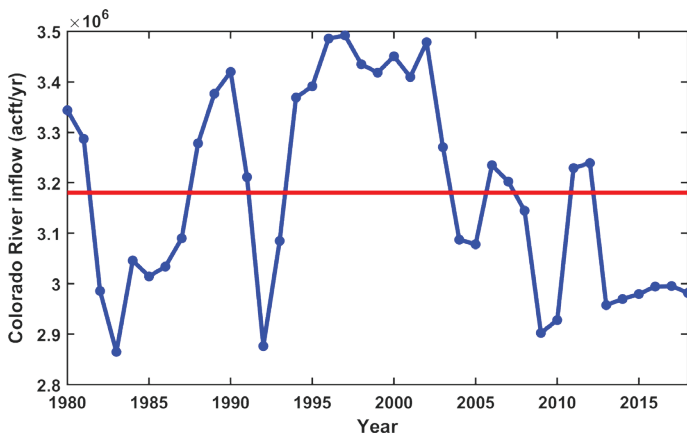


FIGURE 2.3 Annual Colorado River inflows at Pilot Knob (USGS 09527500). The red line shows a 39-year mean annual inflow. Credit: Hoori Ajami. Source: USGS.

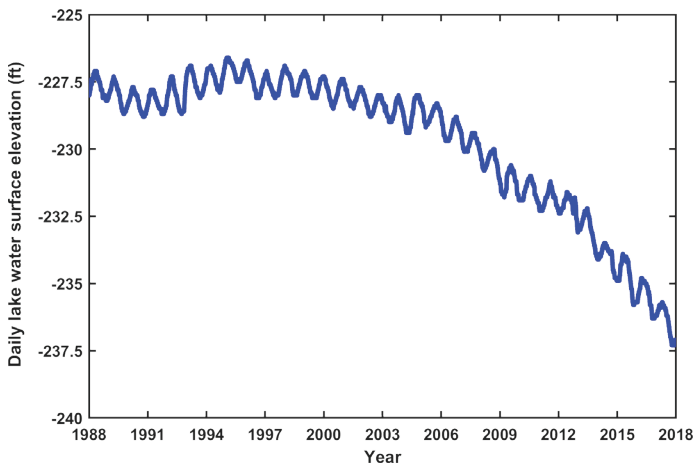


FIGURE 2.4 Daily lake water level observations at the Salton Sea near Westmorland (USGS 10254005) indicate a total lake water level decline of 8.7 ft (2.65 m) since 1988. Credit: Hoori Ajami. Sources: USGS; National Geodetic Vertical Datum of 1929.

3.2×10^6 ac-ft/yr (3.95 km^3 /yr) (Figure 2.3); however, these deliveries have declined in recent years (Box 2A). Like other endorheic basins, Salton Sea has experienced a significant decline in lake water levels. Lake level observations near Westmorland indicate a total decline of 8.7 ft (2.65 m) since 1988 (Figure 2.4). Similarly, analysis of satellite imagery over the same period shows a decrease in lake area from 369.1 mi^2 to 339.5 mi^2 (Yao et al., 2019). Significant declines in lake water level and area between 1995 and 2018 coincide with declining trends in annual inflows to the Salton Sea, suggesting that lake-level declines may accelerate with future increases in air temperature and higher evaporation rates. Any further lake-level declines should be a top human health and environmental concern, as they will likely amplify crises already unfolding with lake water quality (Chapter 3), regional air quality due to lakebed exposure (Chapter 4), and ecological collapse of the unstable lake ecosystem (Chapter 5).

Surface Water

SURVIVAL OF THE SALTON SEA is tied primarily to irrigation runoff and drainage from major agricultural regions in the basin: Coachella Valley to the north and Imperial and Mexicali Valleys to the south. Agricultural lands cover 15% of the watershed area (1158 mi^2) based on the 2001 National Land Cover dataset. The abundant agricultural productivity in this arid watershed is dependent on the conveyed Colorado River inflows via the All American Canal to the US portion of the watershed. Morelos Dam, located on the Mexico-Arizona border, diverts Colorado River water to the Mexican portion of the Salton Sea Watershed with a mean annual flow of 1.86×10^6 ac-ft/yr (2.3 km^3 /yr) (1980–2005). An extensive system of irrigation canals on the northern part of the All American Canal distributes water across the agricultural fields in the Imperial Valley and Coachella Valley irrigation districts. On average, 10 percent of the Colorado River inflow is transferred via the Coachella canal to the agricultural fields of the Coachella Valley, and the rest is transferred to the Imperial Valley.

Although most of the Colorado River inflows are used for irrigation, a small proportion is allocated for industrial and residential users. Irrigation water not used by crop evapotranspiration drains to the Salton Sea via the New and Alamo rivers in the south and

Salton Sea Origins and History

BOX 2A

1900s — The origin of the Salton Sea today is a result of uncontrolled Colorado River floods that occurred in 1905–07. During this period, continuous Colorado River inflows caused the lake water level to rise and reach a depth of 195 ft below sea level (-195 ft) (Figure 2.5). Starting in February 1907 with the closure of the break on the Colorado River’s levee, lake water levels started to decline because evaporation exceeded inflows.

1920s — Irrigation development in the Imperial and Mexicali Valleys in the 1920s resulted in agricultural return inflows to become equal to the lake evaporation rates, subsequently stabilizing the lake water level to -250 ft until 1925 (Blaney, 1955). Due to safety concerns, the Federal Government issued an Executive order in 1928 to limit entry of public lands to regions below -220 ft elevation and designate any area below -220 ft as the Public Water Reserve.

1930s — After water shortages in 1931 and 1934 caused a temporary decline in the lake water level, Salton Sea’s surface elevation began to increase once more, raising concerns regarding encroachment and damage to the neighboring lands.

1950s — In 1950, when the lake level was -238 ft, projections indicated lake level would rise and stabilize at -220 ft by 1980, and monitoring efforts were focused on accurate estimation of lake evaporation rate. By 1954, further expansion of irrigated agriculture and several severe storm events had caused lake water levels to reach -235.8 ft (Figure 2.5).

1980s–2010s — During the 1980–2018 period, the mean annual Colorado River inflows to the Salton

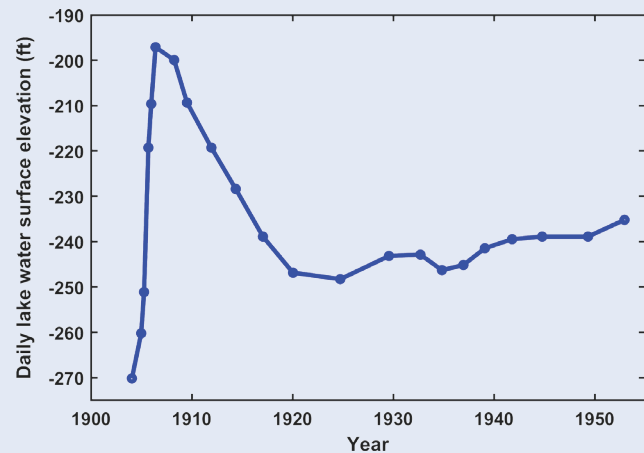


FIGURE 2.5 Historic water levels in the Salton Sea, from its formation due to uncontrolled Colorado River floods 1905–1907 through its recreational heyday in the 1950s.

Credit: Blaney, 1955.

Sea watershed at Pilot Knob Hydroelectric Plant were 3.2×10^6 ac-ft/yr ($3.95 \text{ km}^3/\text{yr}$); however, these deliveries have declined in recent years. In 2003, the Imperial Irrigation District began transferring water from agricultural users in the Imperial Valley to municipal users in coastal southern California. To reduce the impact of the water transfer on the Salton Sea, “mitigation water” was temporarily directed to the Salton Sea; however, delivery of mitigation water ceased on December 31, 2017 (Barnum et al., 2017).

2020s — The future of Colorado River inflows to the Sea is highly uncertain. Survival of the Salton Sea today is tied primarily to irrigation runoff and drainage from major agricultural regions in the basin and their associated water management decisions.

the Whitewater River in the north as well as via many agricultural drains that discharge directly into the Sea. Continuous daily flow measurements at three US Geological Survey (USGS) gaging stations at the perimeter of the Salton Sea indicate total mean annual inflows of 1.1×10^6 ac-ft/yr ($1.35 \text{ km}^3/\text{yr}$) to the Salton Sea during 1980–2018 period. About 95% of the total measured inflows to the Salton Sea originates from the Alamo and New rivers in the south with the rest from the White-

water River in the north (Figure 2.6). The Alamo and New rivers originate from Mexico, and their flows at the international boundary are 2,100–3,620 ac-ft/yr and 108,400–145,000 ac-ft/yr, respectively (CA Water Boards, 2020). According to the Imperial Irrigation District, the agricultural drains inflows to the Salton Sea are estimated at 95,000 ac-ft/yr (CH2M Hill, 2018); however, no public dataset is available to determine the long-term variability of drain inflows. Other than direct precipi-

tation and irrigation runoff, the only other sources of water to the Salton Sea are ephemeral flows from dry washes including Salt Creek in the east and San Felipe Creek in the west and groundwater.

Groundwater

THE EXACT CONTRIBUTION of groundwater inflow to the Salton Sea is uncertain. Estimates vary between 15,000–50,000 ac-ft/yr (Case III et al., 2013; Hely et al., 1966). Hely et al. (1966) estimates of groundwater inflows to the lake are: 30,000 ac-ft/yr from the Coachella Valley, 10,000 ac-ft/yr from the San Felipe Creek and less than 2,000 ac-ft/yr from the Imperial Valley. It is also possible that subsurface lake discharges into groundwater aquifers—representing an important loss of lake water that is not considered explicitly in the models informing current management plans.

Groundwater in the Salton Sea watershed consists of shallow and deeper aquifer systems that extend to 2,000 ft and 20,000 ft in depth, respectively (Tompson et al., 2008). There are seven groundwater basins around the lake: Coachella Valley, Chocolate Valley, Clark-Ocotillo Valley, East Salton Sea Basin, West Salton Sea Basin, Orocopia Valley, and Imperial Valley (Case III et al., 2013). In the Imperial Valley, shallow groundwater aquifers in the perimeter of the valley are recharged by the mountain runoff and are more productive than the aquifers in the central region with

low permeability sediments. The quality of groundwater is highly variable, and in certain aquifers salinity is high, resulting in poor water quality for irrigation.

Groundwater has been a major water source for agricultural, municipal and domestic users in the Coachella Valley since the 1920s. While importation of the Colorado River water to the Coachella Valley in 1949 reduced groundwater level declines until the 1970s, increased demand for water and subsequent groundwater pumping caused groundwater level declines of up to 98.4 ft (30 m) in some locations (Sneed et al., 2014). Interferometric Synthetic Aperture Radar (InSAR) measurements during 1995–2010 indicate a land subsidence rate of up to 0.15 ft/yr (45 mm/yr) (Sneed et al., 2014). Given any further land subsidence can significantly impact infrastructure in the region, the Coachella Valley Water District has been developing managed aquifer recharge projects to reduce groundwater level declines. Currently, the Coachella Valley groundwater basin is classified as one of the state’s medium priority basins according to the recent groundwater basin classification under the Sustainable Groundwater Management Act by the California Department of Water Resources. A projected 82% increase in population by 2030 is expected to further impact groundwater resources of the Coachella Valley (DWR, 2020).

The natural groundwater recharge rate in this arid watershed is very low except at the mountain front re-

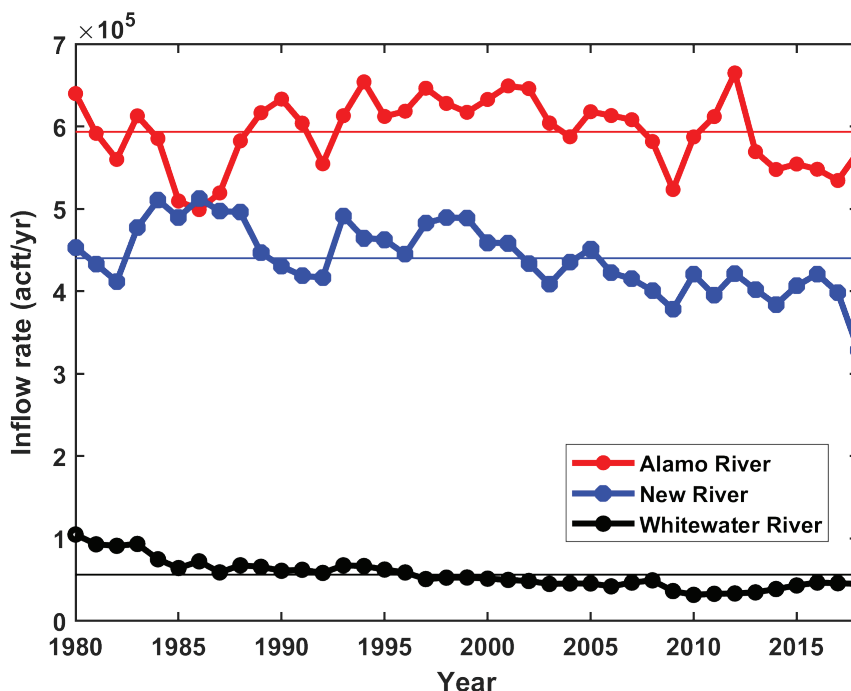


FIGURE 2.6 Annual river inflows to the Salton Sea as measured by the USGS gauges at the mouth of Alamo River (USGS 10254730), New River (USGS 10255550) and Whitewater River (USGS 10259540). Solid lines indicate 39-year mean annual inflows. Significant declines in lake water level and area between 1995 and 2018 coincide with significant declining trends in annual inflows to the Salton Sea, suggesting further declines in lake level with future increases in air temperature and higher evaporation rates. Credit: Hoori Ajami. Source: USGS.

Climate Change Impacts

BOX 2B

PROJECTED INCREASES in global average temperature and the resulting reduction in snowpack in the Rocky Mountains are expected to decrease Colorado River inflows in the future. Depending on the global climate model (GCM) projections and emission scenarios, Colorado River flows will decline by 35–55 percent at the end of century (Udall and Overpeck, 2017), making less water available to downstream users, including Californians. Although Colorado River water allocations are based on a complex set of agreements, some users may need to reduce water use if the Colorado River shortages continue.

The Colorado River Drought Contingency Plan is one of the most recent provisions introduced to address water shortages among the seven Western states, including California, with rights to Colorado River water. Projected mean annual precipitation for the Inland desert region of California that encompasses the Salton Sea indicates a drier mid-century (2035–2064) and a wetter late-century (2070–2090) relative to the historic period (1951–1980) (RCP 8.5) based on the 10 GCMs representative of California’s climate (Hopkins et al., 2018). Although uncertainty of precipitation projections from GCMs is large, future climate change impact assessments should use results from multiple climate models and implement coupled surface water–groundwater models to simulate dynamic feedback processes between changes in land cover, land use, groundwater recharge, and surface runoff in response to changes in precipitation, temperature and human water use.

gions near the Coachella Valley and West Mesa, both of which are recharged by the mountain runoff. Other sources of recharge in the watershed emanate from irrigation recharge in agricultural areas (314,000 ac-ft/yr from the Coachella Valley and up to 250,000 ac-ft/yr from the Imperial Valley) and localized recharge from the All American Canal, Coachella Canal and other canals and reaches in the watershed (Tompson et al., 2008). Although leakage from the All American Canal and Coachella Canal was high in early years, subsequent lining of these canals in 2007 and 1980, respectively, reduced recharge to the watershed (Coes et al., 2015). No accurate long-term estimate of groundwater recharge is available, and future investigations should focus on estimating groundwater recharge from mountain runoff and irrigation. It is highly recommended to develop coupled surface water–groundwater models to better understand hydrologic processes and to design conjunctive surface water–groundwater management strategies to reduce the impacts of water transfers and agriculture on the Salton Sea.

Uncertain Future

FUTURE SALTON SEA LAKE LEVELS are highly uncertain. Colorado River deliveries are projected to decline, and there are serious drawbacks to the models currently in use to predict future lake water levels. The Imper-

al Irrigation District (IID) SALSA2 model, which is the basis for the Salton Sea Management Program’s projected estimates for Salton Sea hydrology and salinity conditions, predicts that the Salton Sea inflow rates will stabilize around 700,000 ac-ft/yr by 2045 and will result in a lake water level of -260 ft (CH2M Hill, 2018). However, it is expected that the Colorado River flows will decline in the future due to population growth and reduced snowpack and prolonged droughts from climate change (Udall and Overpeck, 2017) (Box 2B). These shortages could result in potential water cutbacks to lower basins states as outlined in the Colorado River Drought Contingency Plan. Furthermore, competing demand among urban and agricultural users and natural ecosystems for water make future projections of lake water level highly uncertain.

The drawback of using statistically based models such as SALSA2 for these predictions is that they are trained based on historic data and do not consider non-stationary, hydrologic response due to changes in climate or land cover. Furthermore, detailed information about the SALSA2 model equations and parameters are not publicly available (CH2M Hill, 2018) and cannot be verified independently.

Alternative modeling approaches such as the Salton Sea Stochastic Simulation model consider a semi-distributed modeling approach to understand system



THE NEW RIVER, with abundant growth on its levees, near its terminus in the Salton Sea. Jonathan Nye

dynamics using empirical parameterization (Kjelland and Swannack, 2018). Although these types of models provide an overall understanding of the system behavior, they are not physically based and cannot be used as predictive tools for a wide range of scenarios (Kjelland et al., 2019). Furthermore, their parameterization does not allow assessing the impacts of changes in spatial distribution of crop types or canals.

In summary, it is extremely difficult to project future lake water levels and the area of exposed playa given models currently in use combined with the hydrologic and socio-economic complexities surrounding the Salton Sea. Lake-groundwater interactions are complex, and observational data are not available to quantify the exchange fluxes between groundwater aquifers and the lake. Furthermore, future streamflow and changes in water management practices and cropping patterns are uncertain. Any predictions about future lake levels require improving hydrologic models and climate change projections for the region and engaging stakeholders for scenario development.

Research Needs

THE LIVELIHOOD OF THIS ARID WATERSHED is impacted by projected declines in the Colorado River flows, com-

peting demands among urban and agricultural users and natural ecosystems for water, and increases in the exposed dry lakebed impacting human health. The key science need is to define the optimum lake water level to reduce lakebed dust and maintain wildlife habitat while recognizing the intersection between the Salton Sea and agricultural water use in the watershed.

Previous research efforts were focused on accurately estimating lake evaporation to determine the balance between inflows and outflows (Hely et al., 1966). Answering this question today requires understanding of the subsurface hydrologic processes and lake-groundwater interactions through implementation of several key tasks (Box 2C):

- Determine lake-groundwater connectivity by drilling monitoring wells perpendicular to the lake perimeter at several key locations.
- Characterize hydraulic parameters of the aquifers located inside the watershed.
- Quantify subsurface drainage rates to the lake from neighboring agricultural lands.
- Develop a distributed coupled surface water-groundwater model to understand and quantify lake water level dynamics in response to changes in Colorado River inflows, climate change

CURRENT RESEARCH: Lake-Groundwater Interactions

BOX 2C

UNDERSTANDING WATER FLOW both above ground and in the subsurface is crucial to determining optimal Salton Sea water levels and designing effective mitigation strategies. With an award from the National Science Foundation's Innovations at the Nexus of Food, Energy and Water Systems (INFEWS) program, researchers at UC Riverside are setting up a coupled surface water-groundwater model for the Salton Sea watershed using the SWAT-MODFLOW package (Ajami et al., 2020). New estimates for water exchange between the lake and adjacent groundwater aquifers should be available soon and may help explain unexpected water level declines in recent years.

One of the major challenges of this ongoing hydrologic investigation is lack of access to datasets collected by various agencies in the Salton Sea watershed (Ajami et al., 2020). Future efforts should focus on setting up a public data repository for the watershed and implementing adaptive management programs. Success of such programs requires engaging various stakeholders in design and implementation of the management scenarios while considering climate change impacts on water resources.

and agriculture management practices, and groundwater use.

- Involve stakeholders in developing alternative management scenarios to inform decision making and mitigation strategies.
- Assess feasibility of pumping saline groundwater to maintain lake level.

These tasks will be crucial in answering science questions identified a decade ago in the Hydrology and Water Quality focused technical group formed to facilitate restoration efforts at the Salton Sea (Case III et al., 2013). As hydrologic processes are likely to be very different depending on which scenario plays out in the coming decade, perhaps the main question that we need to ask today is whether recent investments for the Salton Sea restoration will solve the problems associated with dust, the ecosystem and agricultural production. By focusing on advanced monitoring and hydrologic modeling efforts to save the Sea, it may be possible to maintain agricultural production and reduce land subsidence and toxic dust exposure, as well as to provide a healthy environment for the communities living in this region.

Failure to invest resources in these research efforts will increase the likelihood of scenario 1 (continued decline) leading to a crisis: The lake water levels will continue to decline as the current trend in lake water levels indicates. The decline could possibly worsen due to changes in subsurface water flows, higher evaporation rates, or lower Colorado River inflows owing to

a lower snowpack and population growth or changes in water allocations due to droughts. Alternatively, we can intentionally direct water to the Sea (e.g., water purchases, wetland impoundments, or imported water from the Gulf of California) to stabilize lake levels (scenario 2) or possibly even raise water levels (scenario 3, recovery). These goals should be informed by developing coupled/integrated surface water-groundwater models and setting-up extensive monitoring network to assess effectiveness of our management decisions and adapt our approach based on the system response to reverse the current declining trends in the Sea. The main science question for water importation is how much water needs to be diverted from other sources or users to raise and maintain lake water level at an optimum level? Furthermore, what is the optimum level for the Salton Sea to maintain human health and wildlife?

We can be optimistic that Colorado River inflows will remain at their current rates or slightly lower in future and that lake water levels will eventually stabilize (scenario 2, stabilization). Defining the "optimal" lake level will depend on the costs of achieving that outcome, which means that the costs and benefits of various mitigation strategies will need to be explored and understood, including strategies such as water diversion, wetland construction, reduced pumping, increased fallowing and water importation. Above all, understanding the spatial dimension of the problem is crucial to determining optimal lakes levels and effective mitigation responses.

3

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 addition, 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-

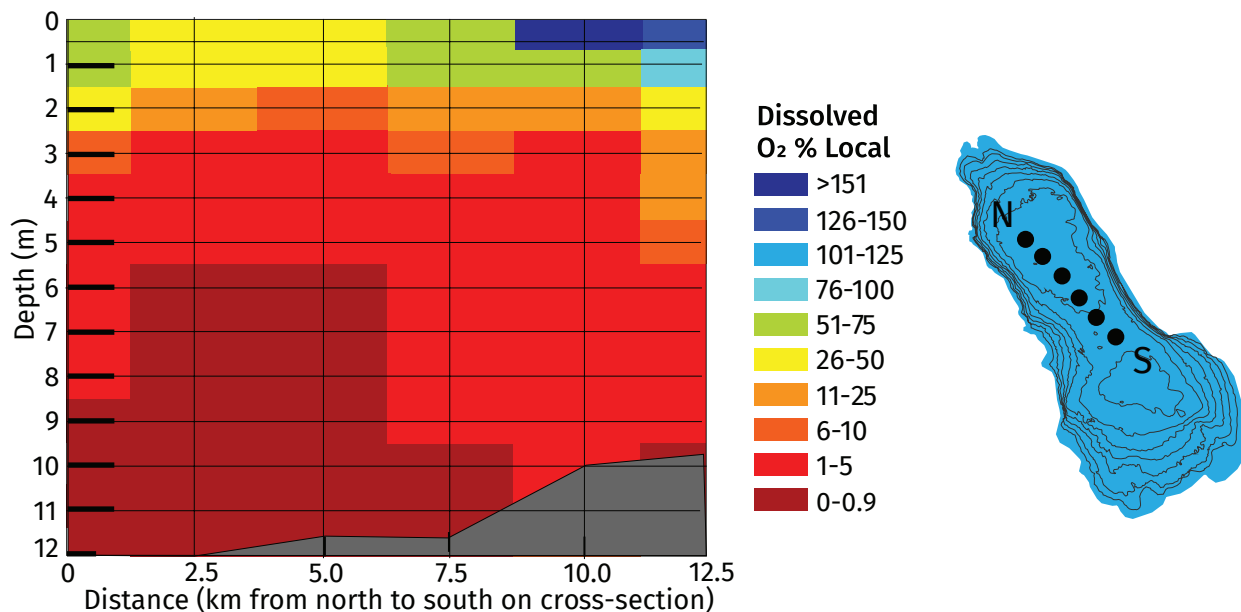
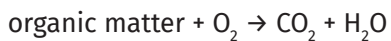


Figure 3.1 Dissolved oxygen sampled at horizontal transects in the northern portion of the lake during an upwelling event in August 2020. The general trend shows that oxygen (O_2) decreases with depth and anoxia—defined as less than 1% dissolved O_2 —is persistent in the deepest waters. Credit: Caroline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



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



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 transport of fine-grained toxic dust to distant populated areas (see Chapter 4)?

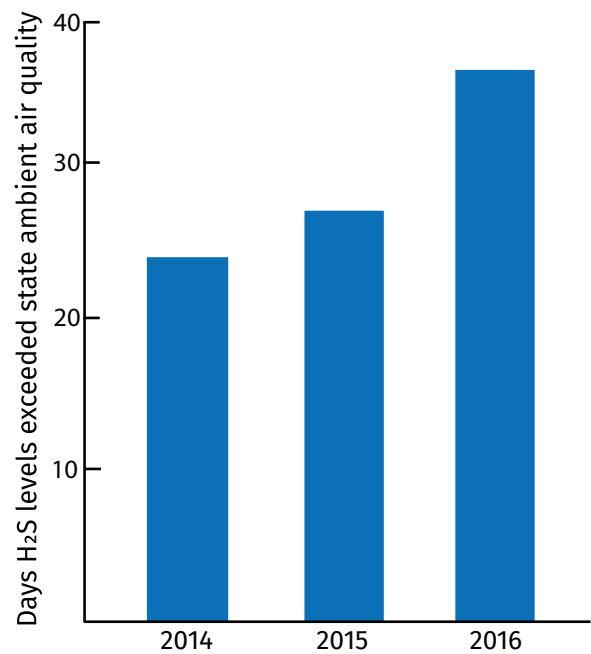


Figure 3.2 The number of days when hydrogen sulfide (H_2S) levels surpassed state ambient air quality standard of 30 parts per billion per hour at the Near-Shore Air Quality Monitoring Station. Credit: Caroline Hung. Source: South Coast Air Quality Management District.

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 en-

riched 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.

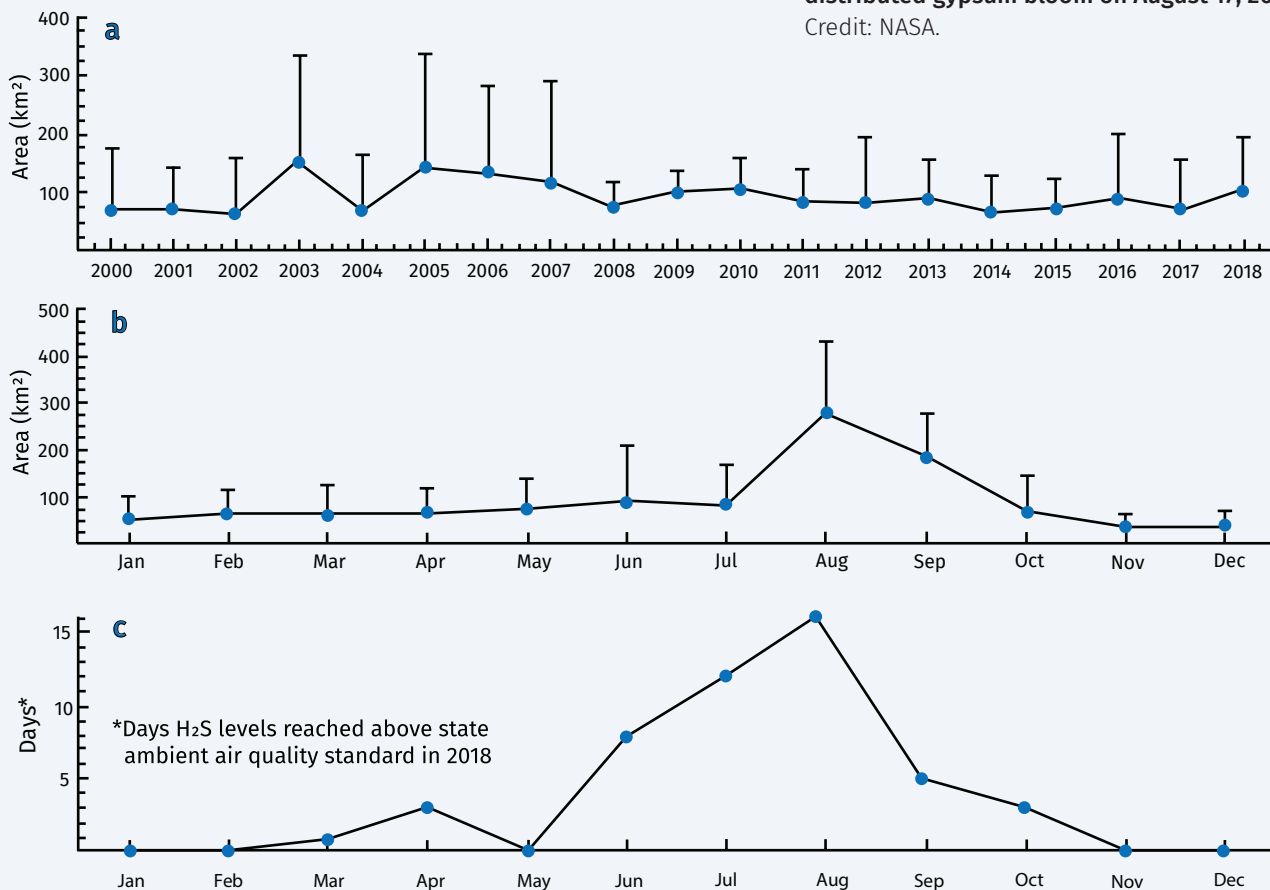


Figure 3.4 Gypsum bloom area in the Salton Sea from 2000 to 2018 presented as annual (a) and monthly (b) averages (Adapted from Ma et al., 2020). The monthly trend for days when H₂S concentration exceeds state ambient air quality standards (>30 ppb) at the Near-Shore site is shown in (c). Data for (c) 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 Víaú, 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.

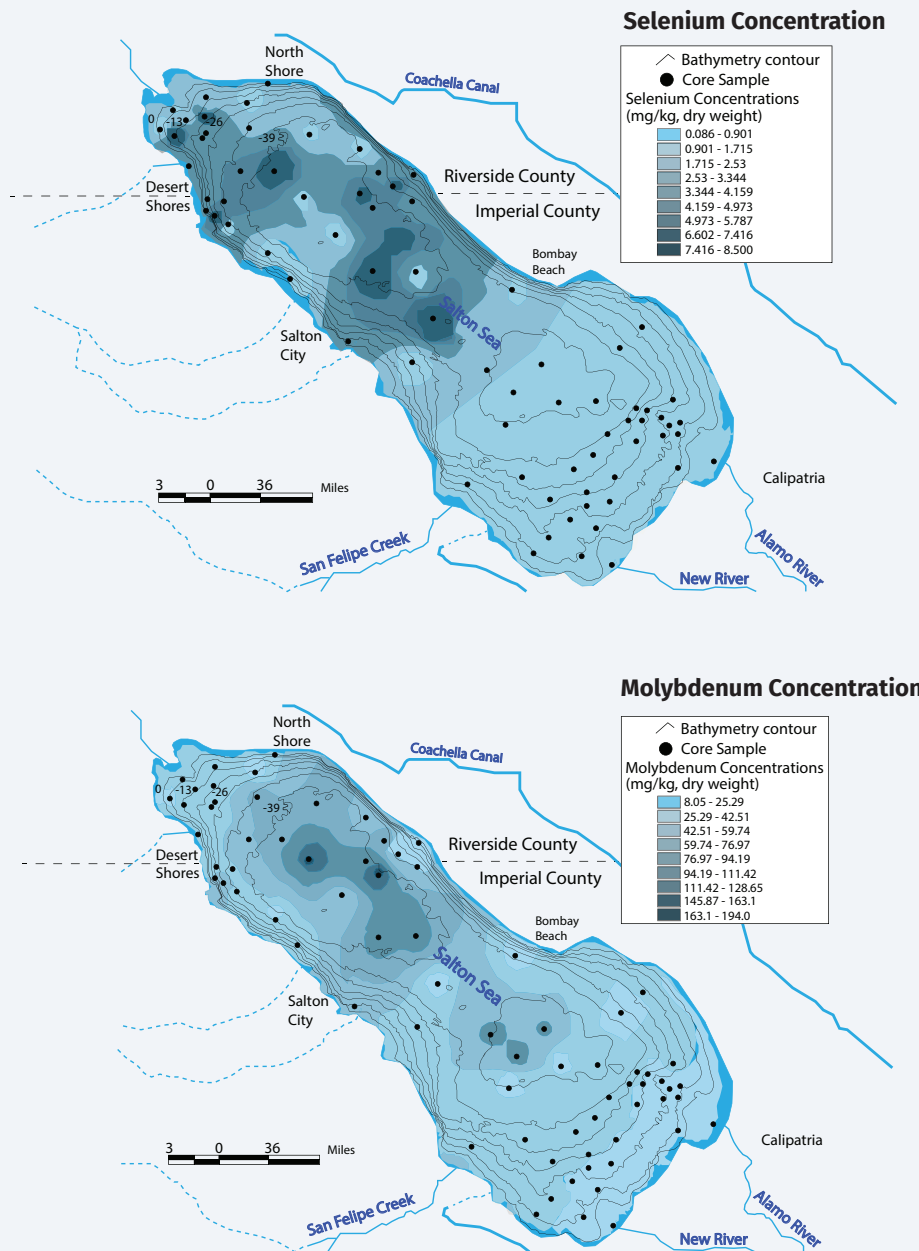


Figure 3.5 Bullseye pattern for selenium concentration (top) and molybdenum concentration (bottom) in bottom sediments of the Salton Sea. Darker areas, which are sediments most highly enriched in selenium, tend to be in the deepest portions of the basin. Credit: Caroline Hung. Sources: Bathymetry with 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 contin-

ue 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 (H₂S) 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 H₂S levels in surrounding communities and work with atmospheric circulation modelers to predict regional propagation of frequent H₂S in air masses.
- Assess health and life-quality risks to surrounding communities linked to more frequent, persistent, and likely more concentrated H₂S release from the Sea.
- Work with air quality researchers and atmospheric circulation and climate specialists to introduce H₂S detection in Salton Sea's waters and surrounding regions to forecast H₂S 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.

4

Air Quality

Particulate Matter, Pollutant Gases and Atmospheric Transport at the Salton Sea

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HIGHLIGHTS

- The state of the Salton Sea is tied intrinsically to air quality in the surrounding communities through the emission of particulate pollutants, toxic gas and gas-phase pollutant precursors.
- A large fraction of coarse particulate matter at sites closest to the shore of the Salton Sea is associated with emissions from the lakebed and sea spray.
- Airborne dust fluxes at sites close to the Sea are already in the high range of values observed at Owens Lake, Calif., before mitigation efforts began there.

Air quality around the Salton Sea, located between the Imperial and Coachella valleys of southern California, is impacted by emissions from the surrounding arid lands, urban and other anthropogenic emissions upwind, emissions from the dry lakebed, or playa, and direct emissions from the Sea itself. Atmospheric emissions of pollutants can be categorized into particulate matter (PM) and gaseous

pollutants, with PM having gained most attention in recent years given that its concentration has regularly exceeded the national and state ambient air quality standards. Air quality standards for PM, which refers to solid and liquid particles suspended in the air at sizes in the range of a few nanometers to tens of microns (μm), are set for mass concentrations of particles up to $2.5 \mu\text{m}$ in aerodynamic size ($\text{PM}_{2.5}$) or up to $10 \mu\text{m}$



DUST BERMS constructed to reduce windblown dust along the exposed southern shore of the Salton Sea. Jonathan Nye

in aerodynamic size (PM_{10}). PM is known to have adverse effects on the pulmonary and cardiac systems (Pope, 2000). One of the mechanisms for these effects is through oxidative stress and inflammation caused by certain components of PM, e.g., redox active metals, quinones and other oxidized organic components (Lakey et al., 2016). In addition to their chemical composition, the size of airborne particles has a major influence on the extent of negative impacts on pulmonary health since smaller PM (e.g., $PM_{2.5}$) can penetrate deeper into the lungs.

PM can be emitted directly into the atmosphere by mechanical processes (e.g., wind blowing over dry deserts or large bodies of water or breaking waves), forming “primary PM,” and can also form in the atmosphere through oxidation reactions of gaseous pollutants, leading to “secondary PM.” Not all gaseous pollutants are reactive and immediately harmful, however. For example, greenhouse gases such as methane (CH_4) and carbon dioxide (CO_2) are long-lived pollutants

that, once emitted, can remain in the atmosphere for decades, posing impacts on the earth’s radiative balance as they accumulate over time. Given the recent environmental changes at Salton Sea, it is necessary to investigate how environmental changes at the Sea impact air quality under current and possible future management scenarios. In the worst case scenario, the ongoing decline of lake levels will expose greater than 400 km² by 2038 (assuming lake water level is -255 ft or less), exacerbating the creation of all major classes of atmospheric pollutants: PM emissions from the playa and the Sea, reactive gases that can form secondary PM, and greenhouse gases.

Atmospheric Pollutants

WHEN CONSIDERING LOCAL AIR QUALITY in the Salton Sea region, it is critical and non-trivial to identify the different types and sources of atmospheric pollutants that are at play. The major pathways to produce atmospheric pollutants from the Salton Sea include

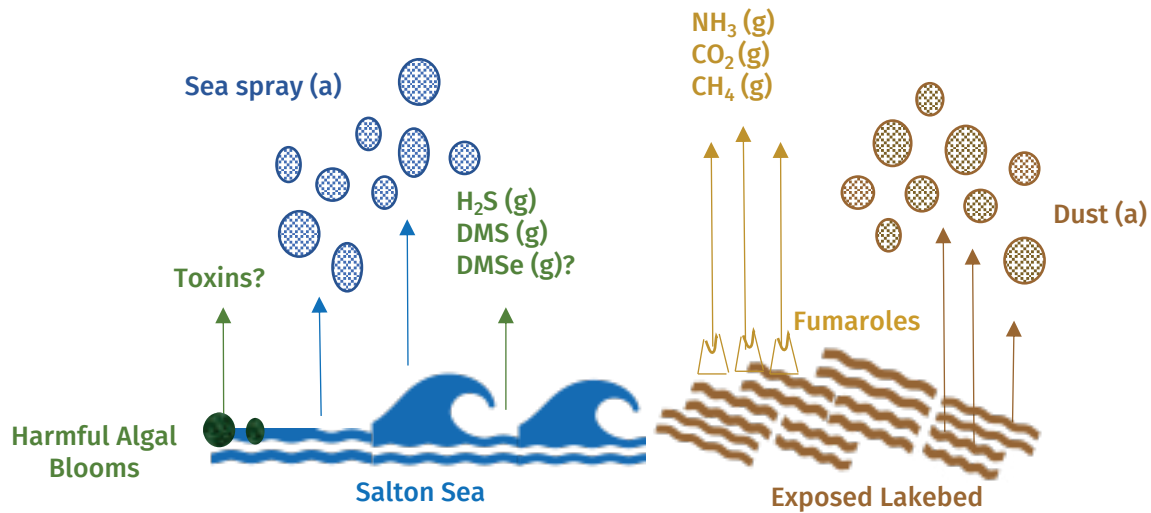


Figure 4.1 Major sources of gas-phase (g) and aerosol-phase (a) pollutants at the Salton Sea.

Credit: Roya Bahreini.

direct emissions of PM (i.e., sea spray and dust aerosols); emissions of reactive trace gases that may lead to formation of secondary PM (e.g., dimethyl sulfide [DMS], dimethyl selenide [DMSe], and ammonia [NH_3]); and emissions of unreactive, greenhouse gases (e.g., carbon dioxide [CO_2] and methane [CH_4]) (Figure 4.1).

Direct Particulate Matter

THE MAJOR FACTORS controlling the extent of direct emissions of PM from arid lands are soil crust type, which depends partly on soil composition and soil moisture; soil aggregate size distribution; surface roughness; and atmospheric wind strength (Alfaro et al., 2004). The possibility of increased PM emissions are of concern given the already high concentrations of PM_{10} in the region. Although hourly concentrations of PM_{10} have been measured at several air quality monitoring stations around the Salton Sea (IID et al., 2017), until recently the composition of PM was unknown, and the contribution of different sources to PM loading in the region was unclear.

In a 2015 study, size-dependent aerosol samples were collected at Salton City and Bombay Beach during short periods of time in the summer and winter to investigate sources of atmospheric dust by comparing concentration ratios (i.e., enrichment factor or EF) of elements in the atmospheric dust samples with those of local arid crustal surfaces and playa (lakebed) samples (Frie et al., 2017). For elements with a significant non-crustal source—for example, those with an anthropogenic source such as cadmium—the EF is high-

er than 1, meaning that there was considerably more of these chemicals in the dust than there should have been if the source had not been influenced by human activities (Box 4A).

Conversely, for elements that predominantly stem from arid crustal surfaces the EF value approaches 1. Figure 4.2 shows the enrichment factors for various elements in the PM filter and soil samples collected from different playas as well as the arid lands around Salton Sea (Frie et al., 2017). For sodium (Na), calcium (Ca) and selenium (Se), playa EF is significantly higher than that of the arid soils around the Salton Sea. This observation suggests that these elements are good indicators of playa influence on PM samples. Additionally, for sodium and calcium, PM EF lie in between the playa and soil ranges, suggesting mixing of two different sources for these elements. PM EF of selenium, however, is significantly higher than either playa or soil samples, indicating an additional source is responsible for concentrating selenium on PM.

Size-dependent elemental composition corroborated the mixed contribution of arid-crustal surfaces and non-desert sources to the observed PM since concentrations of elements thought to be associated with dust from terrestrial sources (e.g., Ca, aluminum [Al], Na, iron [Fe], titanium [Ti]) were enriched on particles larger than a micron (supermicron), while those from non-desert sources (chromium [Cr], nickel [Ni], cadmium [Cd], and Se) were concentrated more uniformly among the submicron particles (Figure 4.3). This result is expected: mechanical processes that form pri-

BOX 4A

Composition and Size of Dust Particles

ABSENCE OF KNOWLEDGE on the chemical composition or size distribution of the dust in the Salton Sea region has limited our understanding of the human health impacts of dust until recently. Researchers at UC Riverside conducted studies in 2015 that indicate at least 9% of the coarse particulate matter (PM₁₀) in regional dust samples comes directly from the dried lakebed, or playa. For some elements, such as sodium (Na), the playa is the source for 40–70% of the total (Figure 4.2). Sorting the size of dust particles by element further indicated that a gas-phase form of selenium (Se) may be coming from the playa or sea spray (Figure 4.3). Like many metals, selenium is an essential nutrient in small doses but toxic at large doses.

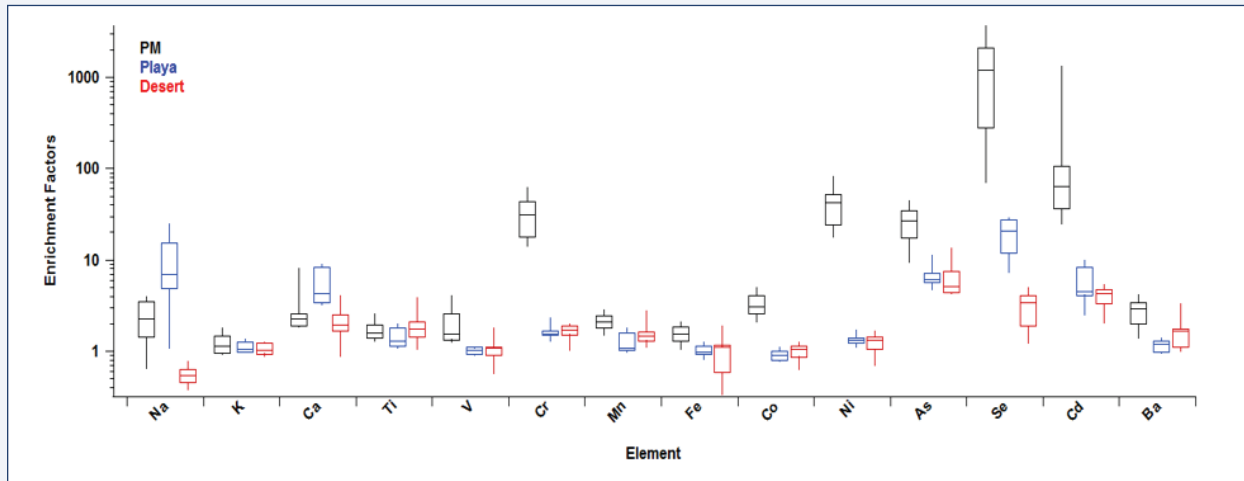


Figure 4.2 Elemental enrichment factors determined for particulate matter, playa, and arid desert lands. Box and whiskers depict 10th, 25th, 75th, and 90th percentile values, the horizontal lines show the median. Credit: Frie et al. (2017).

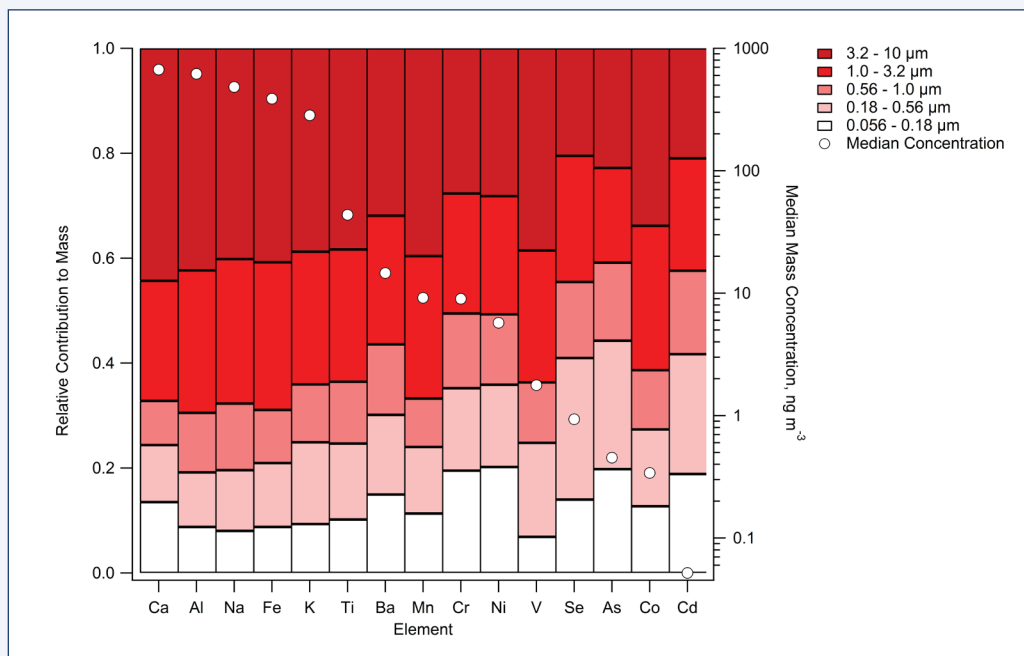


Figure 4.3 Size segregated elemental composition of particulate matter. Credit: Frie et al. (2017).

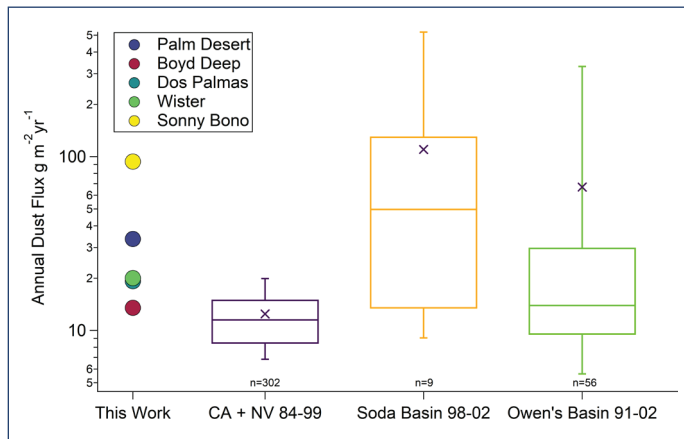


Figure 4.4 Estimates of annual dust flux at several sites around the Salton Sea as well as several historic records in the US Southwest. Box and whiskers depict 10th, 25th, 75th, and 90th percentile values; horizontal lines show the median; crosses show the mean. Credit: Frie et al. (2019).

primary PM generate larger particles, whereas secondary atmospheric oxidation processes concentrate the condensing components on submicron particles. Because Se was more equally distributed between submicron and supermicron sizes (Figure 4.3), it is likely that a gas-phase source of Se exists in the region.

There are also elements (e.g., Cr, cobalt [Co], Ni, Cd) whose PM EF is significantly higher than either playa or arid soil EF while playa and arid soil EFs are in a similar range. This observation confirms a strong contribution of atmospheric anthropogenic sources to these elements. Using a source apportionment technique (EPA's PMF 5.0), combined with total PM₁₀ concentrations measured close by, and the composition of playa sampled by Buck et al. (Buck et al., 2011), it was estimated that during this sampling period, the arid and desert lands contributed to ~45% of PM₁₀ (Frie et al., 2017) while the playa sources contributed by up to ~10% to PM₁₀ concentrations. The contribution of playa sources to Na concentration of PM₁₀ was significant at 40-70% (Frie et al., 2017).

A follow up study in 2017–2018 placed monthly samplers at a control site (University of California's Natural Reserve at Boyd Deep Canyon), an urban location (Palm Desert), on the lakebed (Sonny Bono National Wildlife Refuge and Wister), and open desert with moderate distance from the shoreline (Dos Palmas). The estimated deposition mass flux show that even with only ~60 km² of playa being exposed, dust fluxes were higher than the historical median values in the US Southwest.

Even at Owens Lake before mitigation when ~260 km² of the lakebed was exposed, fluxes were lower than those measured in the Salton Sea region (Figure 4.4) (Frie et al., 2019). Owens Lake, a closed-basin, saline lake on the eastern side of the Sierra Nevada in California, has gone through a similar desiccation processes in the 20th century due to water diversion to Los Angeles, creating a brine pool in its center surrounded by the dried lakebed. In 1987, the southern Owens Valley exceeded the 24-hr average national ambient air quality standard for PM₁₀, prompting the local air pollution control district to establish a monitoring network of PM₁₀ surrounding the lake. In the following years and after establishing the State Implementation Plans, the California Department of Water Resources was ordered to mitigate dust emissions by implementing a variety of dust control measures on ~127 km² of the emissive lakebed. In 2019, when ~43% of the lakebed was under dust control measures, the number of exceedance days were reduced to four from 37 back in 2000 before start of mitigations. After dust control measures were put in place, the average PM₁₀ exceedance value in 2019 was at 280 micro-g/m³, substantially reduced from 1,087 micro-g/m³ in 2000 (Allen et al., 2020).

It is worth noting that the brine at Owens lake is dominated by sodium carbonate and sodium sulfate (Mihevc et al., 1997), which form fragile and erodible crusts. At the Salton Sea, sodium chloride, calcium sulfate and magnesium sulfate have been observed as the principal evaporite minerals. Sodium chloride is expected to form a stable crust, but the two sulfate-based salts are not (Frie et al., 2019). Such playa emissions are seasonal and their influence at the sites closest to the Sea was most significant during late spring/early summer. Factors enriched in elements related to the playa and Salton Sea were identified only at the Sonny Bono National Wildlife Refuge and Wister sites, while the factor representing the Colorado river sediments had the highest contribution at Dos Palmas and Wister sites (Frie et al., 2019). Another factor characterizing the local soils contributed more uniformly to the collected mass at all locations.

Although these studies have been highly valuable in understanding the current influence of playa emissions on local PM and the potential impacts on human health, ongoing measurements are needed to examine how dust concentrations, composition, and size change with time because the exposed lakebed in the

future may not have the same physical and chemical characteristic as currently exposed areas. Once the salt crust erodes, the potential increases for generating dust from the underlying sediments, which may have very different composition and higher concentrations of toxic elements (Vogel & Henry, 2002) (Chapter 3).

Additionally, dust events are sporadic and episodic (Box 4B); therefore, their signature in the month-long samples at locations farther from the source might have gone unnoticed in the previous studies. None of the studies completed thus far have investigated detailed organic matter content of PM, which potentially could be laden with pesticides and herbicides. The high input of agricultural runoff to the Sea during the last several decades and the high toxicity associated with certain organic pesticide and herbicide residues causes additional concern, as do various bioaerosols (Box 4C). These compounds can also be suspended in air through production of sea spray from the Sea or dust from the playa. Future studies aiming at a more comprehensive chemical analysis of PM would be highly valuable and critical to fully understand the potential health impacts of atmospheric PM.

Reactive Trace Gases

PREVIOUS STUDIES have shown variable, but at times

significant, emissions of sulfur containing gases, e.g., hydrogen sulfide (H_2S) and dimethyl sulfide (DMS), from the Sea. Depending on water temperature and stratification levels in the Sea as well as atmospheric wind speeds, hydrogen sulfide produced deep in the Sea can be brought up to the surface, where it can partially degas into the atmosphere. Under the right conditions, up to 25% of sulfide produced in the Sea can end up in the atmosphere (Reese et al., 2008). Once in the air, H_2S has a daytime atmospheric oxidation lifetime of ~10 hr, leading to the production of sulfur dioxide, another toxic gas. Further, another reduced sulfur species that is typically measured in the air over the oceans is the methylated form of hydrogen sulfide, namely DMS. Reese and Anderson (2009) measured very high concentrations of DMS in surface waters from 0–2 m depth. These high concentrations of DMS are correlated to chlorophyll-a and dimethylsulfoniopropionate (DMSP) that are chemical markers of algae activity. They result in high rates of transfer of gaseous DMS to the atmosphere—rates up to two orders of magnitude higher than the DMS emission rates from other lakes or the open ocean (Lana et al., 2011; Reese & Anderson, 2009). Similar to hydrogen sulfide, DMS has a daytime lifetime of ~10 hr before it reacts to form other compounds.

The Colorado River and the sediments it carries are

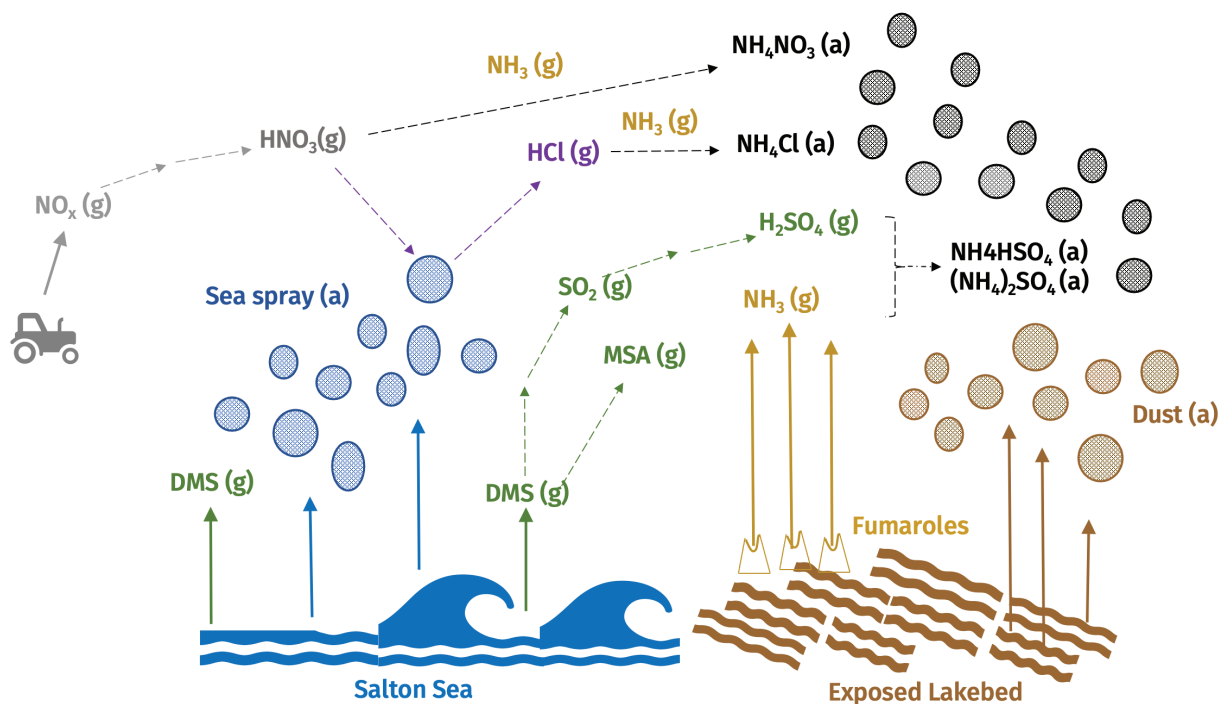


Figure 4.5. Diagram depicting chemical interactions of various reactive gas-phase (g) and aerosol-phase (a) pollutants at Salton Sea. Solid arrows show emissions; dashed arrows show chemical reactions. Credit: Roya Bahreini.

known to be high in Se. Because of the decades-long input of water from the Colorado River to the Salton Sea, Se concentration in the Salton Sea and its sediments are also relatively high (Xu et al., 2016). Microbial activity in water, soils, and sediments can convert selenium to solid elemental Se, metal selenide, or gaseous methylated selenium (e.g., dimethyl selenide, DMSe) (Kausch & Pallud, 2013; Vriens et al., 2014; Winkel et al., 2015). Methylated selenium species are volatile and can enter the atmosphere. Once in the air, these compounds oxidize and form secondary PM, as demonstrated in a recent laboratory-based study (Ahmed et al., 2019). Secondary selenium aerosol components have not been directly measured in the PM collected around Salton Sea. The relatively high EF of Se in PM samples, however, as well as the more uniform distribution of Se on submicron PM, suggests that Se on PM is likely derived from oxidation of methylated Se species and the resulting products containing Se. Unlike sulfate, DMSe-derived oxidation products forming secondary PM may lead to elevated toxicity linked to oxidative DNA damage and a negative immune system response to airway inflammation in human epithelial lung cells (Ahmed et al., 2019). It is unknown how concentrations of H₂S, DMS, and methylated Se in the water and air or the concentration of their oxidation products in PM will evolve due to changes in the biological activities and physical conditions of the water column under future scenarios.

In addition to gaseous species directly emitted from the Salton Sea or its playa, ammonia gas is emitted from the fumarolic vents on the geothermal fields located at the southern edge of the Salton Sea (Tratt et al., 2011). Ammonia flux from these vents is estimated to be up to 25% of the total regional flux (Tratt et al., 2011). Ammonia is a common base that reacts with the acidic components of submicron PM (typically, nitrate, sulfate, bisulfate, or chloride) and is also recognized as a facilitator for new particle formation (Figure 4.5). Such emissions are therefore indirectly critical in controlling the local and regional levels of submicron PM.

Greenhouse Gases

PREVIOUS STUDIES have examined release of concentrated plumes and diffuse seepage of CO₂ and CH₄ from the main seep field of the Salton Sea geothermal system, namely the Davis-Schrimpf field, at the south-

Atmospheric Transport Patterns

WITH INCREASING CONCERN over pollutants originating from the Salton Sea and its surrounding dry lakebed, transport patterns derived from local surface wind data are useful tools for understanding historic and future exposure to pollution from these sources. Based on 10-meter wind measurements taken from long term monitoring sites (US EPA) in the Coachella and Imperial Valleys, monthly wind direction patterns can be analyzed to reveal seasonal patterns in exposure risk for communities throughout the Salton Sea basin.

At the Indio station in the Coachella Valley (Figure 4.6, top), winds are predominantly from the north and west (blue and green fills, respectively) during much of the year. However, southerly winds are not uncommon, and become increasingly frequent during summer months, at times due to strong pressure gradients related to the North American monsoon driving winds originating from the Gulf of California—so-called “gulf surges” (Adams and Comrie, 1997). Interannual variability in wind direction outside of the summer months may also be a result of synoptic events including Santa Ana winds, characterized by easterly winds driven to the California coast by high pressure systems over deserts on the far side of the Sierra Nevada mountains (Raphael, 2003). Regardless of the cause, these types of events likely contribute to the variability apparent in the observed surface wind direction shown here. Imperial Valley wind dynamics, represented by measurements taken at the Niland station off the southeast coast of the Salton Sea likewise see a summertime shift towards more frequent daytime southerly winds, on average (Figure 4.6, bottom).

Diurnal patterns measured at local stations further demonstrate the significance of wind variability observed across the Coachella and Imperial Valleys. Filtering hourly wind-speed data to include only regional dust event days, defined as those days during which multiple air quality monitoring stations reported daily PM₁₀ concentrations that were at least one standard deviation above the station

BOX 4B

mean, shows that a large fraction of those regional dust event days have historically included midday winds blowing from the south (Figure 4.7, top). Based on these observations, exposure to PM₁₀ during these types of Coachella Valley dust events would be expected to disproportionately include dust originating from the Salton Sea or the surrounding dry lakebed, making the physical and chemical properties of this growing dust source an important knowledge gap. These patterns are not constant or uniform across the region, reflecting key differences in local topography and resulting upslope and

downslope wind patterns. A similar analysis of winds measured at the Niland station during Imperial Valley dust events shows frequent early morning winds from the east, with afternoon and evening winds dominated by winds from the west. The seasonal and diurnal variability in transport patterns observed at stations across the valley points to the importance of understanding the timing, quantity, and composition of emissions generated during high-wind dust events in order to most effectively understand and mitigate any health impacts caused by potentially contaminated particulates.

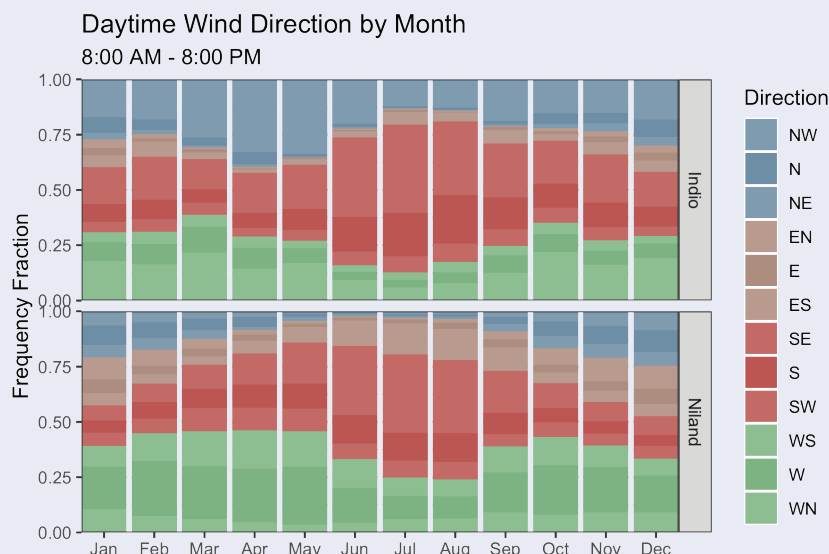
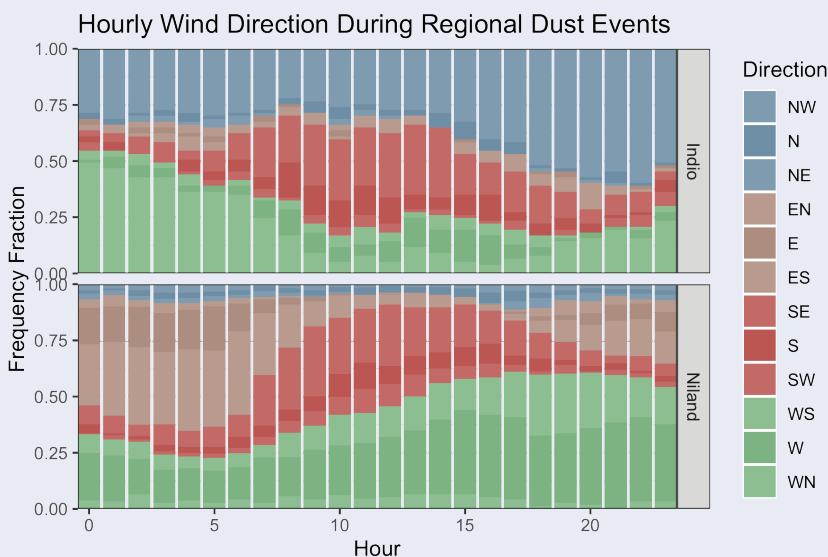


Figure 4.6 Frequencies of hourly daytime wind direction at Indio (Coachella Valley) and Niland (Imperial Valley) stations. Credit: William Porter. Source: EPA Air Quality System (EPA AQS) network.

Figure 4.7 Hourly wind speed frequencies for regional dust event days, defined as days during which multiple local stations (in the Coachella Valley or Imperial Valley for the Indio and Niland stations, respectively) exhibit daily PM₁₀ values exceeding the station mean by at least one standard deviation. Credit: William Porter. Source: EPA Air Quality System (EPA AQS) network.





Dust storm along Highway 111 on May 11, 2018. Jonathan Nye

eastern edge of the Salton Sea (Mazzini et al., 2011). Based on measurements from 91 vents and 81 soil degassing stations on a 20,000 m² area, daily emission rates of CO₂ and CH₄ were estimated to be 9,410 kg CO₂/day and 44.5 kg CH₄/day, respectively, with only 25% of the emissions originating from the vents (Mazzini et al., 2011). These emission rates translate to 3841 MT CO₂/yr (i.e., metric ton of equivalent CO₂, assuming global warming potential of 25 for CH₄), which is equivalent to CO₂ emitted from ~835 typical passenger vehicles in a year (assuming 11,500 miles driven per year and 22 MPG fuel efficiency) (EPA, 2018). Compared to regional anthropogenic sources, these emission estimates are not significant. It is worth noting though that total emission rates of CO₂ and CH₄ from the Salton Sea geothermal system are likely higher than the current estimates since additional emissions of CO₂ and CH₄ are expected from areas outside the Davis-Schrimpf field site and along the Salton Trough.

Future Air Quality

THE TRENDS in the amounts and composition of atmospheric emissions in the future depends on the extent of the lakebed being exposed, the type and composition

of the exposed area, as well as the quantity and quality of the water in the Salton Sea under each scenario presented in Chapter 1. Under scenario 1, it is expected that more than 400 km² of the lakebed will be exposed by 2038. This scenario will bring out the worst air quality as far as direct PM emissions are concerned and has the potential to also suspend more toxic elements from the heavy-metal-enriched sediments that are located in the deepest areas of the Salton Sea lakebed. Depending on the quality of water in the remaining parts of the Salton Sea, conditions may favor more frequent production of plankton and harmful algal or cyanobacterial blooms, thus increasing the chance of trace gas volatilization and airborne mobilization of algal toxins, as well as the mobilization of potentially toxin-producing bacteria. Under this scenario, currently submerged fumaroles will also get exposed, contributing to direct emissions of reactive and non-reactive gases to the atmosphere.

Under the stabilization scenario, many of the same atmospheric emission implications apply. The only significant difference would be if enough water were directed to the Sea to halt the shoreline retreat before the most toxic sediments beneath the center of the lake are

Microbial Emissions

BOX 4C

AN EMERGING AREA of research worldwide is called aerobiology, or the study of the movement in air of “bioaerosols,” which include bacteria, fungal spores, pollen grains and viruses. Often these bioaerosols also include non-living matter to which the biological particles are attached, including soil or mineral particles and water droplets.

Researchers in the UC Riverside Department of Microbiology and Plant Pathology study the bioaerosols that make up some fraction of the aerosol phase emissions of sea spray from the Salton Sea and the dust emissions from the exposed playa. Compounds produced by microorganisms—during harmful algal blooms, for example—can also be picked up and transported as aerosols (Figure 4.5). The potential for microbial toxins to become airborne is of particular interest, as harmful algal blooms will likely become

more frequent as lake volume decreases and the concentration of nutrients grows.

As the Salton Sea becomes smaller and more saline, which is predicted in all scenarios, the environment and ecosystems in and around the Sea will experience changes. The microbiology of the Sea and playa will in turn shift the microbial communities that are picked up as bioaerosols. Microbial responses to these environmental fluctuations may differ by the sensitivity of the particular microbial group (Allison & Martiny, 2008), coupled with the dynamic features of the abiotic environment. Clarifying how these disturbances impact microbial assemblages and ecosystem performance across systems (Biggs et al., 2012) within the Salton Sea Basin is crucial to its long-term sustainability, and will provide valuable information to augment successful management strategies.

exposed, thereby avoiding the hazard related to dust emissions from these sediments.

The best outcome for air quality is expected under scenario 3, where sufficient water is imported to the Sea to recover some of the lost lake volume and re-wet dry lakebed. Depending on the extent of the exposed lakebed, significant reduction in PM and associated microbial emissions could be achieved under this scenario. Of concern is the maintenance of water quality (e.g., salinity and oxygen content) under this scenario, which will still have impacts on emissions of trace gases by volatilization and potentially toxins through sea spray generation. Additionally, if water levels are high enough to allow fumaroles to remain submerged, ammonia and greenhouse gas emissions from these sources will be limited.

Research Needs

UNDERSTANDING THE CURRENT IMPACTS of the Salton Sea emissions and reliable prediction of atmospheric emissions from the Salton Sea in the future requires detailed, process-level understanding of several key elements and continuous research to reassess these elements given the rapidly changing dynamics of the

system. These elements are highlighted as follows:

- Thorough chemical finger-printing, including that of the trace organic constituents (e.g., pesticides), of dust sources is needed for successful and complete PM source apportionment efforts.
- Size-dependent composition—including specific elements such as selenium, chemical ionic species, and organic compounds—of PM needs to be measured on a regular basis.
- Gaseous emissions from the Sea need to be characterized, and the extent of their influence on PM_{2.5} formation should be investigated.
- Seasonal emission potential of different lakebed types needs to be investigated under atmospherically relevant conditions (e.g., hot and dry) and in relation to physical and chemical characteristics of the lakebed and its moisture content.
- Relationships between gaseous emissions from the Sea and the chemical and biological state of the Sea need to be investigated to better understand future emissions of these species given the different management scenarios.

5

Ecology

Ecosystems of the Salton Sea and Surrounding Environments

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HIGHLIGHTS

- Federal and California state air quality regulations, endangered species laws, and protections of migratory waterfowl will necessitate action as increasing salinity causes the die-off of all fish species within the next few years.
- Excessive nutrient flows into the Sea trigger harmful algal blooms and dead zones, threatening wildlife and human health.
- Planned construction of wetland habitats may benefit certain species of non-fish-eating birds; however, there are currently no official plans to maintain or restore a fully functioning lake ecosystem.

The Salton Sea is host to a significant number of species of conservation importance, as well as the ecosystems that support them. These ecosystems include the lake itself, the lake margins—riparian zones and the increasingly exposed playa—as well as the vast agricultural ecosystems bordering the Salton Sea. The functioning of these ecosystems is essential for the survival of many valued species, including the

federally endangered desert pupfish and hundreds of migratory bird species. The ecology of the Sea is dynamic and unstable, regularly fluctuating due to the extreme environmental conditions and biotic responses. The salinity of the Sea—already at 74 parts per thousand—will continue to rise as the sea shrinks, leading to a catastrophic collapse of the aquatic food web if the current trend is not halted (SSMP, 2021).



CONSTRUCTED WETLAND designed to provide bird habitat at the southern end of the receding Salton Sea. Jonathan Nye

Aquatic Primary Production

PRIMARY PRODUCERS in the Salton Sea include several photosynthetic and chemosynthetic organisms, ranging from wetland plants to free-floating algae and photosynthetic microorganisms in the Sea itself and its margins. These primary producers, which form the base of the Salton Sea food web, are supported by an overabundance of abiotic nutrients supplied to the Sea via agricultural runoff and untreated sewage originating from Mexico. This nutrient load results in high rates of primary production and subsequent die-off of aerobic organisms, such as tilapia, within oxygen-starved regions known as dead zones. These zones form when prolific primary producers die and sink into the water column, consuming oxygen during their decomposition (Beman et al. 2005, Chaffin and Bridgeman 2014, Heisler et al. 2008).

When there are blooms of algae species that produce toxins, the events are called harmful algal blooms,

or HABs (Reifel et al., 2001; Tiffany et al. 2007a; Tiffany et al. 2007b). Harmful algal blooms are signs of polluted waters that occur from areas along California's coast to river systems to the Salton Sea. The Salton Sea's waters contain two major HAB organisms—dinoflagellates and cyanobacteria—that are toxic to organisms including humans (Carmichael and Li, 2006). Dinoflagellates are microscopic single-celled organisms that can grow by photosynthesis or by taking up organic molecules dissolved in nutrient-rich water. These organisms are coated by specialized armor plates made of calcium carbonate. At certain times of their life cycles, they excrete compounds known to be neurotoxins (Hackett et al., 2004). These toxins can accumulate in fish tissues and be passed to organisms consuming those fish, including pelicans.

Other HABs consist of species of cyanobacteria, primitive photosynthetic organisms, such as *Microcystis aeruginosa* that also produce toxins that cause fish and wildlife poisonings (Carmichael and Li, 2006;

Kenefick et al., 1993). Cyanobacterial toxins are tied to vast mortalities of eared grebes in the Salton Sea (Anderson et al. 2007). In particular, microcystin, a toxin produced by cyanobacteria, has been found in acute concentrations within the livers of *Podiceps nigricollis* (eared grebes), that perished at the Salton Sea (Carmichael and Li 2006). Organisms like this not only produce toxins but also create conditions whereby their biomass causes anoxic events (see Chapter 3 for a more detailed discussion of microbial metabolism in the water column).

In addition to toxins produced by the primary producers, agricultural chemicals and naturally occurring elements that have accumulated to potentially toxic levels in the Sea and are contained in the primary and secondary consumers can bioaccumulate in the tissues of predators such as fish and birds. For instance, selenium, DDT and PCBs were identified in fish muscle tissue having been passed through the food web from primary producers to small invertebrates and insects then into fish (Figure 5.1) (Sapozhnikova et al. 2004; Moreau et al. 2007).

High rates of primary production support an array of zooplankton in the Sea, including ciliates (Reifel et al. 2007). The overabundance of respiring microorganisms results in the consumption of a significant amount of oxygen, so much so that at depth, where atmospheric mixing does not penetrate, the Sea is low in dissolved oxygen. Microorganisms in the absence of oxygen operate using alternate metabolic path-

ways, producing hydrogen sulfide (H_2S), which is toxic to animal life in high concentrations. During high wind events, mixing of deep and shallow waters result in hydrogen sulfide release to the atmosphere (Chapter 3) and fish kills (Figure 5.1).

Agricultural Interfaces

THE SALTON SEA is connected closely with adjacent terrestrial and wetland ecosystems. It is embedded in the extensive desert ecosystem of the Sonoran Desert, which is characterized by shrublands dominated by *Larrea tridentata* (Creosote bush). While the desert ecosystem may have limited direct interaction with the Salton Sea, it does provide ecological context. Agriculture dominated ecosystems are also extensive in the Salton Sea region. Agricultural decision making has a major role in affecting water and nutrient inputs to the Sea. With increased efforts directed towards increasing both agricultural water and nutrient efficiency, and coupled with increasing agricultural land abandonment, unintended nutrient and pesticide inputs to the Salton Sea are decreasing (Box 5A).

Wetlands

THE IMPORTANCE of the Salton Sea's wetlands on the migratory and resident birds of North America was described famously in Shuford et al. (2002). Since then, however, increasing salinity and nutrient overloads have caused ecological disasters, including major fish

IRRIGATED FARMLAND in the Imperial Irrigation District, which drains into the Salton Sea. Caroline Hung



High-Temperature Agricultural Systems

BOX 5A

HIGH-TEMPERATURE AGRICULTURAL SYSTEMS such as those adjacent to the Salton Sea are prevalent in the southern United States and will become even more common with future warming (Hatfield et al. 2014). Most U.S.-grown winter vegetables are farmed in the Imperial Valley south of the Sea. Tree crops—for example, dates, grapefruits, and nuts—are grown in the Coachella Valley to the north. High-temperature environments are known to increase the potential for biological activity arising from highly non-linear responses to temperature and moisture. The Salton Sea region has become a case-study for improved understanding of agriculture in such conditions. Agricultural dynamics in the region depend extensively on irrigation, and during the summer, evaporation rates can be greatly elevated (Oikawa et al. 2015b; Lu et al. 2017).

High-temperature agricultural systems can be locations of unusually high nitrogen losses through soil trace-gas emissions, but these emissions may be reduced with readily achievable management changes (Liang et al. 2015). Funding mechanisms for such approaches are limited; however, one approach may be to connect emissions to either carbon markets or water markets. Initial estimates demonstrate that modifying fertilization and irrigation practices in a high-temperature environment can reduce losses of nitro-

gen to the atmosphere by 50%. By reducing these emissions, nitrogen-use efficiency can substantially be increased and thereby reduce the need for potentially polluting fertilizer. Implementing such changes to the Imperial Valley and Coachella agricultural areas could have positive impact on life in the Sea itself.

Soil nitrogen oxide (NO_x) emissions nearby the Salton Sea are more than an order of magnitude greater than standard agricultural NO_x model predictions. These emissions are associated with standard management practices for summer forage crops: the combination of high temperatures and pulsing dynamics associated with drying and rewetting of irrigated soils. For example, soil NO_x emissions observed in a high temperature, fertilized agricultural area of the Imperial Valley ranged between 5 and 900 nanograms of nitrogen in a square meter within a second, some of the highest instantaneous fluxes ever measured. These emissions were associated with an increase in regional ozone, an important component of poor air quality. Reducing NO_x and nitrous oxide emission pathways could improve nutrient-use efficiency, reduce demands for fertilization, and minimize the negative life cycle impacts of these trace gases to human health, adjacent natural habitats, and greenhouse gas concentrations (Chen et al. 2011; Zhang et al. 2013).

kills and avian diseases (Figure 5.1). Today, wetlands surrounding the northern and southern shorelines where the Whitewater, New, and Alamo rivers drain into the Sea are potential habitats supporting remnant populations still able to take advantage of the area.

Heavy-metal poisoning of wildlife is a concern for existing and planned wetland habitat, however. Water in agricultural drains regularly test at toxic levels (Xu et al. 2016). If this water is used to supplement water destined for wetland habitat, the accumulation of toxic metals along the food chain (bioaccumulation) could adversely impact the health of fish and birds, especially those at high trophic levels. Investigation of groundwater and geothermal water in the southern

portion of Salton Sea have been also found to contain high levels of arsenic and other heavy metals that may impact wildlife (Flores-Galvan et al. 2017).

Wetland ecosystems, at the interface between the Salton Sea and upland desert or agricultural lands, are key ecosystem components that interact strongly with the Sea. Riparian wetlands can have a role in the hydrologic dynamics, with greatly elevated evaporation rates and can be a water loss pathway that depends on both lake water and plant dynamics. At the same time, wetlands can influence nutrient dynamics through either plant uptake or biogeochemical transformation. Compared to native deserts or retreating shoreline, wetlands can stabilize the land surface and reduce



Figure 5.1 Schematic diagram of variables resulting in fish kills. The extent and severity of fish kills are the result of four interconnected variables: Algal blooms and phosphorus cycling from the Alamo River (dark green), algal blooms and phosphorus cycling from the New River (light green), algal blooms and total dissolved solids in the Salton Sea (orange/yellow), and seasonal temperatures (blue/orange). Credit: Kjelland et al. (2018).

dust emissions. Wetlands associated with the Salton Sea are also connected to key species conservation concerns. These wetlands are a key stop for migrating bird species spanning much of the western United States, Canada, and Mexico. They are also associated with aquatic habitat for the desert pupfish.

More information about ecosystem and conservation roles of Salton Sea wetlands are needed to assess

and manage these ecosystems to achieve policy goals. The 2018 Salton Sea Management Plan describes building Species Conservation Habitats: diked ponds with water pumped from agricultural drains, groundwater, and the salty Salton Sea open waters. The ponds are projected to allow for the growth of endangered desert pupfish, tilapia, as well as important invertebrates for feeding wildlife. There is no guarantee that these

BOX 5B

Threatened Food Webs

ENDANGERED SPECIES LAWS and waterfowl protections will necessitate action as increasing salinity causes the die-off of all fish species in the Salton Sea within the next few years. More focus on wetlands that emerge naturally as the Sea recedes could provide critical new habitat with minimal taxpayer investment.

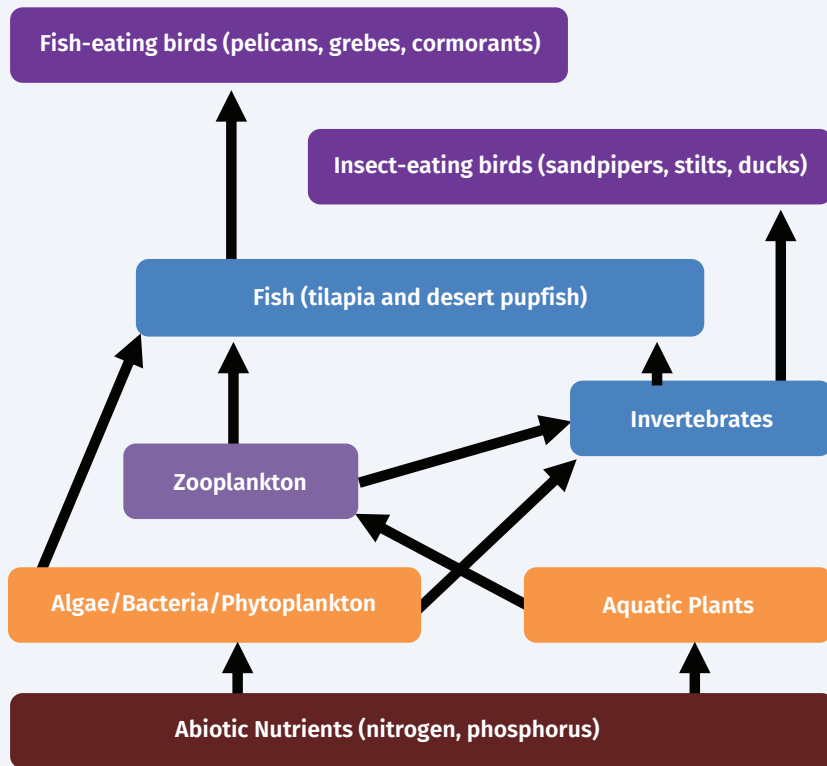


Figure 5.2 Simplified Salton Sea food web. CREDIT: Jonathan Nye.



Brown pelican. Jonathan Nye



Tilapia carcass. Dana Swarth

expensive. engineered habitats will prove sustainable in the short term or long term, however.

A more cost-effective strategy for developing bird habitat may be to cultivate the new wetlands that are emerging at drain outlets as the Sea recedes. According to U.S. Fish and Wildlife biologist T. Anderson (personal communication, July 9, 2021), these vegetated areas are “doing a fine job suppressing dust and producing entirely new thriving ecosystems at no cost to taxpayers” and can be improved and sustained with minimal modification or maintenance.

Aerobiology

MICROORGANISMS THAT LIVE in and around the Salton Sea, surrounding playa and wetlands, and nearby agricultural systems, have an impact on the air quality

of the region. As the Sea recedes due to reduced water inputs in all scenarios, it exposes additional playa and increases atmospheric dust levels (Chapter 4). Similarly, in fallow agricultural fields and disturbed ecosystems nearby, topsoil can be transported into the air as dust. In addition, due to intense wind eddies that occur frequently over the Salton Sea, sea spray can be transported as well with the dust. Dust and sea spray from these diverse sources are composed of organic and inorganic materials, including adhering microbes, which can be transported locally or long distances, even between continents (Aciego et al. 2017). As these materials are picked up and transported, the entrained microorganisms on particles add to the biological diversity of the air, studied by an emerging field of research called aerobiology. The composition of this



ENDANGERED DESERT PUFFISH, which inhabits shallow waters in and around the Salton Sea, can tolerate higher temperatures and salinities and lower oxygen levels than most fish.

Copyright Minden Pictures

aeolian microbial community can have an impact on functioning of local and global ecosystems, potentially impacting human health.

Aquatic Food Webs

ANIMALS SUPPORTED BY THE SEA'S ECOSYSTEMS include fish and birds, supported by algae and arthropods. Fish in the sea today are restricted to tilapia (*Oreochromis mossambicus* x *O. urolepis*), by far the dominant species in the sea; desert pupfish (*Cyprinodon macularius*), an endangered species; sailfin mollies (*Poecilia latipinna*); and western mosquitofish (*Gambusia affinis*); with other introduced species of fish unable to cope with increasing salinity in recent years (Martin & Saiki, 2005). Tilapia were likely introduced by the escaping fish farms and through introduction by the California Department of Fish and Wildlife for control of noxious weeds and insects (Costa-Pierce, 1999), while desert pupfish are a native species to the American southwest. The primary constraints on the survival of these species include the temperature and salinity of the sea, both of which fluctuate wildly throughout the year due to seasonality associated with freshwater in-

flows. In general, annual average salinity is increasing beyond the physiological limits of these animals.

Tilapia venture to the bottom sediments to lay their eggs and are found in all parts of the sea in the winter. They migrate to nearshore and shallow waters in the spring and as hypoxia and sulfide levels increase, and return to the open, deeper waters in the winter as dissolved oxygen levels increase (Caskey et al. 2007). Tilapia are mixotrophic organisms feeding both on algae and other small animals, including small arthropods and smaller fish. In recent years the lower oxygen content has become too low for tilapia to survive resulting in massive fish die-offs (Cardona et al. 2008).

Desert pupfish are less commonly found in the Sea, as their primary habitats are in the fresher waters of the riparian zones and wetlands, though they travel through the sea between various breeding habitats (Figure 5.4). Tilapia and other non-native fish likely predate upon pupfish eggs, though the extent to which tilapia impact pupfish is unknown (Martin et al., 2009). Desert pupfish populations find refuge in channels and creeks around the sea, though can travel through the sea connecting populations (Riedel, 2016).

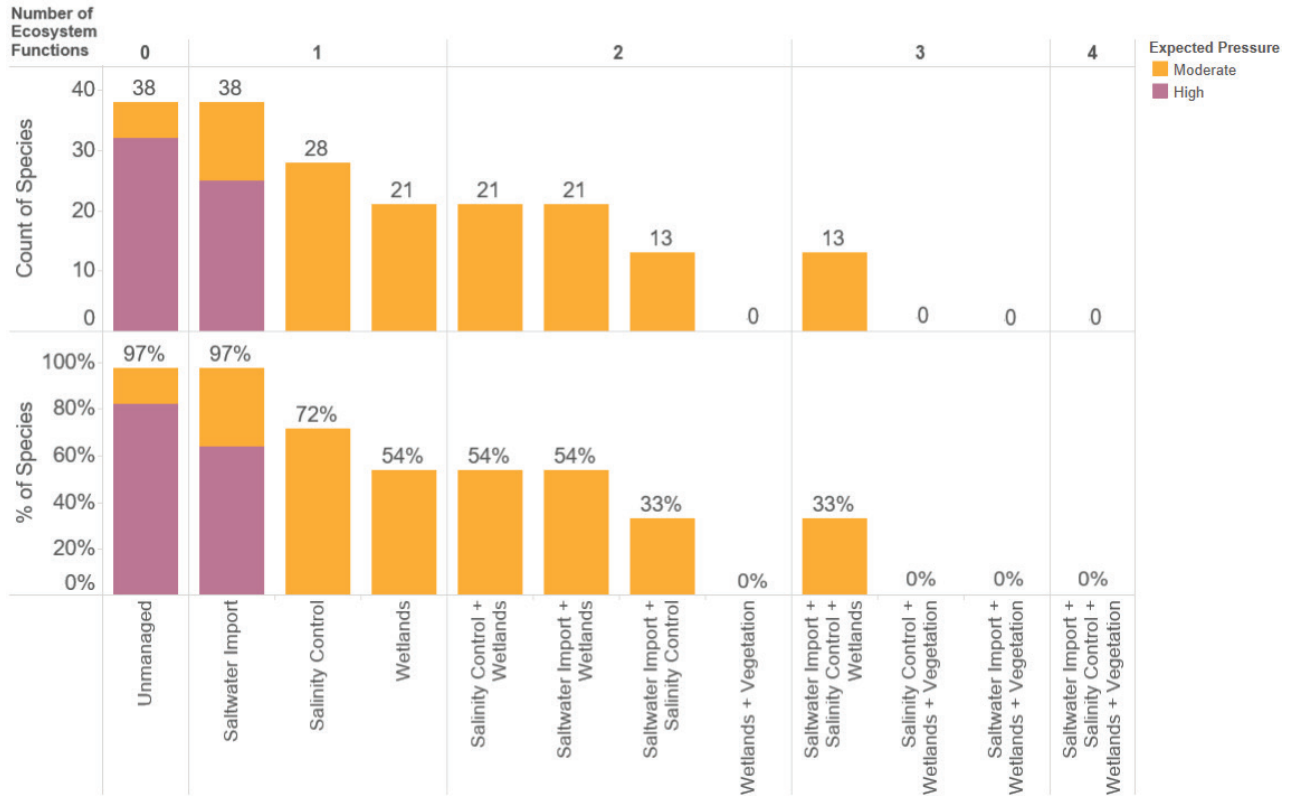


Figure 5.3 Calculation of expected pressures on ecosystem functioning of the Salton Sea. Different mitigation strategies have different expected pressures on species. Combining different mitigation strategies decreases the expected pressures on species. Credit: Forney (2018).

Conservation efforts have established more populations of pupfish beyond the native and historic habitat such as Salt Creek and the Trifolium Drain into various agricultural drains around the lake to stem long term declines in pupfish populations. However, these drains and creeks often only connect to the sea seasonally in the winter. Ultimately pupfish survive in agricultural drainage systems rather than the sea itself, partly due to predation pressures and ideal habitat and breeding space. (Martin & Saiki, 2005).

The Salton Sea can support as many as 350 different species of birds. Most bird species are migratory, occupying the sea in the winter months. The birds of the Salton Sea fall into two categories: invertebrate eating birds (insectivorous) and fish-eating birds (piscivorous). Insectivorous birds benefit more readily from the wetland habitat managed by the Fish and Wildlife Service in Sonny Bono Salton Sea National Wildlife Refuge. The insectivores feed largely in the wetlands and riparian zones while piscivores are largely subsisting on the tilapia in the littoral zone of the lake where their prey congregate.

Piscivorous birds are highly susceptible to fluctuations in populations of their prey, resulting in bird populations fluctuating as well (Hurlburt et al. 2009).

Piscivores include pelicans, gulls, cormorants, terns and many others, typically migrating from coastal marine areas and other saline lakes (Lyons et al, 2018). Lyons et al.’s 2018 study of Caspian terns (*Hydroprogne caspia*) shows that these birds congregate near the margins of freshwater inputs to the Salton Sea in the north and the south, including the Whitewater, Alamo and New river deltas where fish are likely to congregate due to lower salinities and water temperatures. Ecosystem modeling of decreased freshwater inputs show that populations of piscivorous birds at the Salton Sea are very likely to be negatively impacted by reduced water availability from implemented QSA agreements (Kjelland & Swannack, 2018; Upadhyay et al. 2018).

Research Needs

THE SALTON SEA FOOD WEB is currently on the threshold of ecosystem collapse. Without intervention, many higher-level organisms of the Salton Sea—fish and fish-eating birds—will almost certainly disappear. It is likely that the current levels of intervention will

have the same result. Only with sustained effort can we maintain habitat suitable for birds, fish, and other organisms in the sea. The way to guarantee continued presence of these valued organisms is by controlling salinity, oxygen levels and temperatures. We may not be able to control rising temperatures and the increased frequency of heat waves due to climate change, but California can control the freshwater inputs into the Sea to maintain a healthy food web that benefits not only wildlife but also the people living nearby.

Connections among organisms and interspecies relationships are more complicated than the simplistic food web presented above (Box 5B). For example, certain species may have a larger impact than expected given their relative biomass on the ability of other organisms to survive, a concept known as keystone species or ecosystem engineers. While tilapia may not be the perfect model of a keystone species, it is likely that the food web will collapse with their disappearance. The Salton Sea represents a key stopping point for migratory bird species travelling along the Pacific Flyway, a migration route stretching from the Arctic to the tropics. The loss of this resource for migratory species would be potentially devastating in its impact to the sustainability of populations of these species.

Under any of conceivable future scenarios for Salton Sea management, naturally created wetlands may have greater potential for supporting wildlife than expensive, constructed habitats. To test this hypothesis, research must be funded to answer some key questions: What species are these wetlands supporting now? And what is their potential for long-term sustainable habitat? Can they be integrated into Salton Sea Management plans for deep water ponds? How much water is needed to maintain wetlands at a size that could significantly impact—and improve—migratory and resident bird habitat?

No matter how management of the Salton Sea develops over the coming decades, it is certain that there will be large—and possibly irreversible—changes to the ecosystem that pertains today. Everyone wants the beauty and majesty of the area to be enhanced, not degraded further than it has already. Partnering research with restoration efforts has the greatest potential to determine if the Salton Sea Management Program is heading in the right direction. An independent assessment of ecosystem functioning in its broadest sense is an important component for Salton Sea's future.

Three Possible Futures for Lake Ecology

We consider probable outcomes for Salton Sea ecology based on hypothetical scenarios for future lake levels:

Continued Decline

WITHOUT INTENTIONAL INTERVENTION, lake levels will continue to decline, even as wetlands are constructed on exposed lakebed.

If lake levels continue to decrease, the results will likely be devastating to most larger organisms living in and near the Sea. As the Sea shrinks, we know the salinity will increase to levels precluding the survival of fish species. With oxygen levels decreasing, hydrogen sulfide levels rising, increased salinity and high temperatures, the lake will become uninhabitable for tilapia. Although desert pupfish have specific adaptations for saline conditions, they are unable to survive for longer periods of time, rendering the Sea impossible to traverse for individuals traveling between breeding habitats.

It is also assumed that as the Sea shrinks in size, HABs will increase in prevalence. Furthermore, these conditions will also reshape the species composition of organisms at lower trophic levels with conditions more favorable to extremophile microorganisms and arthropods. Piscivorous birds will all but disappear in the absence of suitable prey. Insectivorous birds may survive in areas such as managed wetlands; however, changes in the insect community near the shoreline may result in a lack of suitable prey for these birds. Ultimately the biodiversity, productivity and functioning of the aquatic ecosystem in this scenario will collapse. Key questions:

- Will there be changes in the organisms at the base of the food chain? Will phytoplankton-produced toxins be enhanced?
- When will the endangered pupfish be extirpated? Will there be remnant populations in river outflow channels?
- We expect bird populations to decline, but will they disappear altogether? Will migratory birds lose a key stopover site?

Stabilization

A CHANGE TO CURRENT water policy could intentionally direct a limited amount of Colorado River water to the Salton Sea.

If enough freshwater enters the lake to keep salinity levels in check, keeping tilapia populations stable, then perhaps piscivorous birds will remain. However, for tilapia to survive the Salton Sea would require higher inflows of freshwater rather than less, so it is likely that this scenario will result in the disappearance of fish and piscivorous birds. Microorganism and insect community composition, on the other hand, would likely reflect what occurs in other highly saline aquatic ecosystems, such as Mono Lake, where a prevalence of brine shrimp and flies support insectivorous birds. Key questions:

- How much water needs to be delivered to keep the ecosystem functional as it is today?
- Will created wetlands form suitable habitat for many of the important species?
- Can mitigation and conservation efforts be economically sustained?



WETLAND near the Salton Sea. PHOTO CREDIT to Irfan Khan. Copyright ©2019. Los Angeles Times. Used with permission.

Recovery

WITH LONG-RANGE PLANNING and significant capital investment, a significant new source of water could be pumped into the Salton Sea.

Water importation presents the best possible case for the survival and stability of fish and bird populations. However, the source of water will determine the Sea's community composition. Saltwater importation from the Gulf of Mexico may result in salinity too high for tilapia survival despite higher lake levels. Freshwater importation and wetland management is the best way to sustain the biodiversity, productivity and functioning of the Salton Sea ecosystem as we know it. Even with freshwater introduction, climate change may result in temperatures and oxygen availability incompatible with fish and birds. Key questions:

- What are the relative problems or opportunities that will originate from fresh or saltwater importation?
- How will food web structure change as lake volume and salinity change?

BOX 5C

6

Human Health

Health Disparities and Respiratory Illness in Salton Sea Communities

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HIGHLIGHTS

- Continued environmental degradation at the Salton Sea accompanied by increased production of dust and other air and water pollutants has already impaired the economic and social fabric of the region.
- In communities already subject to disparities in social and economic status, the environmental hazards are evident from the epidemiology of diseases, especially pulmonary diseases such as asthma.
- Comorbid factors including the high incidence of obesity, poverty, poor access to health care, and chemical exposures from agriculture work further degrade the quality of life, driving additional impacts on mental health in the community.

According to the 2010 U.S. Census, there are 130,000 people living within 15 miles of the Salton Sea, with another 650,000 directly affected by the dust emitted from the shoreline and surrounding desert and agricultural landscapes (Johnston, 2019). These areas around the Salton Sea face many socioeconomic disparities with potential impacts on health, including linguistic isolation, lack of education, lack of funding

and health profession shortages. These disadvantages likely exaggerate ongoing health disparities within these communities. Not only are there lesser access to health care providers but also a higher incidence of health problems, including the regional respiratory health crisis associated with windblown dust.

The drying of the Salton Sea is exposing dry lakebed, or playa, and increasing levels of ambient aerosol dust



INNER CANAL at Desert Shores, left behind as the shoreline receded. Caroline Hung

(Box 6A). Dust storms have been linked with cardiovascular mortality, asthma hospitalization, Chronic Obstructive Pulmonary Disorder (COPD) and decreased pulmonary function, problems that are only expected to get worse in the coming years (Johnston et al., 2019).

The high prevalence of asthma around the Salton Sea is already making headlines, as 1 in 5 Imperial County residents have been diagnosed with asthma. The national U.S. prevalence for asthma is 7.7% for adults and 8.4% for children, in stark contrast to the 22.4% prevalence seen in these counties (Branin and Martinez, 2007). These rates are high even in comparison with other nearby regions. A comparison with neighboring cities near the Mexico–U.S. border, thereby controlling for location and demographics with a cross-border population, showed that while some areas in Imperial County had exceptionally high rates of asthma prevalence of 26.5%, comparable cities near the Mexican border had rates of only 5.8%.

It is evident that respiratory disease is already a

public health crisis in the regions around the Salton Sea, particularly among children. Currently, Imperial County sees twice the number of pediatric asthma emergency room visits as California’s average (California Department of Public Health). Children are immunocompromised from the impacts of air pollution, as their lungs and immune system are still developing. This not only makes children susceptible to asthma episodes or respiratory distress, but also at risk for long-term effects such as a decreased lung growth and airway inflammation.

Particulate matter (PM_{10}) levels found in the area frequently exceed California’s 24-hour standard of 50 micrograms in a cubic meter ($\mu\text{g}/\text{m}^3$). They also regularly exceed federal standards of $150 \mu\text{g}/\text{m}^3$ in a 24-hour period. These excesses often occur during dust episodes lasting multiple days. These excesses are expected to lead to increased mortality, with previous work showing that increases of $100 \text{g}/\text{m}^3$ in PM_{10} can be expected to produce a 16% increase in death rate (Pope

et al., 1992). Occupational exposure to PM₁₀ has been linked to COPD, Organic Dust Toxic Syndrome (ODTS), bronchitis, pneumoconiosis, rhinitis, and asthma (Cohen, 2014). PM₁₀ can furthermore serve as a carrier for pollen allergens, further exacerbating allergic asthma in the area and increasing health risks.

Living further away from the exposed area reduces the risks of long term respiratory conditions; however, even at a greater distance from the Sea there is a link to an increased prevalence of cough, wheeze, bronchitis symptoms, eye irritation and nasal irritation (Figure 6.1). Additionally, the acreage being impacted by the dust particles is increasing dramatically, as exposed areas went from 862 to 16,542 acres between 2013–2016 (Formation Environmental, 2018). Therefore, it is predicted that the rate of asthma will increase in this area and may even be underreported and undiagnosed right now, specifically in children of Mexican origin.

Respiratory Symptoms

There is still work to be done in identifying possible connections between dust particles and their components to the respiratory symptoms seen in the area (Box 6A). Geothermal vents at the southeast margin of the Salton Sea are observed sources of free ammonia, which is known to cause coughing, nose and throat irritation (Tratt et al., 2011). Salton Sea playa has also been found to contain a relatively high fraction of soluble sulfate (Frie et al., 2017), which is known to further exacerbate allergic asthma. Mineral dust is also primarily made up of silica, which is known to cause chronic bronchitis or pneumoconiosis. Inhalation of dust exacerbates respiratory effects, increases hospital admissions, increases blood pressure and decreases lung function in young adults (Ostro et al., 2009). Dust storms become even more problematic as studies show that the dust can be associated with allergens, microbes, fungi, and viruses. This means that there is not only potential for asthma and respiratory distress

with dust storms, but also infections and mass transmission of infectious disease.

In addition, contaminants in the Salton Sea such as pesticides and heavy metals (e.g., selenium, arsenic) can be carried as components of the dust particles generated from playa emissions, and these compounds could also have effects on respiratory health. Pesticides are known to impact pulmonary health in the context of direct inhalation during agricultural activities (Hernandez et al., 2008). These components are commonly detected in agricultural runoff (Sapozhnikova et al., 2004). These compounds may be largely sequestered in the bottom sediments (Schroeder et al., 2002); however, these sediments may become exposed and emissive as the sea continues to shrink.

Finally, another factor that needs to be taken into account is the ecological instability in the drying Salton Sea itself and its contribution to environmental hazards associated with playa dust. For example, cyanobacteria detected in the Salton Sea can contribute potent liver toxins that may contribute to migratory bird deaths (Carmichael and Li, 2006). These and similar microbial toxins may be an important contributor to the playa dust with consequent pulmonary health impacts for humans as well.

Vulnerable Population

The communities living around the Salton Sea are primarily low-income, rural, and Latino, making them particularly vulnerable to the detrimental effects of low air quality and the long-term effects of chronic disease. In particular, inadequacies already exist in asthma management among Hispanic Americans, the predominant local population. High uninsured rates contribute to these vulnerabilities: 33% of adults and 15% of teens and children are uninsured in Coachella Valley (UCLA Center for Health Policy Research, 2011), however other factors leading to these disparities need to be addressed.

Table 6.1 Current and projected populations that will be affected by Salton Sea dust. Coachella Valley populations beyond 2035 County projection estimate at 1% annual growth rate. Source: Cohen (2014)

	2013	2015	2020	2035	2045	Source
Coachella Valley	469,248	488,300	576,161	842,960	931,150	Riverside County Projections
Imperial County	179,527	192,707	222,920	277,418	311,360	California Dept. of Finance
Total	648,775	681,012	799,081	1,120,378	1,242,512	

Components and Sources of Dust

NOT ALL COMPONENTS OF WINDBLOWN DUST are equally harmful to human health. Particulate matter is known to have adverse effects on the pulmonary and cardiac systems (Pope, 2000), but in the Salton Sea region, dozens of different types of coarse particulate matter up to $10\ \mu\text{m}$ in aerodynamic size (PM_{10}) originate from at least eight sources on the lake and surrounding landscapes (Figure 6.1). Fumaroles above the Salton Sea Geothermal Field emit free ammonia known to irritate mucus membranes, for example, and the exposed lakebed, or playa, along the receding shoreline releases sulfate (SO_4^{2-}), which is known to exacerbate allergic asthma. Most PM_{10} sources will become more prevalent as the acreage of playa increases.

Further research is critical to help regional planners design the most efficient mitigation plans as the Sea continues to shrink. Without establishing clear epidemiological connections between specific

dust components and known respiratory illness in local communities, it is impossible to discern what mitigation efforts will have the biggest pay-off from a public health perspective. If we rely only on the simplest association between pulmonary health and windblown dust, then increasing acreage of exposed playa will likely produce the worst outcome in terms of health effects.

If we take into consideration the role of specific dust sources, however, the worst case scenario may be surprisingly different. Consider a case in which microbial toxins from harmful algal blooms in the Salton Sea turn out to be the greatest health threat. In this hypothetical situation, designing a plan to reduce of biological toxins in the lake may be a more cost-effective public health investment than constructing dust mitigation berms on the playa to lower the overall production of dust.

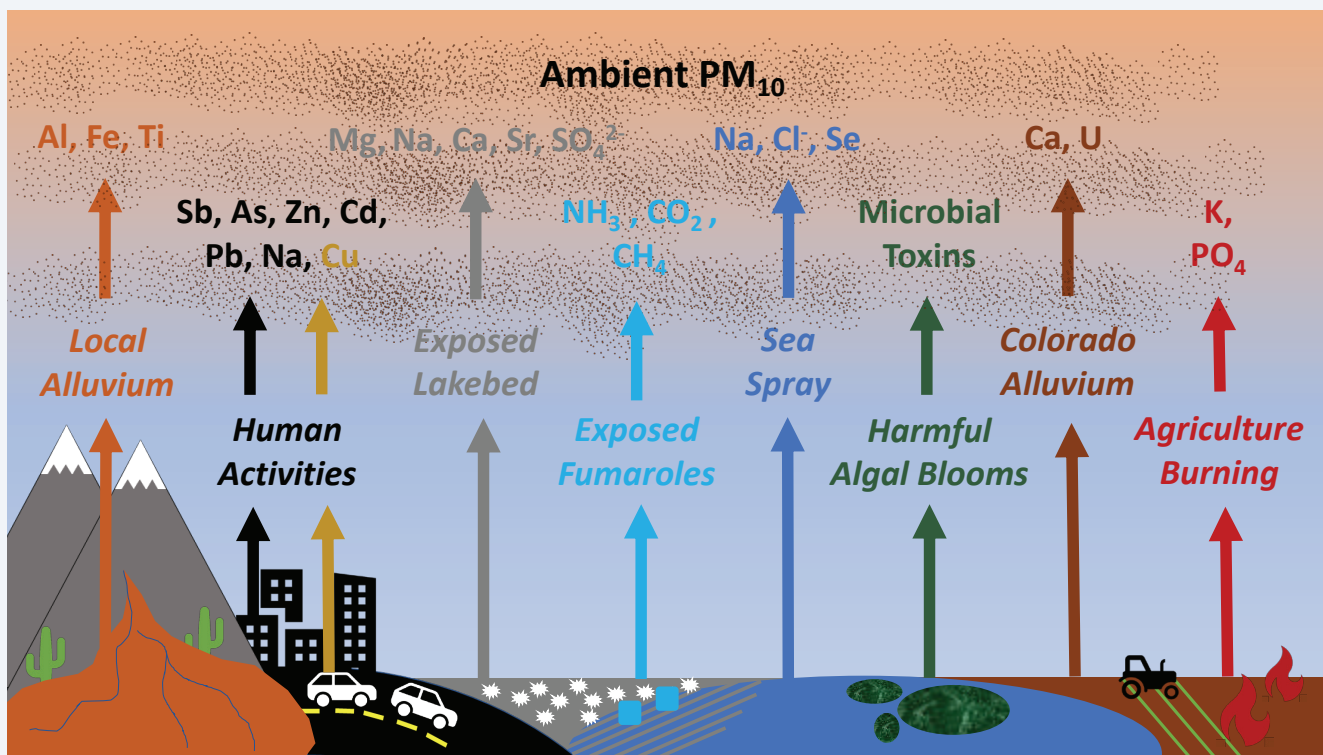


FIGURE 6.1 Sources and components of coarse particulate matter (PM_{10}) in and around the Salton Sea. Some of these components, such as microbial toxins and selenium (Se) are much more dangerous to human health than others. Credit: Alexander Frie and Roya Bahreini.



A significant percentage of people who identify as foreign born, primarily from Mexico and Latin America, experience unique barriers in language and culture. Compared to the California average of 22.1%, Imperial and Coachella counties have higher rates of English learners in public schools with 43.8% and 53.6%, respectively (California Department of Education, 2019), pointing toward communication obstacles that adversely affect quality of health care. Potentially due to these reasons, Hispanic populations are also less likely than other populations to seek medical care, opting for self-treatment and home remedies before seeking medical attention at a traditional healthcare facility. Thus, inadequate health education among communities may lead to the suboptimal medication use, adherence to treatment and preventative care measures.

Comorbidities can also have a significant impact. This area suffers from some of the highest rates of adult and pediatric obesity (UCLA Center for Health Policy Research, 2011), where obesity is linked to worse overall asthma control outcomes potentially due to synergistic effects through inflammation. Overall, linguistic barriers, the lack of cultural competency of healthcare providers and inadequate health education within communities carry transgenerational effects and negatively impact asthma management trends.

Agricultural Workers

Situated within the thriving agricultural hubs of Eastern Coachella Valley and Imperial County, the Salton Sea communities have a comparatively large percentage of the population working in these industries. For the farmworker communities such as Mecca, Thermal, Oasis and North Shore, specific data on health impacts is difficult to assess; however, it is reported that more

AGRICULTURAL FIELDS in the Imperial Valley. Jonathan Nye

than a third of the population lives below the poverty line, with poverty levels as high as 43% in Oasis (U.S. Census Bureau, 2018). The immediate impact on agricultural workers, brought about by the long hours outdoors and physically intense labor, may further aggravate potential exposure to harmful pollutants.

Agricultural workers are already disproportionately affected by respiratory conditions and are at higher risk for developing chronic conditions, yet a majority do not have health insurance (Ayala et al., 2001). An evaluation of agricultural worker health and housing found that many of these workers not only suffer from the healthcare disparities already mentioned, but also through struggling home environments where mobile homes make up a significant proportion of housing coupled with hazardous electrical hookups, contaminated well water and inadequate septic systems (Branin and Martinez, 2007). This area experiences some of the harshest weather during summers and unreliable air conditioning can pose a threat through further exposure to the poor air quality as open windows are the only ventilation option.

Moreover, the agricultural industry is a significant contributor to Salton Sea pollutants through irrigation runoff containing pesticides, such as organophosphorus insecticides, chlorpyrifos and industrial contaminants as well as contributing to aerosolized particulate matter (Johnston et al., 2019), in addition to direct hazards to the workers as part of agricultural activity.

Mental Health

There is also the issue of the effects on mental health and the existing difficulties in care. As recently as 2019,

BOX 6B

Health and Socioeconomic Disparities

COMMUNITIES SURROUNDING the Salton Sea face an alarming deficiency in access to health care. The U.S. national average of Primary Care Physicians (PCPs) is 68 per 100,000 people in rural areas and 84 per 100,000 people in urban areas (Pettersen et al., 2013). By contrast, only 52 PCPs serve the roughly 130,000 people who live within 15 miles of the Salton Sea (21 PCPs in Imperial County, at the southern end of the lake, and 31 PCPs in Coachella Valley at the northern end), which qualifies this region as a Medically Underserved Area (MUA). Coachella Valley and Imperial County also face additional socioeconomic barriers. For example, California’s average poverty level

is 12.8%, while poverty levels in Imperial County and Coachella Valley are 23.2% and 19.9%, respectively. This disparity is also apparent in per capita income: Imperial County residents average \$16,920 per year while Coachella Valley residents average \$25,595, much lower than the California state average of \$37,124. Educational achievement also lags behind state averages, with high school diploma attainment rates 14% lower in Imperial County and 11% lower in Coachella Valley. The discrepancy is even greater for higher education, with bachelor degree attainment rates 20% lower than state averages in Imperial County and 18% lower in Coachella Valley (U.S. Census Bureau, 2018).

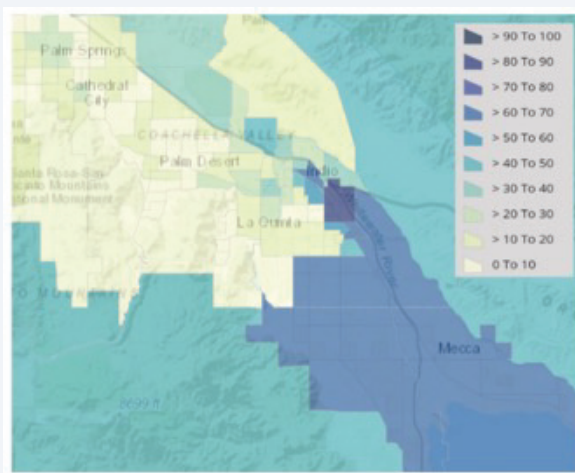
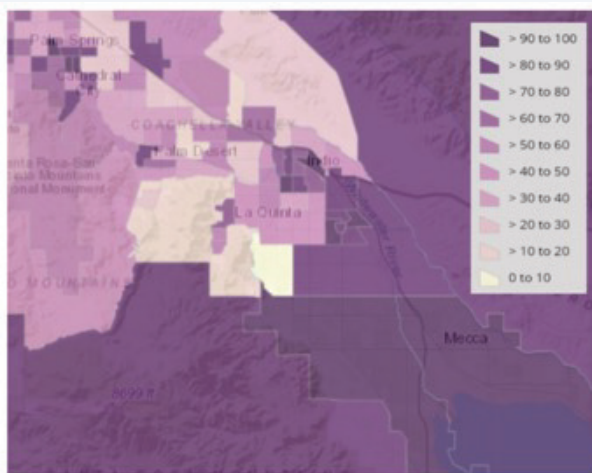


Figure 6.2 Coachella Valley poverty percentiles (left) and pollution burden percentiles (right). Adapted from the CalEnviroScreen 3.0 Overall Results and Individual Indicator Maps provided by the California Office of Health Hazard Assessment (OEHHA). Credit: Faust and August (2017).

Coachella Valley community leaders reported mental health as the issue requiring the most priority due to the risk of significant impact to the community, a worsening prospective and the severe lack of resources (Eisenhower Health, 2019). In 2005, of all the counties in California, Imperial County and Riverside County had the two lowest percentages of those who reported to see mental health specialists in the last year, with only 4.2% and 5.2% in each county respectively as well as some of the lowest per capita rates of mental health providers and resources- Imperial county being the lowest in almost all categories. This need is further

complicated when the language sensitive communication of mental health is paired with linguistic barriers and the stigma around mental health issues within Hispanic communities.

Additionally, some studies have identified migrant farm workers as particularly vulnerable to psychological distress (Ayala et al., 2001) and others have found a relationship between mental health and asthma severity, particularly with anxiety and depression (Ledford and Lockey, 2013). With already high documented rates of anxiety in Imperial County, the lack of access to mental health providers and resources is a worrisome



OLD DOCK along receded shoreline. Jonathan Nye

disparity that may be exaggerated by health effects of the pollution and decreasing property value.

This discussion has been based largely on various data sources that point to a connection between playa dusts and health impacts, and statistical associations between the Salton Sea and the locally high incidence of asthma. These associations are strongly suggestive and have driven the initiatives to mitigate local dust generation and address the problem of the retreating Salton Sea. However, the health impact associations and proposed mitigation activities are based on a number of inferences and assumptions. At UCR, ongoing studies are aimed at establishing direct connections rather than rely on inference, and we propose that many more targeted research studies will be critical to validate the assumed connections so that the mitigation and other initiatives are actually directed at solving the true underlying causes of disease.

Research Needs

In the context of possible futures of the Salton Sea, ongoing research will be needed to guide predictions of how each scenario may impact the local health effects. As noted here, work is still needed to identify

the main contributors to the aerosols with the most potent pulmonary health effects. If we rely only on the simplest association between pulmonary health and dusts, then the first two scenarios, leaving more exposed playa, will likely be worst in terms of health effects. However, if we also take into consideration the role of Salton Sea ecology and potential contribution of biological toxins, then it may be determined that reducing biological toxins may have a greater impact on health than improved dust levels from reductions of exposed playa. Thus, changes in the salinity may have disproportionate impact on ecosystem and microbiome stability, with impact on microbial toxin production. Indeed, one possible outcome from Scenario 1 is that at a higher end salinity, the ecosystem stabilizes and toxin production drops. Moreover, at higher salinity, pesticides and heavy metals in the water and food chain may be more stably sequestered in sediments, reducing their presence in playa dusts.

Thus, ongoing research is essential for understanding the various environmental hazards and their impacts on health. One area where new research is absolutely critical is in the detailed epidemiology of

clinical disease in the various Salton Sea communities. The aerosols in the region show seasonal changes due to wind direction and variation in emissivity at different locations around the sea (Chapter 4), so populations affected by the aerosols may also show variation in clinical symptoms. In addition, the clinical term “asthma” is a rather general diagnosis referring only to airway hyperreactivity. Given the apparent connection to environmental aerosols in the region, there may be a number of factors leading to clinical asthma, which may be rather different from those inducing more conventional allergic (or “atopic”) asthma. A detailed clinical study is critically needed to establish the actual clinical entity diagnosed as asthma in the region. If the underlying cause for airway hyperreactivity is connected to some previously unknown source at the Salton Sea, this knowledge could drive a more targeted and appropriate strategy for mitigating the health impacts.

Because available evidence implies a direct relationship between the Salton Sea and health impacts, the evident ecologic instability of the sea may also be a key factor; yet there are no studies focused on the changing ecology and its potential impact on health in the region. The contributions of the local geochemistry and pesticide and chemical runoff into the sea may further stress the system. The health impacts could be through microbial components or toxins that may contribute to the aerosols; while some studies have tracked chemical sources of dusts, a pathway from the sea’s organic and biological components into local aerosols has not yet been established.

Finally, this compilation refers to scenarios representing different mitigation strategies. For the reasons discussed here, since we have not yet identified the key sources of health impacts at the Salton Sea, evaluating the effects of the different mitigation scenarios will have to depend on understanding which effects are most important to the health effects, whether it involves ecological stability, overall dust emissions from exposed playa, or other factors. Moreover, it is not clear whether any of the critical health disparities will be addressed by any of the scenarios, since restoration of the local economy and associated improvements in health care access are not addressed.

In sum, these are not insurmountable issues. It is our hope that the discussion in this report will begin to provide the necessary focus on the key issues affecting health in the region.

Current Research

BOX 6C

FOUR ONGOING, INTERDISCIPLINARY research projects at the University of California, Riverside (UCR) address health issues at the Salton Sea. The overall goal of these studies, led by researchers in the BREATHE Center and the Center for Health Disparities Research in the UCR School of Medicine, is to determine health responses to the particulate compositions around the Salton Sea to provide insights on the local disparities and risk factors to health. Of particular interest is understanding how local aerosols contribute to the incidence of childhood asthma with the hope of leading to better diagnosis and treatment of pulmonary disease in the region.

- 1** A Community Advisory Board in East Coachella Valley has been created to build a network among families living with asthma. The board will act as a conduit to obtain qualitative data on asthma-like symptoms to assess impact on local resident families.
- 2** Atmospheric modelers are studying spatial patterns of aerosol and pollutant transport to determine population exposures.
- 3** Environmental scientists and microbiologists are identifying elemental and microbial sources of aerosol particles and their sources in and around the Salton Sea such as topsoil, drying lakebed or marine organisms.
- 4** Biologists and medical experts are studying animal models in environmental chamber exposures to simulate and assess the effects of aerosol particulates and aerosolized environmental components such as Salton Sea spray. Preliminary studies have been examining the impact of local aerosols on pulmonary inflammation and their potential relationship to asthma. Future studies will examine the combinatorial effects of pollution, particulates and biological components from the area.

7

Geothermal Resources

Lithium and Other Geothermal Mineral and Energy Resources Beneath the Salton Sea

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HIGHLIGHTS

- Salton Sea management plans should consider economic opportunities to expand the region's active geothermal industry, as the receding shoreline opens new land suitable for construction of both wetlands and new geothermal infrastructure.
- The existing industry has tremendous potential to become a world-class producer of lithium and other metals, which can be extracted from geothermal brines. Expanding current electrical production would boost California's capacity to meet legal mandates for more renewable energy and lower greenhouse gas emissions.
- These efforts would lead to substantial local job creation and increased tax revenues, which would greatly benefit the local economy.

California has some of the most aggressive greenhouse gas (GHG) mitigation and renewable energy generation targets in the world and will likely mandate even more ambitious goals on both fronts. Key targets include the Renewable Portfolio Standard (RPS), which reduces GHG emissions to 40% below 1990 levels by 2030 and also reduces Short Lived Climate Pollutants. There are several programs in place aimed

at helping the State achieve these RPS targets, including the cap-and-trade program, energy efficiency requirements, the Low Carbon Fuel Standard, vehicle-related programs, and vehicle miles traveled targets. Reductions of emissions and increased use of renewable energy will be required across multiple sectors in order to achieve these goals. Under the current RPS established by California Senate Bill 350, the state's



GEOTHERMAL POWER PLANTS at the Salton Sea Geothermal Field. Jonathan Nye

mix of electric power will consist of 40% renewables by 2024 and 50% by 2030. California Senate Bill 100 accelerates the required penetration of renewables into the electricity grid and will achieve a 60% RPS by 2030 and 100% by 2045.

Geothermal electric power production from the Salton Sea Geothermal Field (SSGF) is one source of renewable energy that will help California meet its legislated targets. Potential production of lithium from the SSGF geothermal brines can also reduce import reliance and lower the costs of manufacturing batteries for electrical vehicles and devices, furthering the GHG goals of the state and nation. In 2020 California Assembly Bill 1657 established a Commission on Lithium Extraction in California to review, investigate, and analyze certain issues and potential incentives regarding lithium extraction and use in California.

Current Power Production

CALIFORNIA HOSTS the largest geothermal electrical capacity in the nation and in the world, producing

nearly 11,000 GWh of electricity annually, or just over 5% of the total electricity produced in the state from all sources (California Energy Commission, 2019). A total of 43 geothermal power plants in the state have an installed electrical capacity of 2,730 megawatts (MW) of electrical power. The Salton Sea Geothermal Field (SSGF), located at the southeast edge of the Sea, is the second largest geothermal electricity producer in the state, with eleven plants having an installed generating capacity of 432.4 MW (US Energy Information Administration, 2021). These turbines utilize steam with temperatures of up to 250°C from production wells that are typically 1 to 3 km deep. A recent estimate of the SSGF's geothermal reserves to 3 km depth indicates that this reservoir has very large geothermal reserves capable of generating 2,950 MW for 30 years (Kaspereit et al., 2016). As the water level of the Salton Sea continues to drop, additional dry land is exposed suitable for new geothermal development (Figure 7.1).

Unlike solar and wind energy, which are intermittent and sensitive to weather and fires, geothermal

resources supply baseload power available 24 hours a day. However, the development of geothermal power has longer lead times and higher capital costs compared to those intermittent renewable energy resources. Despite its huge heat content, development of the SSGF's geothermal resources lagged behind that of other geothermal fields in California because of a unique feature: the unusually high salinity (up to 28 wt. % TDS) of the hot reservoir brines that causes corrosion and scaling and requires management of solids precipitation. This problem was overcome at each of the power plants operating at the SSGF today by creative-but-expensive chemical engineering, mainly the addition of a reactor/clarifier circuit to remove solids from reinjected brines. Because of the huge penetration of relatively inexpensive solar power in California in a competitive power market, new power purchase agreements are more difficult to obtain for more costly geothermal plants at the SSGF. Therefore, all but one of the existing eleven geothermal plants are now between 20 and 38 years old.

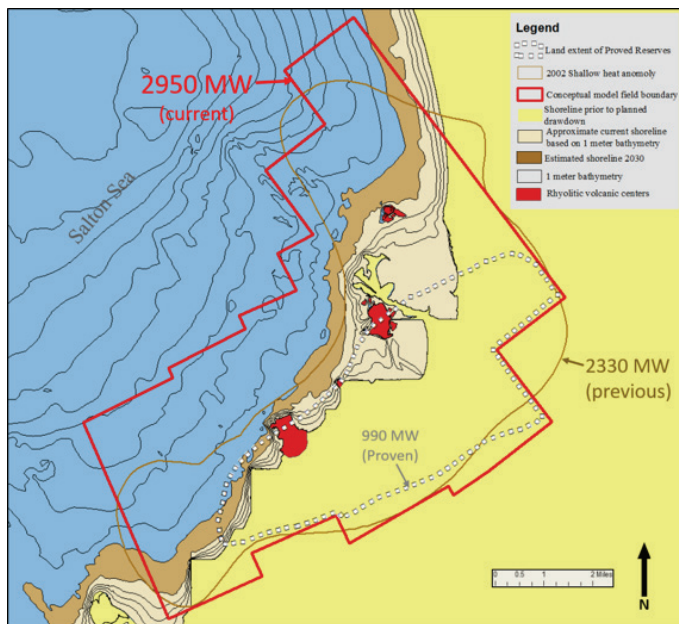


FIGURE 7.1 Outline of previous Salton Sea geothermal reservoir limit based on the shallow heat anomaly shown in brown, with the new boundary based on the new conceptual model shown in red. Proved reserves are shown by the dotted white outline. Light brown is the area (and reserves) that had been exposed by the receding sea as of 2016. By now some of the darker brown area, which is required for a project to be completed, is also exposed. Directional drilling could extend the area by 0.5 mile from pads on the exposed lakebed.

Credit: Kaspereit et al. (2016).

Today, new developments are turning the high dissolved mineral content of the SSGF brines from a liability into an asset. Recently a new geothermal operator, Controlled Thermal Resources, announced its intention to construct a new 300 MW geothermal plant utilizing new wells in the northern part of the SSGF. This expansion has become economically feasible because of the additional revenue that will be generated at this new plant by extracting lithium, manganese, and other metals from the SSGF brines. In recent years, the market for lithium for use in lithium batteries has grown enormously. In 2020 CalEnergy, the operator of ten of the existing geothermal plants at the SSGF, announced that it will spend up to \$12 million to build a pilot plant to extract lithium from the SSGF brines, supported by a \$6 million grant from the California Energy Commission.

In this paper we review the potential for developing this and other nontraditional sources of revenue from the geothermal brines of the SSGF in the context of likely scenarios for environmental mitigation at the Salton Sea. In addition to the potential revenues from extracting metals, we discuss making geothermal power generation more economically competitive with solar by storing energy at times of day when electricity demand is low by making hydrogen via electrolysis of clean water, and by pumped storage.

Strategic Metals

DISCOVERED IN THE EARLY 1960s and sensationalized for their high concentrations of dissolved salts and metals (White, Anderson, and Grubbs, 1963), the hot, hypersaline brines of the SSGF reservoir typically contain about 26% total dissolved solids including 1500 mg/kg manganese (Mn), 500 mg/kg zinc (Zn), and 200 mg/kg lithium (Li) (Table 7.1). Only the hot brines of the adjacent Imperial/South Brawley geothermal field south of the SSGF contain similar levels of dissolved metals. Metal concentrations in the SSGF reservoir brines vary linearly with the level of chlorine (i.e., chlorinity) of the brines (McKibben and Williams, 1989) and are therefore highly predictable (Figure 7.2).

Lithium concentrations in the reservoir rocks are quite variable but more constrained at depth (Figure 7.3), implying that metamorphic reaction with the brines at high temperature has somewhat homogenized their original sedimentary concentrations. The

TABLE 7.1 Representative flash-corrected chemical compositions of geothermal reservoir fluids in the Imperial and Mexicali Valleys. Credit: McKibben and Hardie, 1997.

Field:	Salton Sea	Imperial	Cerro Prieto	East Mesa	Heber
Well:	S2-14	L2-28	M-5	6-1P	5
Temperature(°C):	330	275	300	~ 190	195
Depth (m):	2500–3220	3290–4270	~ 1200	~ 2164	~ 1800
Na	54,800	50,466	5,004	6,362	4,019
Ca	28,500	18,140	284	759	750
K	17,700	9,555	1,203	1,124	333
Fe	1,710	3,219	<1	NA	NA
Mn	1,500	985	1	NA	NA
SiO₂	>588	465	569	257	237
Zn	507	1,155	NA	NA	NA
Sr	421	1,500	NA	NA	41
B	271	217	11	NA	4
Ba	~ 210	2,031	NA	NA	4
Li	209	252	13	NA	7
Mg	49	299	<1	9	2
Pb	102	>262	NA	NA	NA
Cu	7	>1	NA	NA	NA
Cd	2	4	NA	NA	NA
NH₄	330	NA	NA	NA	6
Cl	157,500	131,000	9,370	11,668	7,758
Br	111	NA	31	NA	NA
CO₂	1,580	30,000	2,400	NA	186
HCO₃	NA	NA	NA	221	NA
H₂S	10	>47	180	NA	1
SO₄	53	NA	4	51	66
TDS	26.5%	25.0%	1.6%	2.2%	1.3%

average lithium content in the rocks is 40 ppm compared with >200 ppm in the brines (Table 7.1), indicating that the bulk of the recoverable lithium resource in the geothermal field currently resides within the brines rather than the rocks. This is similar to the case for other valuable metals such as manganese, zinc and copper (McKibben and Hardie, 1997).

The total amount of each metal contained within the utilized brine reservoir (like the reserves of a traditional mine: ore grade times tonnage of ore) has been estimated from data on reservoir volume, porosity and brine composition (McKibben et al., 1990; McKibben and Hardie, 1997). The currently exploited volume of

the SSGF geothermal brine reservoir to a depth of 2 km contains a conservatively estimated 1013 kg of hyper-saline brine. With a density of 1.0 at 300°C, this corresponds to a total of 11 km³ of brine. The total masses of dissolved metals of economic interest in the brines are thus: 15 million metric tons of manganese, 5 million metric tons of zinc, and 2 million metric tons of lithium. These can be considered the “proven reserves” of dissolved metals in the currently exploited geothermal field (Table 7.2). These resource estimates were conservative because only the known, currently drilled, portion of the SSGF brine reservoir to a depth of 2 km in the mid-1990s was considered, whereas more recently

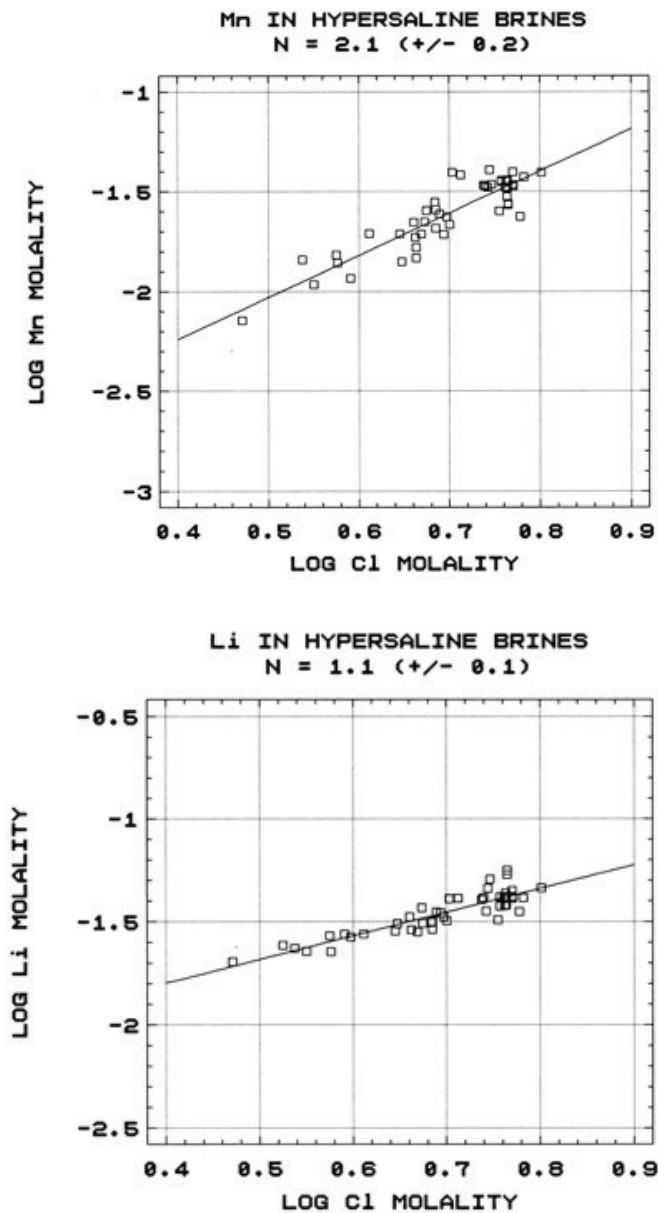


FIGURE 7.2 Variation of dissolved manganese (Mn) and lithium (Li) metal content (in molality: moles of metal per kilogram of brine) as a function of the brine's chlorinity (dissolved chlorine molality) in the Salton Sea Geothermal Field reservoir brines. Credit: Michael McKibben. Source: McKibben and Williams (1989), including unpublished data on lithium.

Kaspereit et al. (2016) estimated the stored energy of the SSGF to a depth of 3 km over a larger area (Figure 7.1). Any expansion of the lateral or deeper dimensions of the brine reservoir would significantly expand these resource estimates. To appreciate the magnitude and significance of these conservative “proven reserves” estimates, it is informative to compare them to the annual global production of these metals from traditional mine sources along with their US production and import reliance (Table 7.2).

Currently, lithium is produced globally from both hard rock mineral mining (mainly in Australia and China) and the evaporation of salt-lake brines (mainly Argentina, Chile, and China). The cost of production from salt-lake brines is about 40% lower than the cost of production from hard rock mines (Canaccord Genuity, 2018). The cost of production of lithium from SSGF geothermal brines has been estimated to be comparable to that for production from salt-lake brines (Besseling, 2018). Production of metals from the SSGF has an added environmental and cost benefit, as these brines are already being brought to the surface to produce steam to generate electricity. The additional circuit needed to extract the metals from these brines would have minimal environmental impacts compared to opening a new hard rock mine (using sulfuric acid) or a new salt-lake brine operation (with high solar water loss).

Hund et al. (2020) estimated for the World Bank that global lithium production would need to increase 500% by 2050 to meet total demand for clean energy technologies, including electric vehicles, batteries for mobile devices, and energy storage batteries. The World Bank predicted that by 2050 cumulative annual lithium demand will grow to ~5,000 metric kilotons and cumulative annual manganese demand will grow to ~7,000 metric kilotons, just for battery technologies alone. Similarly, the United Nations Conference on Trade and Development (2020) reported that the worldwide market for the cathode in lithium ion batteries was estimated at \$7 billion in 2018 and is expected to reach \$58.8 billion by 2024, a nearly ten-fold increase from today. They also note that in Chile, lithium mining uses nearly 65% of the water in the country's Salar de Atacama region, one of the driest desert areas in the world, to pump out cold salt-lake brines from drilled wells. This has caused groundwater depletion and pollution, forcing local quinoa farmers and llama herders to migrate and abandon ancestral settlements.

BOX 7A

Lithium and Other Metals in Geothermal Brines

ANY SIGNIFICANT PRODUCTION of lithium, manganese and zinc from the SSGF brines could make the United States a significant global producer and reduce its large import reliance on these metals, as well as providing corresponding commodity tax revenues to local, state and federal governments. In the case of lithium, the SSGF could potentially become a major supplier of this metal to the global market, eliminating imports of this strategic metal from South America and China.

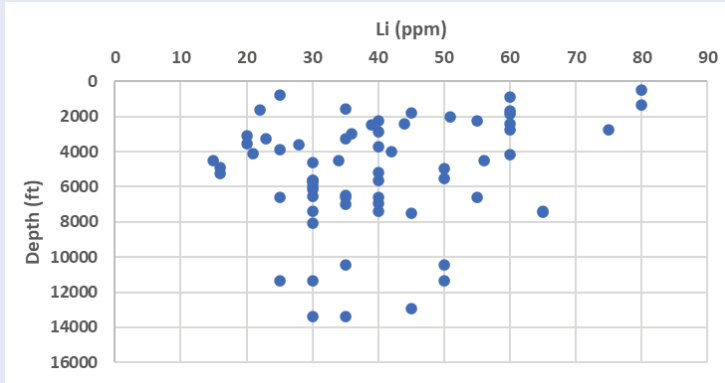


FIGURE 7.3 Variation of lithium (Li) metal content in parts per million (ppm) versus depth for cuttings and core from several drill holes in the Salton Sea Geothermal Field. Credit: Mike McKibben. Source: Unpublished spectrographic data provided to S. D. McDowell, collected in 1971 by D. E. White, L. J. P. Muffler and H. Bastron, USGS.

TABLE 7.2 Total brine metal reserves in the Salton Sea Geothermal Field (SSGF) relative to global production (in metric kilotons), US import reliance and US production. Source: USGS Mineral Commodity Summaries (2020).

Metal	SSGF Proven Reserves	Annual Global Production	U.S. Import Reliance	Annual U.S. Production
Lithium	2,000	77	>25%	Withheld
Zinc	15,000	13,000	87%	900
Manganese	5,000	19,000	100%	None

TABLE 7.3 Potential metal production (in metric kilotons per year, ktpa) from Salton Sea brines based on electrical capacity at nine CalEnergy power plants (Besseling, 2018) relative to US annual consumption. Source: USGS Mineral Commodity Summaries (2020).

Metal	Current Capacity (350 MW)	Projected Capacity (700 MW)	Annual U.S. Consumption
Lithium	17	40	2
Zinc	32	100	950
Manganese	98	310	740

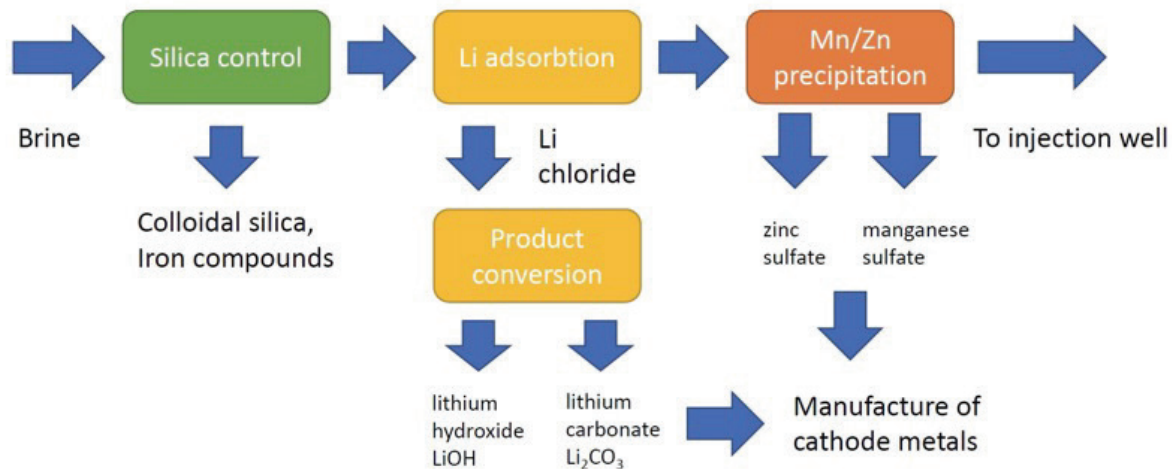


FIGURE 7.4 Scheme for extracting lithium and other valuable chemicals from Salton Sea geothermal brines. Manganese and zinc extraction can precede that of lithium. Credit: Harrison (2010a).

It has also contributed to environmental degradation, landscape damage and soil contamination. Thus, reducing or eliminating US import reliance on lithium by using deeper hot SSGF brines that are already being produced for electricity and then reinjected safely into the geothermal reservoir not only has economic benefits to the United States but also would reduce environmental consequences of traditional mining operations in other locations (Box 7C).

The technology for extracting lithium from saline brines is well known (e.g., Meshram et al., 2014; Murodjon, et al., 2019; Marthi and Smith, 2019; Paranthaman et al., 2017), with direct adsorption/desorption methods being most effective for the hot SSGF brines (California Energy Commission, 2020). Harrison (2010a) describes a sequential scheme for extracting multiple metals from the hot brines (Figure 7.4). Besseling (2018) recently estimated that the nine CalEnergy plants in the SSGF could produce the annual amounts of metals shown in Table 7.3 at both their current electrical installed capacity (350 MWe) and a near future expanded electrical capacity (700 MWe).

Lithium production from the SSGF (17 to 40 ktpa) could easily meet the U.S.'s current demand (2 ktpa) and eliminate its import reliance, as well as supply a significant fraction of the current global production (77 ktpa) (Table 7.2). Obviously, such production levels would have to be approached cautiously so as not cause large price elasticity by flooding the global lithium market. Instead, metal production from the SSGF

should be ramped up gradually to keep pace with rapid growing global lithium demand over time as predicted by Hund et al. (2020) and the United Nations Conference on Trade and Development (2020). This approach would also align itself with the stepwise development and refinement of recovery technologies for high volume geothermal brines.

Need for Flexibility

GEOTHERMAL POWER PLANTS generate readily available stable baseload electric power, but the growth of geothermal electric power generation in California has been slowed by the widespread availability and low costs of solar and wind power (Elders et al., 2018, 2019). The extensive penetration of solar power has resulted in circumstances where there can be overgeneration on sunny days, followed by a deficit when the sun sets (Figure 7.5).

This overgeneration can lead to low renewable electricity prices while also resulting in 'curtailment' of excess electricity. The undeveloped part of the geothermal resource of the SSGF is probably the largest known undeveloped geothermal resource in the world. Fully developing the SSGF's estimated 2.7 GWe of resources thus could contribute substantially to the projected 13 GWe ramp in demand for electricity in California when the sun sets (Figure 7.5). However geothermal wells need to flow at a constant rate to remain stable, so the answer to this dilemma is to develop technologies for storage of renewable energy.

These technologies need to be dynamic and capable of providing load-following while also being commercially profitable. The Imperial Irrigation District (IID), the sole electric utility in Imperial County, operates a 30 MWe pumped storage facility at Pilot Knob near the international border with Mexico.

Pumped Storage

THE SSGF HAS THE POTENTIAL to play an important role in providing an essential service to the local community while developing new revenue streams. This benefit could be achieved by taking advantage of the terrain surrounding the Salton Sea to build pumped storage facilities, by using the electricity generated for electrolysis to produce hydrogen and osmosis to produce deionized water, and by cascading the thermal effluent to produce hot and chilled water for district heating or cooling (Shnell et al., 2018; Elders et al., 2018).

We propose an investigation of the feasibility and economics of building large, pumped storage plants that use the water of the Salton Sea and the electric-

ity of the SSGF as the power source. Augmentation of the geothermal electricity produced alone would add to the problem of oversupply when the sun is shining, but during low demand, the geothermally generated electricity could be used to pump water from the Sea to upper storage reservoirs. When the sun sets, this water would flow down back to the Sea and drive hydroelectric turbines that would produce electricity in the evening hours to supply power when demand rises.

If the upper reservoir was sited in a basin in the hills west of Desert Shores, for example, at an elevation greater than 12 m above sea level (the level of the shoreline of ancient Lake Cahuilla), with the surface of the Salton Sea at ~72 m (-236 feet) below sea level, there is the potential for a hydraulic head of more than 84 m. If the intake in the Sea was in the northern deep basin of the Sea, about 10 m below the lake surface, this would have the added advantage of oxygenating some of the bottom water, which exhibits extreme anoxia. Such a scheme might begin with a modest (<50 MW) demonstration plant which, if successful, could be scaled up to the gigawatt level with its operation inte-

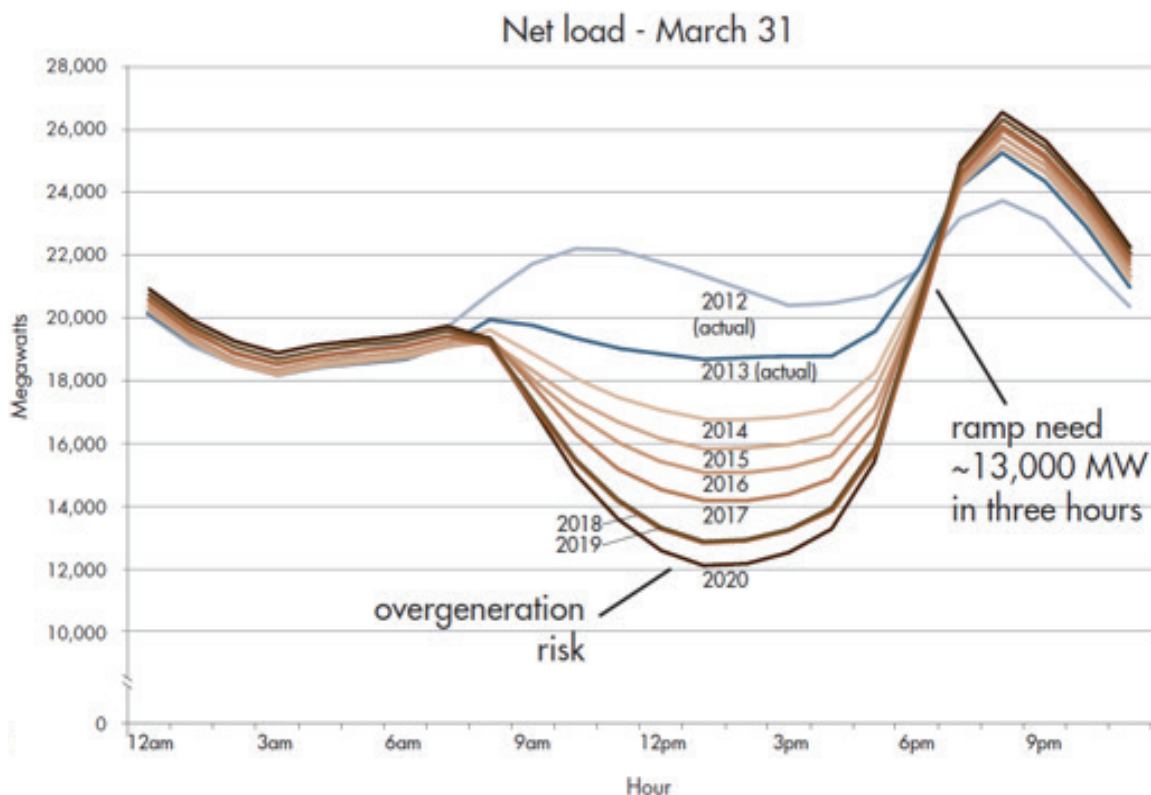


FIGURE 7.5 Projected daily electricity demand, minus wind and solar generation, on a typical spring day in California. There is a risk of overgeneration in the middle of the day and early afternoon, followed by a steep ramp where an additional 13 GWe is needed. Credit: California Energy Commission (2017), Figure ES-4.

grated with the geothermal plants at the south end of the Sea, or possibly using new solar plants. Of course, having the Salton Sea ringed by numerous pumped storage plants would lead to daily fluctuations in lake level that could introduce new environmental issues that would need investigation and mitigation.

Combining Outputs

This concept, shown in Figure 7.6, can be applied to existing or to new wells to be drilled. The SSGF brines would be produced from a reservoir with temperatures of $\sim 300^{\circ}\text{C}$, which delivers fluids to the surface at temperatures of about 250°C . Residual brine after use would be re-injected into the geothermal reservoir. The hydrogen produced could be stored on-site, or elsewhere, as a long-term energy storage medium and be used as an energy dense fuel, or used as feedstock for manufacturing salable products such as ammonia fertilizer or hydrochloric acid, to generate additional revenue streams. There are several commercial electrolysis technology providers with most of them being alkaline or polymer electrolyte membrane electrolyzers (Ivy, 2004; Harrison, 2010b). The lack of market penetration for electrolytic hydrogen is primarily due to its higher production cost compared to producing hydrogen from natural gas. The cost of electrolytic hydrogen

depends heavily on the cost of electricity. Transportation costs and infrastructure availability/compatibility issues also pose challenges to projects where the hydrogen is not intended for ‘captive use’. Although this electrolysis technology was commercialized decades ago, currently it accounts for only $\sim 4\%$ of world hydrogen production (Kelly, 2014). This is primarily due to the higher cost of production by electrolysis and the fact that hydrogen consumption is dominated by large scale industrial processes that require centralized production in high volumes. However, electrolysis using renewable electricity offers an important pathway towards carbon free energy production and usage. Electrolysis also generates very high purity hydrogen and technology options exist for hydrogen production at very high pressures.

High temperature water electrolysis yields higher efficiencies and is a major area of research focus. Detailed reviews of alkaline and solid polymer electrolyte electrolyzers are available in the literature (Kelly, 2014; Millet et al., 2013; Rashid, 2015). Geothermal energy can however be used in a number of hydrogen production configurations using existing commercial technologies. Below are some of the key approaches: (1) utilization of geothermal electricity and heat in alkaline or PEM electrolyzers. (2) utilization of geothermal heat in ther-

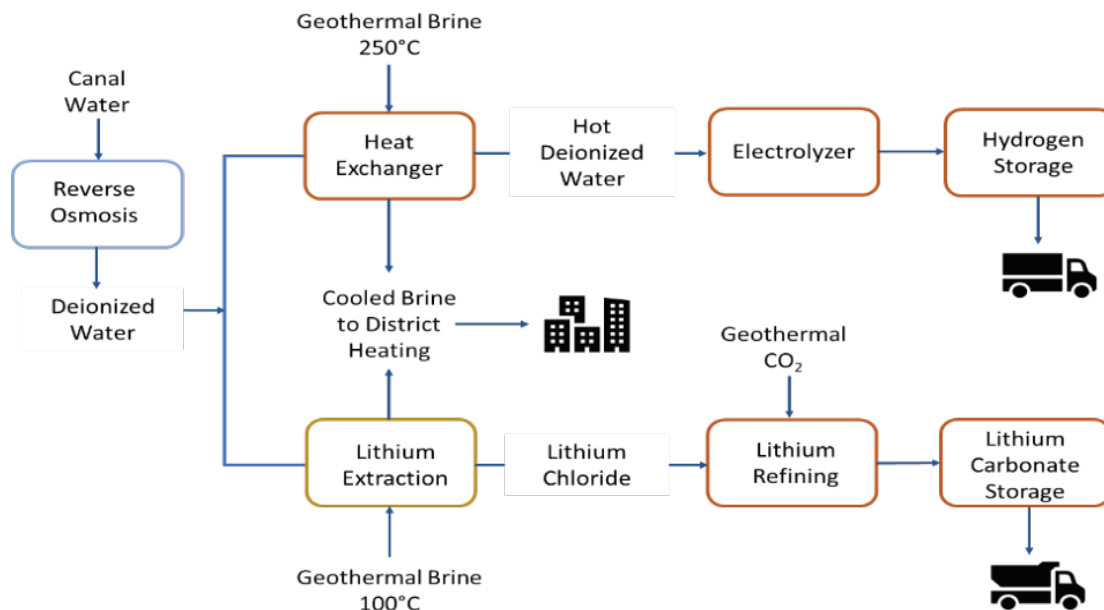


FIGURE 7.6 Conceptual design of lithium and hydrogen extraction from Salton Sea geothermal brines at temperatures of 250°C and 100°C . Direct conversion of lithium chloride to a lithium hydroxide product would be more advantageous for battery manufacture. Credit: Elders et al. (2019).

RESEARCH HIGHLIGHT: Environmental Analysis

BOX 7B

RESEARCHERS WITH THE SUSTAINABLE FUELS INITIATIVE at UC Riverside are working actively to assess the full range of potential environmental impacts of geothermal resource development at the Salton Sea Geothermal Field.

Lithium recovery from geothermal brine involves chemical processing of the spent brine that is produced as part of the geothermal power plant operation. After steam is drawn off to run electrical turbines, the spent brine is clarified and then reinjected deep beneath the ground to replenish the geothermal reservoir and avoid the accumulation of potential contaminants at the surface.

Besides the energy efficiency and recovery cost of lithium, it is important to evaluate the net greenhouse gas (GHG) footprint of the process, the

potential air and other emissions, and the net water consumption. Therefore, a Life Cycle Assessment (LCA) of the overall process should be conducted to estimate the fossil and renewable energy consumption, any criteria pollutant and toxic emissions, and GHG emissions. A Techno-Economic Analysis (TEA) is also necessary to calculate the material and energy balances, net water consumption, and anticipated production costs.

Hydrogen production through electrolysis should also be evaluated through LCA and TEA calculations to understand the environmental footprint and commercial viability. A comprehensive analysis that incorporates a multiple product stream may be necessary for facilities that produce power, lithium or other minerals, and hydrogen.

mochemical processes and hybrid cycles, and (3) direct hydrogen production through separation of hydrogen molecules from geothermal gas vents.

Local Economic Benefits

PRODUCTION OF LITHIUM and other metals, electrolytic hydrogen, and pumped energy storage from the SSGF can provide substantial job opportunities and tax revenues in the Imperial Valley. Besseling (2018) recently estimated employment numbers associated with construction and maintenance of lithium extraction facilities, as well as anticipated revenue and county tax receipts (Table 7.4).

Both pumped storage and commercial hydrogen production at the SSGF would help balance the electric grid. If applied in other geothermal fields the global reduction in GHG will depend on the degree of acceptance by the geothermal industry, but could be large and replicable at geothermal plants worldwide (Elders et al., 2018, 2019). We envision ultimately that new fully integrated geothermal plants at the SSGF will become factories producing hydrogen, metals, and water for heating and cooling, while producing electricity, with much of it consumed internally. The reduction in GHG will come from keeping CO₂ out of the atmosphere by:

(1) displacing hydrocarbon fuels used for the electricity generated, (2) making hydrogen for energy storage, (3) making hydrogen for transportation and for Syngas, (4) creating a domestic supply of lithium for batteries used in Zero Emission Vehicles, (5) producing metals such as manganese and zinc without smelting, and (6) replacing electricity and natural gas used for air-conditioning and space heating.

Potential Outcomes

GIVEN THAT FURTHER GEOTHERMAL technology infrastructure development at the SSGF will be more feasible if the Sea's level continues to decline and exposes more dry, non-agricultural land on which to build foundations for more power plants and mineral/hydrogen production facilities, it is clear that the most favorable reclamation Scenario for adopting these specific technologies will be Scenario 1 in which the Sea is allowed to shrink. Nonetheless, Scenario 2 (managed wetlands areas in the peripheral portions of the Sea) could also allow for additional geothermal power production with pumped storage and nontraditional metals and hydrogen production if wetland mitigation was designed in a complementary manner to additional geothermal capacity, so as to not preclude further geothermal

TABLE 7.4 Anticipated revenue, county tax receipts, and employment figures associated with construction and maintenance of lithium extraction facilities. Credit: Modified from Besseling (2018).

Construction Employment		Full Time Employment	
Construction Period	48 Months	Operations	220
Peak monthly employment	730 workers	Maintenance	130
Average monthly employment	230 workers	Management & Administration	50
			400 Employees
Construction Expenditure		Contractor Expenditure \$18M per year	
Engineering	\$108M	Lease Holder Royalties \$4.5M per year	
Procurement	\$918M	Imperial County Taxes \$20M per year	
Construction Management	\$72M		
Construction (Disciplines)	<u>\$702M</u>		
	\$1,800M		
Cost of Production		Annual Revenue	
Annual Cost of Capital (20%)	\$360M		
Annual Operating Expense (\$4000/t)	<u>\$360M</u>	vs	<u>(90,000t x \$10,000/t)</u>
	\$720M		\$900M

infrastructure development on some of the newly exposed land. Consideration also should be given to the potential impacts of increased traffic and noise, chemical waste disposal, and other environmental factors that are already associated with geothermal development and which would increase if the mineral and energy extraction technologies described above were implemented. All of this will require close cooperation and coordination among the multiple stakeholders involved in reclamation, mitigation, agriculture, and geothermal resource production. Such a “multiple-use optimization” approach to the Salton Sea’s final configuration would also maximize local employment opportunities and tax revenues.

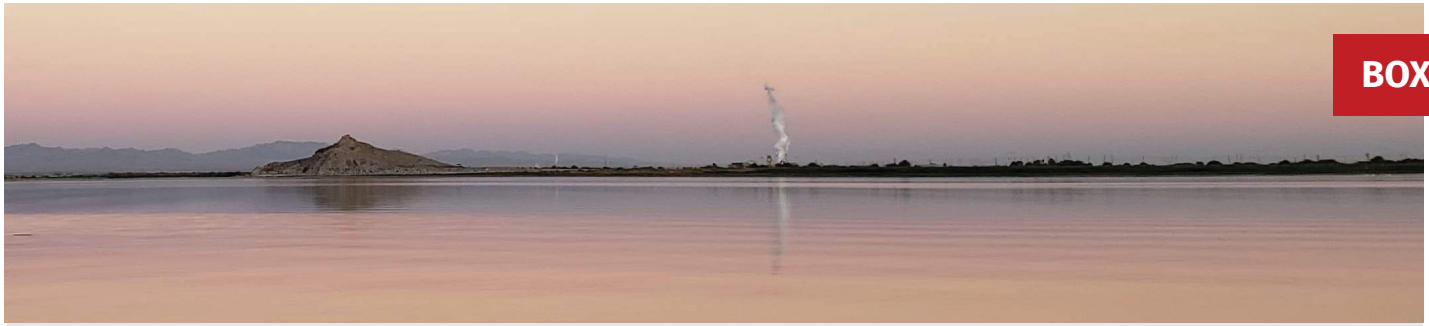
Research Needs

TO REMAIN COMPETITIVE with wind and solar energy paired with battery storage, current and expanded geothermal power production from the SSGF should be designed to be integrated with pumped storage to make it more attractive to utility companies facing large fluctuations in daily electrical demand-to-supply ratios. But even more importantly the geothermal plants of the SSGF should generate additional parallel revenue streams from the extraction of critical metals such as lithium, manganese, and zinc as well as the electrolysis of water to produce hydrogen for energy

storage and production of salable products. Tremendous research opportunities exist in regard to developing and scaling up these technologies to be commercial. In particular geothermal lithium production could enable the geothermal power companies to become a major net exporter and dominant supplier to the expanding global market.

In the future a factory to construct lithium batteries at the SSGF might also be considered, which would bring more employment to the economically disadvantaged population of the Imperial Valley. Production of such nontraditional mineral and energy coproducts will help California meet legislated mandates on renewable energy targets by 2045, provide local jobs and tax revenues, enhance the ability of the United States to produce electrical storage batteries and electrical vehicles domestically, and reduce reliance on environmentally damaging hard rock metal mining techniques and the manufacture of hydrogen from natural gas. The tax revenues could help facilitate funding of reclamation and mitigation efforts at the Salton Sea

Reclamation and mitigation plans should therefore be developed in coordination with the expansion of geothermal power and nontraditional mineral and energy production. Lack of such coordination could result in lost opportunities for the long-term economic benefit of the local region.



BOX 7C

OBSIDIAN BUTTE (left) and a geothermal plant at sunset. Caroline Hung

Global Environmental Advantages

ANY INDUSTRIAL DEVELOPMENT has an environmental impact that should be considered at local, state, national and global scales. Further industrial development at the Salton Sea is currently underway because the subsurface hot saline brines of the Salton Sea Geothermal Field (SSGF) are unique in the world in having the largest known undeveloped potential for both electricity production and for extraction of lithium and other strategic minerals.

ELECTRICITY GENERATED USING GEOTHERMAL STEAM has an extremely low, or zero, carbon footprint relative to using steam produced by burning hydrocarbon fuels. Electrical generation using steam extracted from SSGF brines to drive turbines has been going on for almost 40 years, with all applicable regulatory environmental requirements being met along the way. From the outset, after steam separation, the spent brine is treated to remove precipitated silica and then injected in deep disposal wells. This silica is a minor component of the brine, but because its precipitate carries traces of heavy metals, it is disposed of in certified toxic waste dumps. At the SSGF there is also a minor component of CO₂ that is extracted from the steam and vented to the atmosphere. If future regulations prevent venting the CO₂, the technology exists to sequester this CO₂ by injecting it in disposal wells where it reacts to form carbonate minerals.

PRODUCING LITHIUM as part of the existing process of electricity generation, rather than importing it, is environmentally beneficial from a global perspective. With burgeoning worldwide demand for lithium batteries for electric cars and other applications, a

new industry is developing at the SSGF power plants to extract lithium from the brines. Lithium is present at commercial concentrations accessible with addition of a lithium extraction loop to the existing process of brine production and injection. Lithium extraction from SSGF brines will require a local supply of clean water, which could be generated from steam condensate or from processed saline water that is pumped from shallow wells but is unsuitable for irrigation.

THE MINOR, LOCAL ENVIRONMENTAL IMPACTS of lithium extraction from geothermal brines pale in comparison to the negative consequences of mining, producing, and transporting lithium and lithium battery products from overseas. Currently more than 90% of the lithium used in the United States is imported, with Chile, Australia, and China as the primary producers. In Chile extracting lithium from saline lakes sullies large areas of ecologically sensitive land and consumes fresh water from shallow wells that otherwise could be used for agricultural irrigation. In Australia and China lithium-bearing minerals are produced by hard rock-mining techniques that require blasting and sulfuric acid digestion to make usable lithium products. In addition to the environmental consequences, the considerable carbon footprint to import these products to the United States should not be overlooked.

DEVELOPMENT OF A LITHIUM EXTRACTION INDUSTRY, along with future lithium battery manufacturing, will bring employment to the economically disadvantaged population of the Imperial Valley.

SALTON SEA TASK FORCE — ASK THE EXPERTS



WATER POLICY

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Dr. Schwabe's research focuses on economic issues associated with water use, agricultural production, urban water conservation, ecosystem services, and environmental regulation. His papers have appeared in wide range of peer-reviewed publications, including *Nature Sustainability*, *Proceedings of the National Academy of Sciences*, *Journal of Risk and Uncertainty*, *Land Economics*, and the *American Journal of Agricultural Economics*. He is co-editor of two recent books on water: *Drought in Arid and Semi-Arid Regions: A Multi-Disciplinary and Cross-Country Perspective* and *The Handbook of Water Economics*. Dr. Schwabe received a BA in Mathematics and Economics at Macalester College, an MS in Economics at Duke University, and a PhD in Economics at North Carolina State University. Dr. Schwabe also holds appointments as Adjunct Policy Fellow at the Public Policy Institute of California's Water Policy Center and Adjunct Professor in the Center for Global Food and Resources at the University of Adelaide, Australia.



WATER QUALITY

Timothy Lyons SENIOR MEMBER

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Dr. Lyons' primary research interests include geobiology, biogeochemistry, trace metal and isotope cycles and ecological relationships, and co-evolving environments and life. He also currently leads the 'Alternative Earths' team of the NASA Astrobiology Institute and founded the Alternative Earths Astrobiology Center at UC Riverside. Dr. Lyons is a fellow of the Geological Society of America, the American Association for the Advancement of Science, the Geochemical Society, the European Association of Geochemistry, and the American Geophysical Union. He has been honored with visiting professorships throughout the world and is Honorary Professor at the University of St. Andrews. The UC Riverside Academic Senate named him the 2018 Faculty Research Lecturer. Many of his 50 graduate students and postdocs have gone on to professorships around the world. His professional service includes a dozen editorial positions and numerous panels and advisory boards. He holds a BS from the Colorado School of Mines, MS from the University of Arizona, and MPhil and PhD from Yale University.



WATERSHED HYDROLOGY



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Dr. Ajami's expertise is in surface water-groundwater interactions, climate change impact assessment, hydrologic modeling, spatial analysis, and remote sensing. She received her PhD in Hydrology from University of Arizona and her BSc and MSc in Natural Resources Engineering (Environmental Sciences) from Isfahan University of Technology and Tehran University, respectively. Prior to joining the faculty at UC Riverside, she was a postdoctoral fellow with the National Centre for Groundwater Research and Training in Australia and a Senior Research Associate in the School of Civil & Environmental Engineering at University of New South Wales, Australia. She received the National Science Foundation CAREER award in Hydrologic Sciences.

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Ms. Hung specializes in trace elements redox chemistry and cycling in water columns and bottom sediments. She is leading field and laboratory efforts on the Salton Sea to produce data and interpretations for her doctoral thesis, advised by Professor Timothy Lyons. She received her BA in Geosciences and Biology from Williams College in 2019.

SALTON SEA TASK FORCE — ASK THE EXPERTS

AIR QUALITY

Particulate
Matter

Pollutant
Gases

Roya Bahreini SENIOR MEMBER

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Dr. Bahreini specializes in airborne, ground-based, and laboratory measurements of aerosol composition and microphysical properties to understand aerosol sources and formation, influence on air quality, and direct and indirect effects on climate. Dr. Bahreini received her BS in Chemical Engineering from University of Maryland, College Park, and MS and PhD in Environmental Science and Engineering from California Institute of Technology. Before joining the faculty at UC Riverside in 2012, she was a CIRES Visiting Postdoctoral Fellow at University of Colorado-Boulder, a Research Scientist at CIRES and NOAA-ESRL and University of Denver. She is a National Science Foundation CAREER award winner, and in 2014 she received the Thomson Reuters Highly Cited Researchers and The World's Most Influential Scientific Minds awards. In 2019–2020 she served on the Owens Lake Scientific Advisory Panel of the National Academies of Sciences, Engineering, and Medicine.



EXPOSED PLAYA along the Salton Sea shoreline. Jonathan Nye

Dust
Transport

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Dr. Porter uses numerical and statistical modeling tools to investigate the causes and consequences of air pollution, with a focus on the impacts of policy and chemistry/climate feedbacks. Dr. Porter received his PhD in Physics at Portland State University before working as a Postdoctoral Associate in the Department of Civil and Environmental Engineering at MIT. As a member of UC Riverside's BREATHE Center, Dr. Porter helps to elucidate the sources, transport patterns, and human health impacts of dust around the shrinking Salton Sea with to equip policymakers and stakeholders with the data and forecasts necessary to make informed decisions and protect local communities.

Bioaerosols

Microbial
Toxins

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Dr. Aronson's expertise is the role of soil microbes in ecosystem functions, the dispersal of microorganisms via wind and dust, and the impact of dust microorganisms on human health. She has published more than 30 research papers and is a member of both the Center for Conservation Biology and the BREATHE Center (Bridging Regional Ecology, Aerosolized Toxins, and Health Effects) at UC Riverside. She received her PhD in Biology with a concentration in Ecology and Evolution from the University of Pennsylvania, supported by a Predoctoral Fellowship from NASA, and her BSc in Environmental Sciences from McGill University. Prior to joining the faculty at UC Riverside, she was a NOAA Climate and Global Change Postdoctoral Fellow at UC Irvine. She currently leads a Thematic Cluster as part of the new National Science Foundation Critical Zone Cluster Network.

Rising Salinity

Food Webs

Marilyn Fogel CHAIR

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Dr. Fogel uses a wide range of expertise—including biology, chemistry, geology and astrobiology—to study distinctive isotopes of carbon, oxygen, hydrogen, and nitrogen to trace various phenomena tied to fossilized and modern ecosystems. She joined the UC Riverside faculty in 2016 and was Director of the Environmental Dynamics and GeoEcology (EDGE) Institute until her retirement in June 2020. She received her BS in Biology from Pennsylvania State University and a PhD in Botany and Marine Science from the University of Texas at Austin and worked at the Carnegie Institution of Washington's Geophysical Laboratory as a Senior Scientist and Staff Member for more than 35 years. Dr. Fogel is a Fulbright Scholar and a Fellow of the Geochemical Society, the American Association for the Advancement of Science, and the American Geophysical Union. She served as Program Director in Geobiology and Low Temperature Geochemistry with the National Science Foundation. In 2014 Dr. Fogel received the Alfred Treibs Medal in Organic Geochemistry for lifetime achievement in the field. She was elected to the U.S. National Academy of Sciences in 2019.

Rising Salinity

Food Webs

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Dr. Nye's research focuses on ecology and biogeochemistry of ancient and modern food webs. He uses stable isotope systematics to identify dietary changes, nutrient cycling, and energy flow in marine/aquatic organisms and ecosystems. He earned his BS in Earth Sciences and BA in Anthropology at the University of California, Santa Cruz, and his PhD in Geological Sciences at the University of California, Riverside, before studying the Salton Sea as a Postdoctoral Scholar.

Agricultural Impacts

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Dr. Jenerette's research focuses on regional ecosystem and biogeochemical dynamics occurring throughout the terrestrial-aquatic continuum in the southwestern United States, and he directs the Center for Conservation Biology at UC Riverside. He uses complementary methods of remote sensing, field experimentation, and in-situ environmental sensing to explore dynamics associated with land use changes, including transitions among wildland, agriculture, and urbanization. Dr. Jenerette is an Associate Editor for several journals, including *Landscape Ecology*, *Science of the Total Environment*, and *Frontiers in Ecology and Evolution*, and he has published more than 100 peer-reviewed articles. He earned a BS in Biology from Virginia Polytechnic and State University and a PhD in Plant Biology from Arizona State University.

HUMAN HEALTH

Asthma

Health Disparities

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Dr. Lo has more than 35 years of experience in molecular and cellular immunology with 162 research publications and several years executive leadership in biotechnology. Holding both a PhD and an MD from the University of Pennsylvania, he was an awardee of the first round of Grand Challenges in Global Health from the Bill and Melinda Gates Foundation and is a Fellow of the American Association for the Advancement of Science. At UC Riverside, Dr. Lo is Founding Director of the BREATHE Center (Bridging Regional Ecology, Aerosolized Toxins, and Health Effects), which focuses on air quality and health, and Co-Director of the Center for Health Disparities Research, a National Institute of Health-funded center supporting training and research on health disparities and community engagement.

SALTON SEA TASK FORCE — ASK THE EXPERTS

GEOTHERMAL RESOURCES

Lithium

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Dr. McKibben is a geochemist and economic geologist who studies natural processes responsible for metal and sulfur transport in modern and ancient hydrothermal and volcanic systems. He first visited the Salton Sea geothermal field as a high school freshman in the late 1960s and has since published extensively on geologic and geochemical aspects of that geothermal area. He received his BSc and MSc degrees from UC Riverside in 1976 and 1979 and his PhD from Pennsylvania State University in 1984. He received the Waldemar Lindgren award for excellence in research from the Society of Economic Geologists in 1989 and has served on their Executive Council and on the Editorial Board of their journal *Economic Geology*. He has also served on the Editorial Board of the Geochemical Society's journal *Geochimica et Cosmochimica Acta*. From 2009–2018 he was Divisional Dean of Student Academic Affairs for the science college at UC Riverside, overseeing 6,000 students in 13 majors.



SNOW GEESE in flight at the Salton Sea. Jonathan Nye

Renewable Energy

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Dr. Elders specializes in the investigation of geothermal resources. He has carried out research on this topic in California, Mexico, Iceland, New Zealand, and Japan, focusing on improving the economics of geothermal energy by producing deeper and hotter resources. From 1983–1988 he was the Chief Scientist of the Salton Sea Scientific Drilling Project, which drilled a 3.1-kilometer-deep borehole that reached temperatures of 365°C. Until his retirement in 2000, he directed the Geothermal Resources Program at UC Riverside and supervised numerous graduate students. He was educated at King's College, University of Durham, England, and the University of Oslo, Norway, and taught at the University of Chicago before joining the faculty at UC Riverside in 1969. In 2016 Dr. Elders received the Pioneer Award of the Geothermal Resources Council, and in 2017 he received a Special Achievement Award from the Geothermal Association of Mexico.

Renewable Energy

Arun Raju SENIOR MEMBER

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Dr. Raju focuses on renewable fuels, energy systems analysis including techno-economic and life cycle analysis, CO₂ utilization, and optimization of energy conversion pathways. He has a PhD in Chemical Engineering from UC Riverside with a focus on gasification and related processes and has research experience related to synthetic fuels and chemicals production and power generation via thermochemical pathways, including waste-to-energy processes. Before joining UC Riverside, Dr. Raju was the Director of Research at Viresco Energy, LLC, and later served as the Director of Technology Development at Combustion Associates, Inc.

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