Crisis at the Salton Sea: Research Gaps and Opportunities

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THE EDGE INSTITUTE
UNIVERSITY OF CALIFORNIA RIVERSIDE
SALTON SEA TASK FORCE

Cover Photo: Salton Sea at North Shore Yacht Club—Photo Credit Jonathan Nye
DECEMBER 13, 2020

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ACKNOWLEDGEMENTS

The Salton Sea Task Force received support from the University of California Riverside and the EDGE Institute. We benefited by discussion with Doug Brown and William Ota from UCR's Science 2 Policy program. Assembly member Eduardo Garcia and consultant Keith Ciolino met with the Task Force and provided helpful advice on direction. We thank our reviewers:

- *Edward Avol,* Professor, Clinical Preventative Medicine, USC
- *Michael Cohen,* Senior Researcher, Pacific Institute
- *Shohreh Farzan*, Assistant Professor of Preventative Medicine, USC
- *Stuart Hurlbert,* Emeritus Professor, SDSU
- *Jill Johnston,* Assistant Professor of Preventative Medicine, USC
- *Tina Treude,* Professor of Marine Geomicrobiology, UCLA
- *Scott Tyler,* Foundation Professor, UNR
- *Earl Withycombe,* CalEPA
- *Health and exposure assessment branch*, CARB research division
- *Jon Trujillo and Mike McNamara, CalEnergy*

Conducting research on the Salton Sea. Shrinking water levels make launching watercraft on the lake a difficult task as most boat launch sites are high and dry. Photo Credit—Caroline Hung.

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Marilyn L. Fogel received her B. S. in Biology from Penn State and a Ph.D. in Botany and Marine Science from the University of Texas at Austin. Fogel worked at the Carnegie Institution of Washington's Geophysical Laboratory as a Senior Scientist and Staff Member for over 35 years. Distinguished Professor Fogel joined UC Riverside in the Earth and Planetary Sciences department in 2016 and was the Director of EDGE (Environmental Dynamics and Geo-Ecology) Institute until her retirement in June 2020. Her research 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 modern and fossilized ecosystems. Marilyn is a Fellow of the Geochemical Society, the American Association for the Advancement of Science, the American Geophysical Union and a Fulbright Scholar. She served as Program Director in Geobiology and Low Temperature Geochemistry with the National Science Foundation. In 2014, she received the Alfred Treibs Medal in Organic Geochemistry for lifetime achievement in the field. She was elected to the United States National Academy of Sciences in 2019.

Hoori Ajami is an Assistant Professor of Groundwater Hydrology in the Department of Environmental Sciences at UC Riverside. Dr. Ajami's expertise is in surface water-groundwater interactions, climate change impact assessment, hydrologic modeling, and 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 UCR, 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 is a recipient of the National Science Foundation CAREER award in Hydrologic Sciences.

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Wilfred A. Elders is a Professor Emeritus of Geology in the Department of Earth and Planetary Sciences at the University of California Riverside. He was educated at King's College, University of Durham, England, and the University of Oslo, Norway. He has taught at the University of Chicago (1961-1969), and the University of California, Riverside, (1969-2000). His expertise is the investigation of geothermal resources and 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. Until his retirement he directed the Geothermal Resources Program at UCR and supervised numerous graduate students. From 1983-1988 he was the Chief Scientist of the Salton Sea Scientific Drilling Project, that drilled a 3.1 km deep borehole that reached temperatures of 365^{o}C. In Iceland from 2005-2020 he was the Co-Chief Scientist and Co-Principal Investigator of the Iceland Deep Drilling Project (IDDP), a long term, international, drilling project aimed at exploring for deep, *supercritical*, geothermal fluids. In 2016-7 the IDDP drilled its second well to a depth of 4.5 km, where it encountered supercritical conditions at >620 ^{o}C, on the Reykjanes Peninsula in SW Iceland. 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.

Susan Hackwood is a Professor of the Graduate Division, Fellow of the School of Public Policy and Director of the Center for Science to Policy (S2P) at the University of California Riverside. The overarching goal of S2P is to bring the scientific and policy communities together to strengthen evidence-based policymaking. For two decades she was the Executive Director of the California Council on Science and Technology which advises the state on all aspects of science and technology including energy, information technologies, biotechnology, nanotechnology, stem cell research, healthcare technologies, and climate change. She has a Ph.D. in Solid State Ionics from DeMontfort University, UK. Before joining academia, she was Department Head of Device Robotics Technology Research at AT&T Bell Labs. Later she joined the University of California, Santa Barbara as Professor of Electrical and Computer Engineering and was founder and Director of the National Science

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Timothy W. Lyons is a Distinguished Professor of Biogeochemistry in the Department of Earth and Planetary Sciences and Director of the Alternative Earths Astrobiology Center at the University of California, Riverside. Lyons currently leads the 'Alternative Earths' team of the NASA Astrobiology Institute. He 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 an Honorary Professor at the University of St. Andrews. The UCR 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 record of professional service includes a dozen editorial positions and numerous panels and advisory boards. He holds a B.S. from the Colorado School of Mines, M.S. from the University of Arizona, and M.Phil. and Ph.D. from Yale University. His primary research interests include geobiology, biogeochemistry, trace metal and isotope cycles and ecological relationships, and co-evolving environments and life.

Michael A. McKibben, Ph.D. is a geochemist and economic geologist at U. C. Riverside 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 B.Sc. and M.Sc. degrees from U. C. Riverside in 1976 and 1979 and his Ph.D. degree 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 U. C. Riverside, overseeing 6,000 students in thirteen majors. Presently he serves as Chair of the Department of Earth and Planetary Sciences at U. C. Riverside.

Jonathan W. Nye, Ph.D. is a Postdoctoral Scholar in the EDGE Institute and the Department of Earth and Planetary Sciences advised by Marilyn Fogel. He earned his B.S in Earth Sciences and B.A. in Anthropology at the University of California, Santa Cruz, and his Ph.D. in Geological Sciences at the University of California, Riverside. Dr. Nye's research focuses on ecology and biogeochemistry of ancient and modern food webs. He uses carbon, nitrogen and hydrogen stable isotope systematics to identify changes in marine and aquatic ecosystems, including the Salton Sea.

William C. Porter is an Assistant Professor of Atmospheric Dynamics and Modeling in the Department of Environmental Sciences at UC Riverside. 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 UCR's BREATHE center, Dr. Porter helps to elucidate the sources, transport patterns, and human health impacts of dust around the shrinking Salton Sea, and to equip policymakers and stakeholders with the data and forecasts necessary to make informed decisions and protect local communities.

Arun Raju, PhD is currently Director of the Center for Renewable Natural gas (CRNG) at CE-CERT 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 Ph.D. in Chemical Engineering from UC Riverside with a focus on gasification and related processes. He has experience in research related to synthetic fuels and chemicals production, and power generation via thermochemical pathways, including waste to energy processes. Before joining CE-CERT, Arun 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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Postdoctoral scholar Jonathan Nye celebrating a successful day of sampling the Salton Sea.
Photo Credit – Caroline Hung

Salton Sea at Sunset—Photo Credit Caroline Hung

EXECUTIVE SUMMARY

The Salton Sea, a hypersaline lake in southern California, USA, is in crisis. A combination of mismanagement and competition between federal, state and local agencies has resulted in stalled efforts to address dropping water levels and unstable lake biogeochemistry. This in turn has led to a growing public health crisis as exposed shoreline exposes potentially toxic dust to local and regional communities, while the ecosystem collapses due to rising salinity and anoxia. Although state agencies in California are making efforts to address this crisis, the lack of a science-based approach to addressing the environmental and human health challenges at the Salton Sea prompted the EDGE Institute and Science 2 Policy programs at UC Riverside to launch a multidisciplinary Salton Sea Task Force (SSTF) to identify the critical research necessary to guide policymakers in making decisions about three potential, realistic scenarios facing the Salton Sea over the coming decade.

In this report, three Scenarios have been considered: (1) Business-as-usual, where lake levels decline without intervention; (2) Mitigation, where current plans such as wetland restoration and dust suppression are implemented and some water is diverted back to the Sea; and (3) Water importation, where water from the ocean or local freshwater sources are brought in to stabilize, and possibly increase, lake levels. The SSTF, an interdisciplinary and independent group, has assembled this report for policymakers at local, state and federal governments. The report addresses the outstanding challenges and knowledge gaps related to human health, air quality and dust, hydrology and water resources, ecology, biogeochemistry, minerals, and energy aspects of the Salton Sea. We recommend that California's Salton Sea programs, managed by the Department of Natural Resources, set aside a portion of the funding allocated to mitigation and restoration efforts for a competitive research program open to university and NGO researchers so that action may be informed by ongoing and complementary scientific inquiry.

THE ROLE OF SCIENCE IN A SUCCESSFUL SALTON SEA POLICY

The two primary outcomes the State of California has identified in its efforts to address the problems surrounding the Salton Sea include improving air quality and providing critical environmental habitat for birds along the Pacific Flyway. Four criteria that are often used to evaluate outcomes and, consequently, the success or failure of policy, include effectiveness, efficiency, equity, and sustainability. Without significant understanding and consideration of the science and issues presented in this report, the ability of the State to achieve the outcomes it has identified will be difficult, especially when judged on these widely-used and well-accepted criteria.

Consider, first, the effectiveness of the State's policies in improving air quality and providing critical environmental habitat. A lower bound on effectiveness in the context of a criterion to judge the State's policy is whether there is an increase in the provision of critical environmental habitat and whether air quality improves. Whether critical habitat is improved for birds will depend on the intersection of Salton Sea's water levels, water quality, and other inputs (e.g., food sources) for birds. What this report has shown is that there is still a lack of understanding related to the Sea's water quantity (Chapter 2) and quality (Chapter 3) dynamics. Granted, there is significant attention and investment in wetland restoration, yet the degree to which these efforts end up producing improvements in critical habitat that improve ecosystem function for birds will depend on a variety of other factors (Chapter 5).

From an air quality perspective, similar concerns arise. The State's efforts to improve air pollution largely rely on limiting acreage of exposed playa. Yet, the acreage of exposed playa will depend on the Sea's volume and area, which we learn from Chapter 2 depends on surface water and groundwater interactions of which the science is uncertain. Furthermore, in Chapters 2, 3, 4, and 6, it's clear that air pollution is likely a function of declining surface and subsurface inflows and changes in the chemistry of the lake, neither of which is fully understood. Consequently, the degree to which State policy will indeed lead to improvements in air quality and critical habitat for birds is highly unknown; this report, though, provides State policy makers and scientists guidance and direction on where efforts on the science side of the ledger would provide more clarity on these issues.

From an "efficiency" perspective, the success of the State's policies is even more concerning. Efficiency, within the economic lexicon, is defined by an outcome for which net benefits – i.e., total benefits less total costs – are maximized. While it's a high bar to expect the State to achieve an efficient solution, even a less demanding cost-effective criteria 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), or the lack of understanding of the outcomes associated with current mitigation efforts to restore critical habitat or reduce air pollution (Chapters 3, 4, 5), any quantifiable measure of the benefits is indeterminate; consequently, discussions of efficiency are premature until a better understanding of the science is garnered. Similarly, whether the State is pursuing a cost-effective approach is questionable as well, since the "outcomes" are largely unknown.

Therefore, given cost-effectiveness is defined as the minimum cost to achieving a particular outcome, a natural question arises as to "what outcome?" Without a firmer understanding of this, assessments as to the cost-effectiveness of the State's efforts are also premature. Indeed, the "rate of return" on the current investments in mitigation as measured by the intended outcomes targeted in the Salton Sea Management Plan are highly uncertain and are not necessarily guaranteed to be positive over time, largely due 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 improving critical habitat and reducing air pollution should be considered alongside what can be gained from further development and investment in the Sea's geothermal and lithium resources (Chapter 7).

More recently, the State has increased its efforts to incorporate local community concerns, input, and insight into its management plans. Considering what might be considered equity issues is an important, notable, and commendable pivot of the State relative to its earlier efforts to address Salton Sea issues which may have been more focused trying to identify cost-effective solutions than on how those distributions of costs and benefits were borne by different communities. Yet, 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). 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, how the benefits and costs of different management plans 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 which such plans are equitable are unclear.

Finally, what is clear from this report is the need for more science to understand how the "system" will evolve over time, including Salton Sea's volume, quality and chemistry, and the generation of aerosol and particulate matter and its transport. These are critical inputs into the restoration and sustainability of critical habitat for birds and clean air for the local communities around the Sea. Because there is still a significant lack of understanding of the dynamics of the system, whether mitigation efforts and investments today will contribute to positive outcomes from an ecological- or human-health perspective in the future is largely uncertain. Both a better understanding of the sciences and continual monitoring and assessment will be required to gauge the effectiveness and return on the State's efforts to sustain successful outcomes, and to recognize when continual investments in a particular strategy need to be reimagined and reconfigured.

CHAPTER SUMMARIES

Chapter One: **Introduction**

The problems facing the Salton Sea are multi-faceted and complex spanning from medical to energy-related concerns. As restoration and mitigation projects begin to ramp up on the northern and southern shores, it becomes increasingly imperative that research continues to guide and inform these projects. We describe three potential scenarios regarding lake level that are associated with specific scientific questions and research gaps. Having independent, university and NGO based research funded in tandem with state and federal funding is needed to solve the complex issues facing the Salton Sea.

Chapter Two: Hydrology and Water Resources

The Salton Sea watershed in southern California and northern Mexico is one of the most productive agricultural regions in the United States. The watershed with an area of 8417.4 mi^2

encompasses the largest inland terminal lake in California, the Salton Sea. Lake-groundwater interactions in this watershed are tightly coupled to the imported Colorado River inflows which provide about 1.1 x 10^6 ac-ft/yr of water to the lake via irrigated agricultural runoff and drainage. Although a significant declining trend in the lake level is observed in the last two decades without substantial changes in the lake inflows, the mechanisms that control lake water dynamics are not well known. Therefore, a key science need is to determine the optimal lake water level to reduce lakebed dust, and maintain wildlife habitat and agricultural production in the basin. Future of this arid watershed will be impacted by projected declines in the Colorado River inflows, competing demands among urban and agricultural users and natural ecosystems for water, and increases in the exposed dry lakebed impacting human health. This trajectory necessitates detailed surface water-groundwater investigation in this watershed to assess the impacts of various management scenarios on the lake level, agricultural production, and water availability. Success of such an adaptive management program requires stakeholder engagement at every step including design, implementation and monitoring.

Chapter Three: Consequences of ongoing and future evolution of salinity and oxygen-availability in the drying Salton Sea

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. 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. Each summer the deeper waters of the Salton Sea lose their oxygen in the face of increasing temperatures, evaporation, and saltiness and high inputs of fertilizer via runoff from adjacent agriculture. It is likely that these conditions form a threat to humans and wildlife that will become longer, more frequent, and potentially permanent in the face of current and planned decreases in water allotments. If current water policy is continued, there will be more dust, and that dust will be more toxic. Further research must focus on predictable patterns of oxygen loss and toxic metal remobilization under the different possible remediation and water management strategies. This little-discussed concern must rank among the major threats posed by the shrinking Salton Sea.

Chapter Four: Air Quality Issues at the Salton Sea

The state of the Salton Sea is intrinsically tied to air quality in the surrounding communities through the emission of both particle-phase pollutants and gas-phase pollutant precursors. While there are many uncertainties involved in quantifying the impacts of a shrinking Salton Sea on local air pollution, measurement and modeling studies suggest that ongoing reductions in inflows will very likely contribute to worsening air quality for local residents throughout the basin and beyond, adding additional burdens on communities already dealing with disproportionately high levels of ambient particulate matter and related respiratory issues. More work is necessary to fully understand the transport, composition, and health impacts of pollutants originating from the Salton Sea and its increasingly exposed lakebed, and to inform and guide mitigation efforts aimed at improving the health and well-being of local communities.

Chapter Five: Ecology of the Salton Sea and Surrounding Environments

The dynamic and unstable Salton Sea supports 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, supported by water and nutrients derived largely from agricultural inputs. Agricultural practices in the region encourage microbial production of greenhouse gases, lower air quality and result in excessive nutrient flows into the Salton Sea. This overabundance of nutrients entering the sea creates an imbalance of algal production resulting in Harmful Algal Blooms and anoxia, threatening wildlife and humans. Rising salinity, temperatures, and declining water levels may disrupt migration patterns for fish eating birds potentially leading to a catastrophic collapse of the aquatic food web. The endangered desert pupfish populations on the margins of the Salton Sea are at risk of becoming isolated, putting them at increased risk of extinction. While wetland habitat restoration may benefit certain species of birds, current plans to restore the sea do not address the core problems limiting ecosystem functioning. Without continued significant freshwater introduction to the Salton Sea, the ecosystem faces collapse due to excessive nutrients, rising salinity, and declining water levels, likely resulting in undesirable outcomes for recreational activities, the regional economy, and public health.

Chapter Six: **Health Disparities, Pulmonary Health, and the Salton Sea**

The ongoing slow motion crisis at the Salton Sea due to the retreat of the sea due to evaporation has multiple consequences, including impacts on the sea's ecology and migratory bird populations. However, the impacts of main concern are on the human residents; in communities already subject to disparities in social and economic status, the environmental hazards of life in the region 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 hazardous aerosols, has already impaired the economic and social fabric of the region; the health disparities and costs to the community will only increase unless steps are taken to address the issues raised here.

Chapter Seven: **Lithium and other geothermal mineral and energy resources beneath the Salton Sea**

The potential for utilizing Salton Sea geothermal plants for extraction of critical metals such as lithium, manganese, and zinc and production of electricity from pumped storage and of hydrogen via electrolysis is reviewed in the context of likely reclamation scenarios for the Sea. Generation of these nontraditional geothermal mineral and energy resources could provide the added revenue stream needed to make expanded geothermal power production at the Salton Sea competitive with solar and wind power. The three possible reclamation scenarios that have been described in this report for the Salton Sea should be carefully evaluated in the context of how they may impact the ability of the region's geothermal industry to expand its traditional geothermal power resources as well as develop new non-traditional mineral and energy resources. The potential for this industry to become a world-class producer of lithium and other critical metals for the U.S. and the world should play a role in this evaluation, as should the ability of the State of California to succeed in meeting mandates for renewable energy and greenhouse gas emissions via the reduction of fossil fuel consumption. Implications of such nontraditional geothermal resource production for substantial local job creation and tax revenues should also be considered. Multiple benefits can be maximized by coordinating the development of additional geothermal expansion with reclamation plans for the Sea, as the receding shoreline opens up new land suitable for both wetlands and geothermal infrastructure construction.


Gypsum laden crust on the edge of the Salton Sea—Photo credit Caroline Hung

CHAPTER ONE

Introduction: Crisis at the Salton Sea: Research Gaps and Opportunities

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Highlight:

- 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 the long term.

In recent years, the Salton Sea has increased in salinity and shrunk in size, leading to the demise of the abundant fish and invertebrate populations and the loss of a vital feeding, resting, and nesting site for millions of birds. Beginning in January 2018, additional water flowing into the Sea was diverted to urban water districts. 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 hundreds of thousands of Californians, many of whom live in disadvantaged and vulnerable low-income communities. Despite vast investments of time and an ample planning horizon, adequate solutions addressing the full range of problems have failed to materialize neither in implementation nor concept. Indeed, over two decades have transpired since the concept of the water transfer between the Imperial Irrigation District (IID) and the San Diego County Water Authority (SDCWA) that would become the 2003 Quantitative Settlement Agreement (QSA) was introduced (Littleworth and Garner, 2019), yet very little has been accomplished.

More recently, though, funds have been appropriated to design and implement a ten-year interim Salton Sea Management plan (SSMP, 2017). The passage of the $7.5 billion Prop 1 bond in 2014 allocated slightly over $80 million for the Salton Sea, funding that would go primarily to the design and documentation of the interim plan with some funding for construction projects. Proposition 68, meanwhile, was passed by California voters in 2018 and consisted of $200 million earmarked towards dust mitigation and other environmental problems emanating from the Salton Sea which affect the region. While there have been some additional smaller appropriations towards Salton Sea restoration activities, the funding to date has focused primarily, if not exclusively, on design and build projects for dust mitigation and habitat restoration in and around the Salton Sea for the interim period (approximately ten years). While such efforts and activities are necessary, there has been little funding for basic research based on the evolving environmental conditions at the Sea today as opposed to the research carried out in the past two decades. A report by Barnum et al. (2017) summarizes research gaps based on a study conducted in 2014. Interestingly, many of the concerns and gaps in this study are still pertinent and highlight the fact that a science-based approach to restoration is needed.

The Salton Sea Task Force at University of California's Riverside campus was created to address this omission and provide guidance to policy makers on what we still need to know to solve the environmental crisis. Management plans and policies 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 the local populations and farming communities in the region, are likely to be uninformed at best, harmful at worst. While support for increased funding to "restore" the Salton Sea is gaining traction, we caution that the funding of policies and strategies not supported by evidence-based science may lead to ineffective, costly, and unsustainable outcomes; in effect, poor investments.

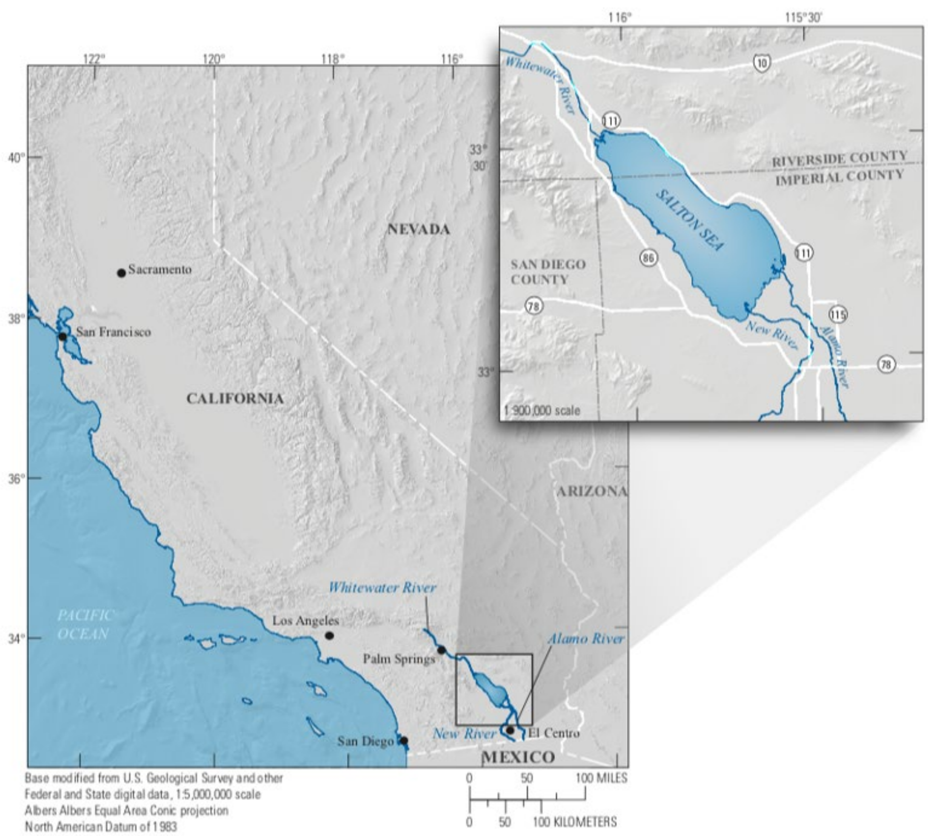

Figure 1.1. Map of the Salton Sea region, via USGS. Barnum et al., 2017.

Although many Californians consider the Salton Sea to be an "accident" caused by humans, the Salton Basin has been the location of an ephemeral body of water going back thousands of years. The Torre Martinez Desert Cahuilla Indians have a long history in the Sea and land under it. Their reservation was established in 1876 and is now partly flooded by the current Salton Sea. The concerns of this group should be addressed as mitigation plans unfold (Figure 1.1; Map of the region).

The Salton Sea's source of water comes mainly from the Colorado River that flows through some of the driest portions of the United States. Today, the water released from upstream dams on the Colorado River is earmarked for use by states and water districts. California holds senior water rights on the majority of it, much of which is allocated to the Imperial Irrigation District (IID) and the Metropolitan Water District (MWD)(see Thrash and Hanlon, 2019).

Figure 1.2. Shoreline with wading birds that feed on invertebrates, 2017.

Over the last 115 years since the current Salton Sea was formed, migratory birds by the millions have made it an important stopover (Shuford et al., 2002; Lyons et al., 2018) (Figure 1.2). Some birds are on their way to the south, while others arriving from Canada and northern United States spend the winter months at the Salton Sea feeding on once abundant fish and invertebrates. Because wetlands have been destroyed over much of California, the Salton Sea has—now more than ever—become one of the most important areas for these birds. Unfortunately, within the last 2-3 years owing to vast environmental change, many of the species that depended on the Sea's fish populations have gone elsewhere (Bradley et al., 2017).

The Sea is shrinking. Why? In 2003, after a protracted and ongoing legal battle, the Quantification Settlement Agreement (QSA) was finalized which largely consisted of a negotiated agreement between IID and the San Diego County Water Authority (SDCWA) that would allow a sizeable amount of water from IID's Colorado River allocation to be sold to SDCWA. To generate the water for transfer and sale, IID engaged in a number of activities, including the fallowing of agricultural lands in the Imperial Valley early into the program, to be followed up later by water efficiency programs (e.g., increasing irrigation efficiency), both approaches supposedly generating water savings that would meet the transfer requirements stipulated in the QSA. To mitigate the impact on Salton Sea volume and the consequences of receding shorelines and exposed playa that would arise from the lower inflows from less agricultural runoff and provide time for a solution, the QSA included 105,000 acre-feet (ac-ft) of mitigation water to be sent to the Salton Sea from 2003 through 2017. As will be shown in this report, while the inflows to the Salton Sea remained somewhat constant from 2003 to 2017, Salton Sea water elevation declined over that period. Since the beginning of 2018, inflows have also declined due to the cessation of mitigation water.

While the QSA served a number of purposes, including facilitating the reduction in California's overall Colorado River water use from 5.2 million ac-ft down to its legal amount of 4.4 million ac-ft annually while providing San Diego -- which had the lowest priority water rights for Colorado River water -- a reliable water source via water transfers from IID, the potential costs extend far beyond the arm's length transfers between IID and SDCWA. The externalities associated with these transfers and the consequent effect on the Salton Sea and surrounding communities are, by all estimates, exorbitant (Cohen, 2014).

In an effort to avert the potentially substantial externalities to both environmental and human health, the Salton Sea Authority created a 10-year management plan. This plan was prepared over the decade by numerous governments, non-governmental organizations, and local stakeholders. In general, the plan relies on some mixture of four strategies (Forney, 2018).

1. Estuarine wetland construction—wetlands or impoundments would be created on the northern and southern shorelines with freshwater combined with the Sea's already salty water to support fish and fish-eating birds.
2. Vegetated wetland construction—wetlands that naturally grow as the shoreline recedes. These would be primarily supplied by surface water inflows from the New and Alamo Rivers and expected to support invertebrates, rails, and migrating geese.
3. Salinity and water quality control—desalination plants or channeling freshwater flows to the shoreline, while allowing the central basins to increase in salinity creating saltier brines.
4. Water imports—typically envisioned as influx from the Gulf of California.

People who live in the region, however, initially wanted to preserve the Sea's shorelines as they were in 2006, or even earlier. The initial plan proposed by the Salton Sea Authority was ambitious and included developing the northern half of the Sea as a recreational fishing and boating destination. This plan, however, was determined to be too expensive by the State. It took another decade to produce the current Salton Sea Management Plan (2017) introducing a significantly scaled back plan primarily limited to the north and south shorelines along with dust mitigation in targeted areas (2020a, b). While the $400 million in estimated capital costs to implement the Phase I interim Salton Sea Management Plan may seem significant, that price tag 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. And to the extent the state and/or federal government may assume liability for such damages -- either voluntarily or through lawsuits -- the mitigation and restoration costs will likely seem insignificant (Figure 1.3).

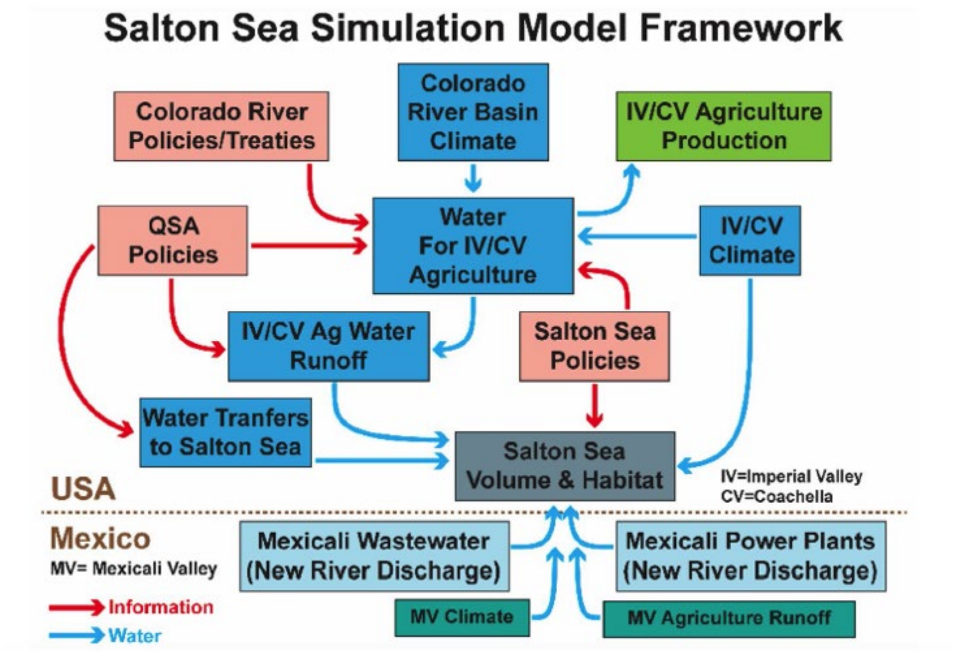

Figure 1.3. Complexity of the water available for the Sea. Policy measures are highlighted in pink and red. The ecosystem (in grey) is affected by at least thirteen parameters. Taken from Kjelland et. al., 2019.

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 the model (Figure 1.1; Kjelland et. al., 2019) are two factors, climate and the local hydrology. Accordingly, UCR's EDGE Institute is conducting a study of the 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. The study 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 California legislators, who will be developing and approving public policy.

Our study team (UCR's Salton Sea Task Force) is considering three different scenarios for Salton Sea's future (Figure 1.4).

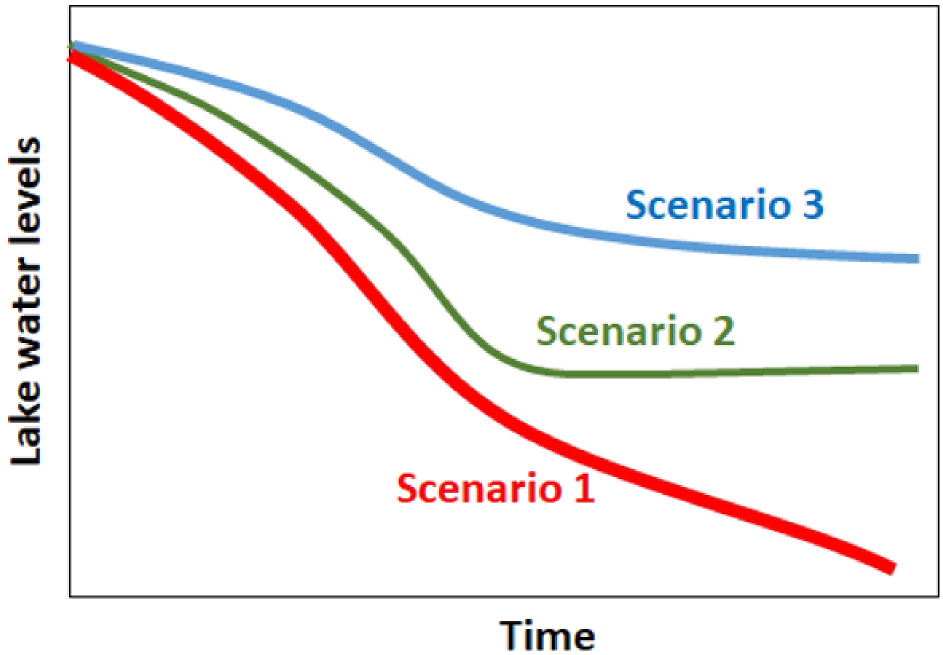

Figure 1.4. Water levels are changing in the Salton Sea. Three different possible outcomes of the water budget—continued decline, stabilization, and water importation—will influence the outcome of the region.

- Scenario 1: The lake water levels will continue to decline as the current trend in lake water levels indicates. We will still have water in the lake but less than today and less than in Scenario 2. The decline in lake levels is driven by changes in subsurface water flows, lower Colorado River inflows owing to lower snowpack and population growth, and higher evaporation rates in the future. The deeper centers of the Sea will increase in salinity, pesticide, and metal content and will become more anoxic. The northern and southern shores will accommodate the state's building of the 3,770 acre Species Conservation Habitat project.

- Scenario 2: The lake water levels will decline but eventually reach a steady state condition with water levels at -255 ft. This scenario assumes that Colorado River inflows will remain at their current rate or slightly lower in future, although future Colorado River inflow projections suggest otherwise. Potentially, water levels might be slightly increased from 2020 levels to suppress dust, stabilize the shoreline, and safeguard endangered pupfish populations.

- Scenario 3: The lake water levels will recover to a certain level by implementing mitigation scenarios (e.g., water purchases; Levers et al., 2020), wetland impoundments, or imported water from the Gulf of California or elsewhere. For example, historic water levels in 2003 and the thirty years prior to this timeframe were stable at approximately –228 feet below sea level (Ajami, this report). Depending how water importation might be implemented, this level is a possible goal. The proposals for Scenario 3 are currently being assessed by the Salton Sea Management Program

Federal and California state air quality regulations, endangered species laws, and protections of migratory waterfowl will necessitate action as high levels of salinity will cause die-off of all fish species within the next few years.

The California State Water Resources Control Board (Order WR 2017-0134) required action to begin partial restoration of the northern and southern shorelines of the Salton Sea (Salton Sea Management Plan Phase 1: 10-Year Plan, March 2017). This plan outlines engineering operations to create habitat for migratory birds, but it is not based on current scientific knowledge of the Sea's ecosystem. Basically, the northern and southern shores of the Sea will have diked ponds fed by gravity flow from the three rivers providing input into the Sea. Wetlands will be allowed to develop as the lakeshore recedes. These areas will have salinity levels much lower than the main body of the Sea, possibly allowing for the growth of fish populations to attract pelicans and other fish-eating species. The management plan has been hampered, however, by difficulties in creating ponds on the northern and southern shorelines. Getting the rights and permits to build the ponds are underway. This summer (2020), the Department of Water Resources selected a contractor to begin the work. Meanwhile, the extent of exposed shore is increasing.

The major impetus for promoting an active research program is the health problems in the region due to the Sea's unstable ecology. Asthma from inhalation of dust has significantly negative impacts on children (20% are estimated to have asthma) in the area as well as adults. The population's average income is less than $35,000 annually, with the demographics including 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 and dry up.

Dust affects air quality in deserts; however, in the Salton Sea area the chemical composition of that dust could be contributing to the particularly high incidence of asthma in children. Because Colorado River water has higher than average concentrations of metals like selenium and molybdenum, dusts originating from exposed shorelines could consist of higher, potentially toxic concentrations of metals (Buck et al., 2011; Frie et al., 2019; SSMP 2020b). With lower lake levels, the unique crust that paves the bottom of the Sea will be revealed. Currently it is unknown whether this crust will be a stable surface or not and the degree to which it will contribute to the 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. Understanding the complexity of atmospheric patterns and geochemistry of dust particles remains unknown (see Chapter 3).

As the salinity increases, organisms living in the Salton Sea have to adapt to living in extreme environments (Figure 1.5). Tilapia—the major fish remaining in the Sea--are struggling to survive. The endangered desert pupfish will find it increasingly difficult to survive. Bird populations that rely on these fish for food are declining. Brown and white pelicans and migratory species from across North America are affected (Lyons et al., 2018).

Declining water quantity and quality is promoting harmful algal blooms that can be toxic to wildlife and people. The future of the southern California deserts and this region in particular is projected to have increased temperatures and lower rainfall. Directly north, Palm Desert, Palm Springs and the other desert cities are home to 350,000 residents who moved there to enjoy clean desert air. Potential future Salton Sea scenarios may jeopardize that outcome.

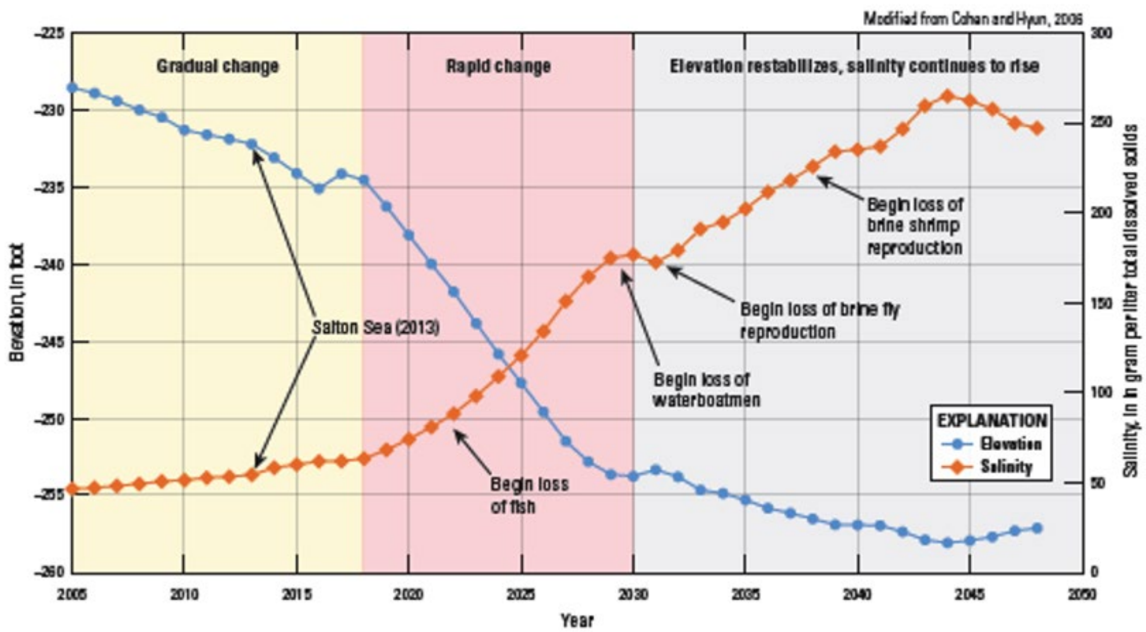

Figure 1.5. Changes to Salton Sea over time. Pink zone indicates period of rapid change owing to increasing water transfer sanctioned by the Quantification Settlement Agreement. Taken from Barnum et al., 2017 with permission.

The Sea is also subjected to extremes in its chemical inputs, particularly as nutrient and pesticide laden runoff from the Imperial Valley agricultural district 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 (see Chapter 3). 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 close scrutiny. The region does hold two possibilities for enhancing funding of ecosystem and dust mitigation projects: geothermal energy and lithium mining (Cantor et al., 2018). California's energy policy requires 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 (see Chapter 7; Elders et al., 2019). Furthermore, geothermal brines contain economic concentrations of lithium, a metal required for batteries and other industrial uses. 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.

Further research is needed to develop a deeper understanding of how the Salton Sea system functions now in 2020 and for at least the next 10 years. 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 university and NGO (e.g., Point Blue Conservation Science) researchers is needed to provide guidance to policy makers, government scientists, and contractors. Further research is needed to address these outstanding gaps in knowledge:

- 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?

- Where does the region's dust come from? Does the Salton Sea's playa or waters contribute 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? How 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 with respect to the scenarios we describe?

- How will the ecosystem in the proposed mitigated 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 might 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 local or directed mitigation efforts to contain hydrogen sulfide releases associated with bacterial decay processes)?

- 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 past exposures to Salton Sea's dust and noxious gases and current health?

- How will the cultural connections of the Torres-Martinez Desert Cahuilla community be affected by the eventual 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?

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The Whitewater River as seen near the headwaters before flowing into the Coachella Valley. Photo credit— Jonathan Nye

The New River with abundant growth on its levees near its terminus in the Salton Sea. Photo credit— Jonathan Nye

CHAPTER TWO

Salton Sea Hydrology and Water Resources

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Highlights:

- Salton Sea's water balance is controlled by complex interactions between agricultural water management practices, evaporation, and surface water-groundwater interaction.
- A key challenge in Salton Sea water management is determining the optimum lake water level to reduce the lakebed dust and maintain wildlife habitat with recognition of the possible agricultural production impacts in the watershed.

Introduction: CLIMATE, HYDROLOGY, AND WATER RESOURCES

The Salton Sea watershed is a closed (endorheic) basin with an area of 8417.4 mi^2 (21,801 km^2), 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 it includes the largest inland terminal lake in California, Salton Sea, with an area of 334 mi^2 (865 km^2) (Yao et al., 2019).

Nearly half of endorheic basins around the world are located in water-stressed regions (Wada et al., 2011) where the lake storage is maintained by the balance between inflows (i.e., precipitation, surface runoff and groundwater inflow) and outflows (i.e., evaporation and groundwater discharge). 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). Similar to other endorheic basins, Salton Sea has experienced a significant decline in lake water levels in recent years. Lake water level observations at the Salton Sea near Westmorland indicate a mean annual lake water level decline of 8.7 ft (2.65 m) since 1988 (Figure 2.2), and the future trajectory of lake water level is uncertain.

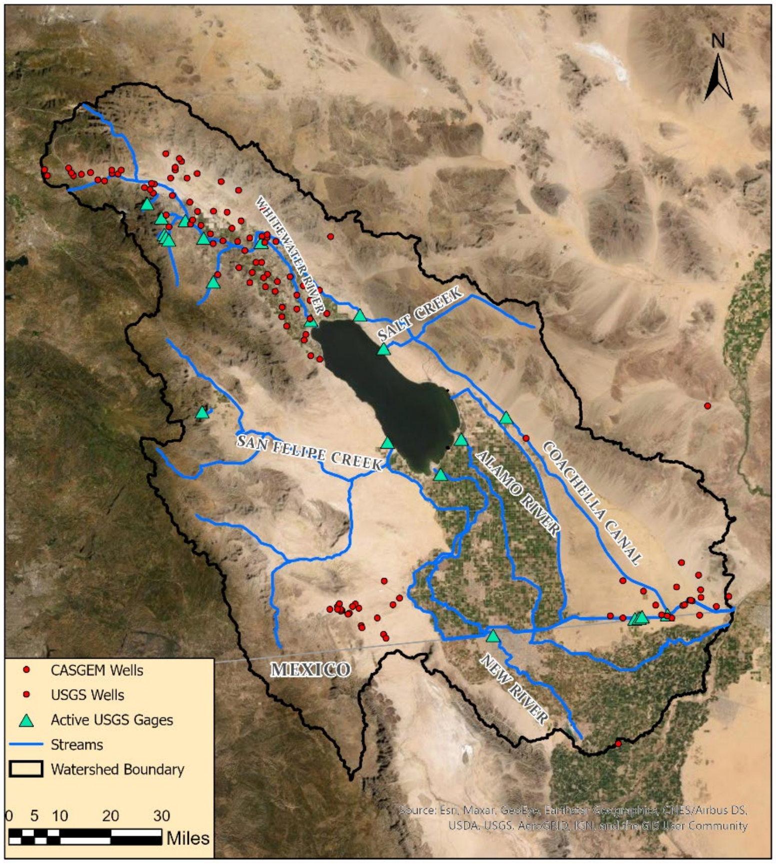

Figure 2.1. Location of the Salton Sea watershed and major streams and drainages.

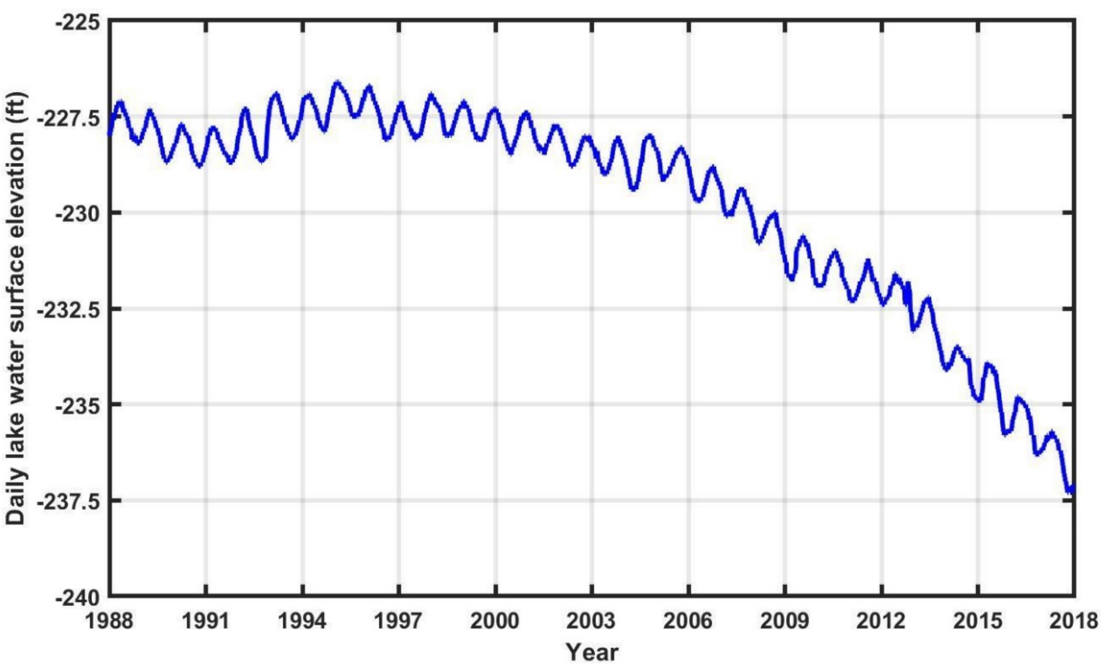

Figure 2.2. Daily lake water level observations at the Salton Sea near Westmorland (USGS 10254005), NGVD 1929

The Salton Sea 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). Its climate 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 49 ^{0}C. Figure 2.3 shows total annual precipitation in the watershed during 1980-2018 indicating cycles of wet and dry periods relative to the long term mean annual precipitation. Annual precipitation in the most recent decade since 2010 has been lower than the 39-year average.

SURFACE WATER

The Salton Sea watershed is one of the most productive agricultural regions in the United States, and 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 x 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 distribute water across the agricultural fields in the Imperial Valley and Coachella Valley irrigation districts. On average, 10% 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. While the Colorado River inflows are used for irrigation, a small amount of water is allocated for industrial and residential users. The mean annual Colorado River inflows to the Salton Sea watershed at Pilot Knob Hydroelectric Plant were 3.2 x 10^6 ac-ft/yr (3.95 km^3/yr) during the1980-2018 period (Figure 2.4). However, these deliveries have declined in recent years.

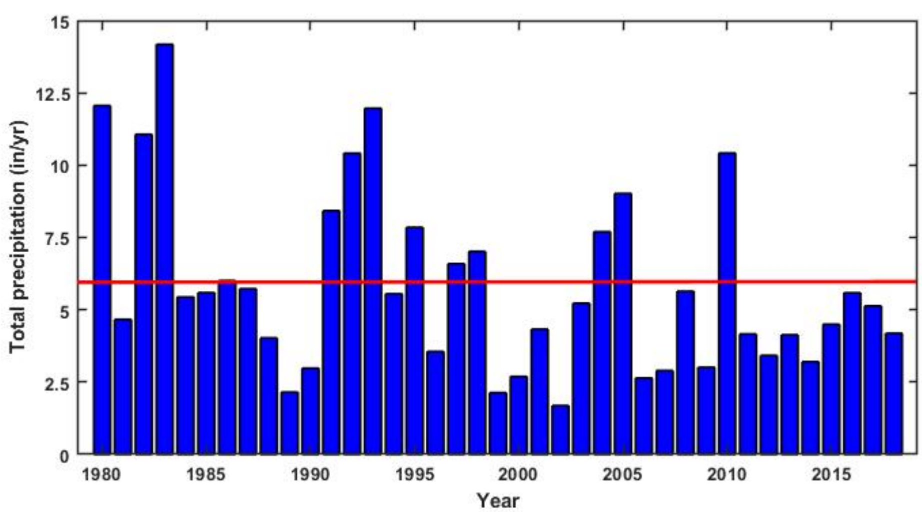

Figure 2.3. Annual precipitation in the Salton Sea watershed from a 4 km resolution PRISM dataset. The red line shows the 39-yr mean annual precipitation.

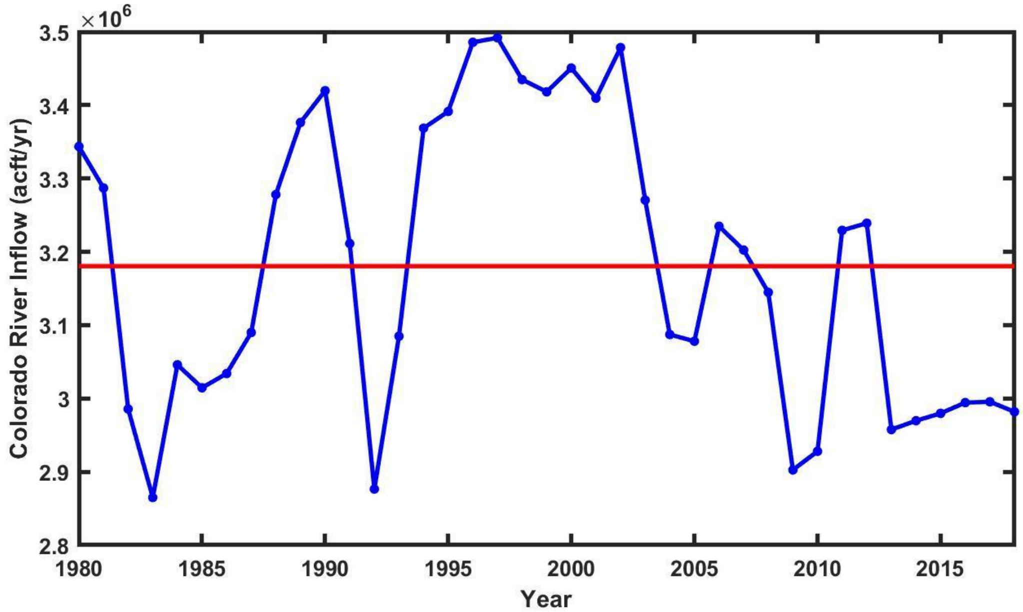

Figure 2.4. Annual Colorado River inflows at the Pilot Knob (ID: 09527500). The red line shows a 39-yr mean annual inflow.

Irrigation water not used by crop evapotranspiration drains off the landscape to the Salton Sea via the New and Alamo Rivers in the south and the Whitewater river in the northern part of the Salton Sea as well as via a large number of agricultural drains that discharge directly into the Sea. Continuous daily flow measurements at three USGS gaging stations at the perimeter of the Salton Sea indicate total mean annual inflows of 1.1 x 10^6 ac-ft/yr (1.35 km^3/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 Whitewater river in the north (Figure 2.5). 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 Valley irrigation district, the agricultural drains inflows to the Salton Sea are estimated at 95,000 ac-ft/yr (IID, 2018). However, no public dataset is available to determine the long-term variability of drain inflows. Besides direct precipitation and irrigation runoff, ephemeral flows from dry washes including Salt Creek in the east and San Felipe Creek in the west, as well as groundwater discharge water to the Salton Sea. The exact contribution of groundwater discharge to the lake is uncertain, and estimates vary between 15,000-50,000 ac-ft/yr (Case III et al., 2013; Hely et al., 1966). Hely and others' (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.

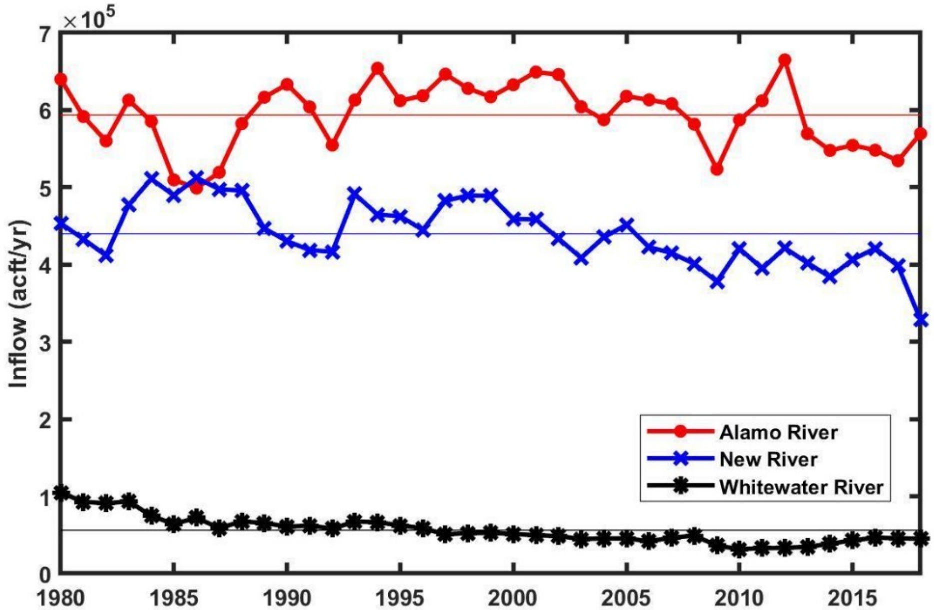

Figure 2.5. Annual river inflows to the Salton Sea as measured by the USGS gauges at the mouth of Alamo River, New River and Whitewater River. Solid lines indicate 39-yr mean annual inflows.

SALTON SEA

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 2.6). Starting in February 1907 with the closure of the break on the Colorado River's levee, lake water levels started to decline because of excess evaporation over the inflows. Irrigation development in the Imperial and Mexicali Valleys in the 1920s resulted in the amount of agricultural return flows to become equal to the lake evaporation rates, subsequently stabilizing the lake water level to -250 ft until 1925 (Blaney, 1955). By 1954, further expansion of irrigated agriculture and the occurrence of several severe storm events caused lake water levels to increase and reach -235.8 ft (Figure 2.6). While water shortages in 1931 and 1934 caused a temporary decline in the lake water level, Salton Sea's surface elevation started to increase, raising concerns regarding encroachment and damage to the neighboring lands. 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.

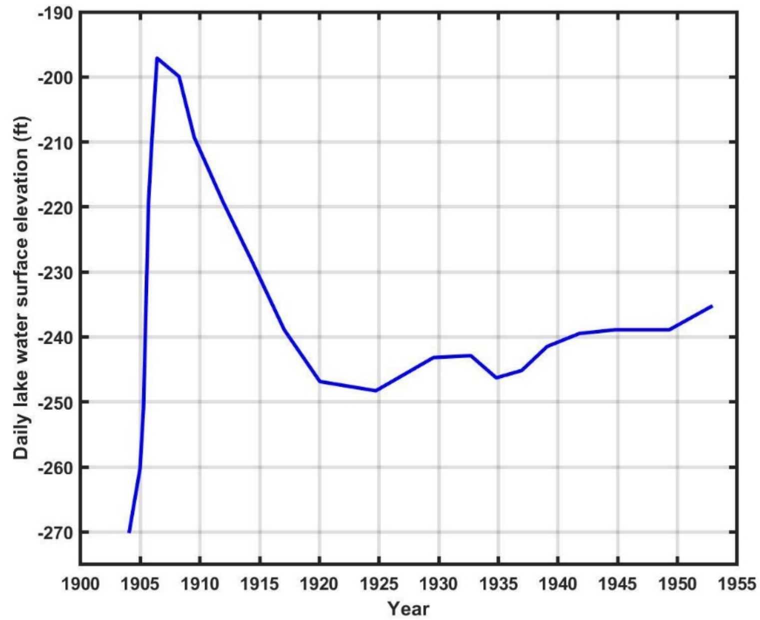

Figure 2.6. Historic water levels in the Salton Sea (Reproduced from Blaney 1955).

While much of the concern in the 20th Century was related to the rising lake water level, the lake trajectory is different today. Lake water level projections in 1950 indicated that the lake water level will stabilize to -220 ft by 1980, and monitoring efforts were focused on accurate estimation of lake evaporation rate. Presently, survival of the Salton Sea is tied to agricultural runoff and drainage from major agricultural regions in the basin: Coachella Valley to the north, Imperial and Mexicali Valleys to the south, and their associated water management decisions.

GROUNDWATER

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 (SGMA) by the California Department of Water Resources.

Looking forward, a projected 82% increase in population by 2030 is expected to further impact groundwater resources of the Coachella Valley (DWR, 2020). **To date, no comprehensive assessment of surface water-groundwater interactions has been performed to quantify lake-groundwater exchange, and explain processes that cause significant declines in the lake water level in recent years. Consequently, efforts to make informed decisions with an understanding of the consequences on water lake levels will be severely limited.**

The natural groundwater recharge rate in this arid watershed is very low except at the mountain front regions 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). While canal leakage from the All American Canal and Coachella Canal were high in early years, subsequent lining of these major canals in 2007 and 1980 respectively has 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 recommended to develop coupled surface water water-groundwater models to better understand hydrologic processes, and design conjunctive surface water-groundwater management strategies to reduce the impacts of water transfers and agriculture on the Salton Sea.

WATER RESOURCES MANAGEMENT CHALLENGES

The Quantification Settlement Agreement (QSA) in 2003 allowed water transfers from agricultural users in the Imperial Valley to municipal use in coastal southern California. To mitigate the impact of the water transfer, the QSA stipulates that the Imperial Irrigation District make "mitigation water" available to the Salton Sea. However, availability of mitigation water ceased on December 31, 2017 (Barnum et al., 2017). Lake water levels at Westmorland show a significant decline from -227.06 ft in 1995 to -234.8 ft in 2016. 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 during 1995 to 2016 coincide with significant declining trends in annual inflows to the Salton Sea (Figure 2.5) suggesting further declines in lake level with future increases in air temperature and higher evaporation rates.

Projected estimates from the Imperial Irrigation District (IID) SALSA2 model that predicts Salton Sea hydrology and salinity conditions indicate 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 (IID, 2018). However, it is expected that the Colorado River flows will decline in the future due to the lower amount of snowpack, prolonged droughts and higher population growth (Udall and Overpeck, 2017). These shortages could result in potential water cutbacks to lower basins such as recent provisions for 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 SALSA2 model has also been used as the basis for developing the Salton Sea Management plan. The drawback of using a statistically based model 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 model equations and parameters are not publicly available (IID, 2018). Modeling approaches such as the Salton Sea Stochastic Simulation model considers a semi-distributed modeling approach to understand system dynamics using empirical parameterization (Kjelland and Swannack, 2018). While 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.

Besides water quantity issues, water quality is another major concern threatening the livelihood of the Salton Sea. The Salton Sea was a freshwater lake at the time of its formation. However, dissolution of natural salts covering the basin floor and dissolved salts originating from agricultural return flow have increased salinity of the lake to over 57 parts-per-thousands in 2015 (CA Water Boards, 2020). Application of fertilizers and pesticides further deteriorated lake water quality (Tompson, 2016).

In summary, it is extremely difficult to project future lake water levels and the area of exposed playa given currently used models and the hydrologic and socio-economic complexities surrounding the Salton Sea. In particular, 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, and requires improving hydrologic models and climate change projections for the region and engaging stakeholders for scenario development.**

CLIMATE CHANGE IMPACTS

Projected increases in global average temperature and reduction in snowpack is 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% at the end of century (Udall and Overpeck, 2017). Therefore, less water will be available for downstream users. While Colorado River water allocations is 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 seven states. 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). While uncertainty of precipitation projections from GCMs is large, future climate change impact assessment should use results from multiple climate models and implement coupled/integrated 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 and temperature and changes in human water use.

FUTURE RESEARCH NEEDS

The livelihood of this arid watershed is impacted by projected declines in the Colorado River flows, competing demands among urban and agricultural users and natural ecosystems for water, and increases in the exposed dry lakebed impacting human health. **The key science question is what is the optimum lake water level to reduce the 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, lake-groundwater interactions, and implementing several key tasks:

1. Determining lake – groundwater connectivity by drilling monitoring wells perpendicular to the lake perimeter at several key locations.

2. Characterizing hydraulic parameters of the aquifers located inside the watershed.

3. Quantifying sub-surface drainage rates to the lake from neighboring agricultural lands.

4. Developing 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 and agriculture management practices, and groundwater use.

5. Involving stakeholders in developing alternative management scenarios to inform decision making and mitigation strategies.

6. Assessing 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, 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 and continue the current water and land management practices will increase the likelihood of Scenario 1 (business as usual) leading to a crisis: The lake water levels will continue to decline as the current trend in lake water levels indicates. There will still be water in the lake but less than today and less than in Scenario 2. The reasons for the decline are changes in the subsurface water flows, lower Colorado River inflows owing to a lower snowpack and population growth or changes in water allocations due to droughts, and higher evaporation rates in the future. Alternatively, we can take action and design mitigation strategies (e.g., water purchases, wetland impoundments, or import water from the Gulf of California) to reach water level of –228 ft. This goal can 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 (Scenario 3, water importation). The main science question for water importation is **how much water needs to be diverted from other sources/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?

Finally, we can be optimistic, and hope that the Colorado River inflows will remain at their current rates or slightly lower in future, and the lake water levels will eventually stabilize at –255 ft with some mitigation plans (Scenario 2, partial mitigation). The question of "optimal" will depend on the costs of achieving that outcome, and thus an understanding of the costs and benefit of various mitigation strategies will need to be explored and understood, including strategies such as water diversion, wetland construction, reduced pumping, increases in fallowing, and water importation. Furthermore, understanding the spatial dimension of the problem is crucial to determining optimal lakes levels and effective mitigation responses. As part of a NSF INFEWS project, a coupled surface water-groundwater model for the Salton Sea watershed using the SWAT-MODFLOW package is currently being set up (Ajami et al., 2020). 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.

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“Green tide” from precipitation of gypsum in the Salton Sea. Photo credit—Caroline Hung.

CHAPTER THREE

The environmental and health risks of changing water depth, salinity, and oxygen-availability in the drying Salton Sea

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Highlights:

- Toxic trace metals and harmful pesticides have accumulated in oxygen-poor bottom sediments of the Salton Sea. As the lake recedes, these metals and organic compounds will likely remobilize to surface waters and be transported into ambient air as dust from the dried playa or released as volatile gases.
- 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.

Introduction: The Drying Salton Sea

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, including contributions related to human activities, including pesticides. The Salton Sea, at a maximum depth of 40 feet, is currently losing water at 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 outflow of water from the Sea other than evaporation, the increasingly saline and oxygen-depleted basin becomes a trap for the inflowing pesticides, metals, and fertilizers.

As the Sea shrinks over the coming decades, increasingly large areas of the playa will be exposed to the winds, resulting in production of 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 that of 8% nationwide (Marshall 2017; read more about *Health Disparities* in 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. Here, we highlight the potential consequences of changing volume of the Sea in terms of the cycling of elements in the waters; the ecological impacts; and related relationships to the past, present, and future compositions of dust sources. These research questions are addressed with the understanding that the behaviors of toxic trace metals, including remobilization, are highly impacted by the changing biogeochemistry—the interplay of living organisms with water and sediment chemistry-- of the water column. These changes are associated with decreasing water levels and are expressed in parameters such as dissolved oxygen, salinity, and accumulation and release of hydrogen sulfide (a toxic gas) in the waters and overlying air. It is highly likely that dust composition and delivery (flux) will continue to change as the lake shallows in the next decades in ways that could become increasingly harmful to surrounding communities.

This chapter begins by explaining the deleterious impacts to local ecological habitats and food webs that result from seasonal oxygen loss and how this condition might be exacerbated with higher temperatures and increasing salinity in the face of warming climate and progressive evaporation. This concern is considered in light of three possible Scenarios for lake management: (1) Business-as-usual, where remediation efforts do not take into consideration the dynamic relationship between declining water levels and windblown dust composition and flux from exposed lakebeds; (2) Mitigation, such as wetland restoration and dust suppression that divert water to the lake; and (3) Water importation, where water from the ocean or local freshwater sources are brought in to stabilize and possibly increase lake levels. All three Scenarios will be influenced by the distribution of toxic metals in oxygen-free (anoxic) bottom sediments that would become airborne dust upon exposure and their relationships to changing lake conditions. In addition to dust contributions, there is a high risk that these toxic metals will be released from the sediments and become enriched in the lake waters with changing oxygen levels. Next, examples are described to specifically highlight the negative impacts associated with transport of selenium and molybdenum as dust from the dry lakebed that could result for public health and livestock. Last, critical remaining questions are defined that should determine future research and offer possible remediation strategies.

Environmental and ecological mechanisms and consequences of oxygen loss

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 man-made activities and to decreased oxygen solubility with increasing salinity. The process of eutrophication starts with the introduction of vast amounts of fertilizer in runoff that becomes concentrated as the waters evaporate. Nutrient overload leads to the excessive growth in primary productivity such as algae, which results in oxygen depletion of the water column driven by bacterial degradation of the dead remains of these primary photosynthetic organisms. These changes in surface lake chemistry negatively impact the entire ecosystem.

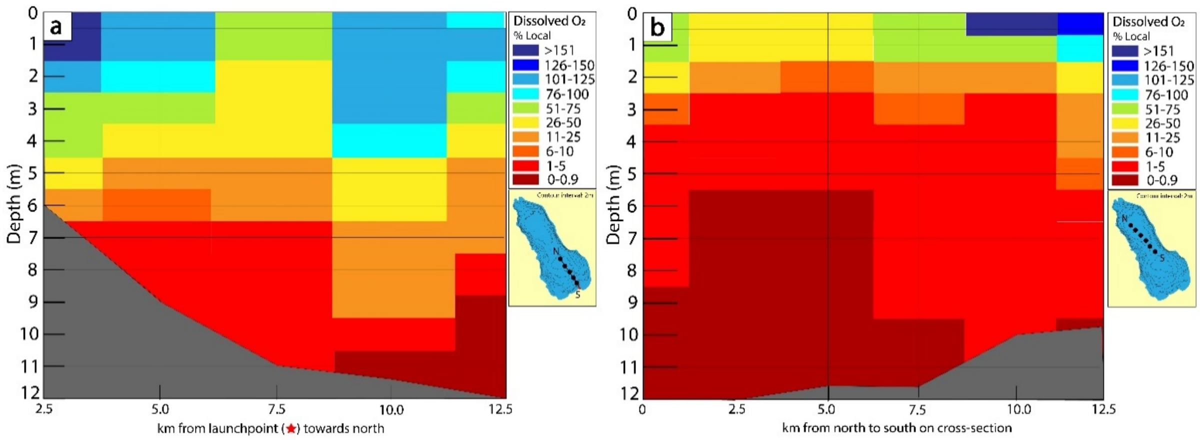

Figure 3.1. Dissolved oxygen sampled at horizontal transects in the **a** southern and **b** northern portions of the lake during a non-upwelling and upwelling day, respectively, in August of 2020. The general trend shows that oxygen loss (anoxia) is persistent in the deepest waters in both the southern and northern portions. However, on days with seasonally intensified winds and associated mixing, oxygen-lean waters reach the surface of the lake (as seen **b)**—along with hydrogen sulfide formed under anoxic conditions—when the chemical and temperature layering or stratification of the lake breaks down.

Excessive nutrient input (nitrogen and phosphorus) 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 that is most persistent and widespread during the summer (Figure 3.1a). On days in the late summer when intensified winds result in mixing anoxic waters into the surface, oxygen-deficiencies can spread (Figure 3.1b), 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 elements 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 reaction of oxygen loss and subsequent production of hydrogen sulfide via bacterial degradation of organic material produced in the nutrient-rich waters can be generalized as follows:

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

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

$$\text{organic matter} + SO_4^{2-} \rightarrow H_2S + 2HCO_3^-$$

Under the hot temperatures of the summer months, these microbial processes are accelerated, and hydrogen sulfide builds up in the bottom waters. On windy days, hydrogen sulfide is released to the surface waters and the air above the lake (Figure 3.1b). There are important implications 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.

Release of foul-smelling hydrogen sulfide and sulfur dioxide as monitored by the South Coast Air Quality Management District (SCAQMD) results in levels that exceed state safety standards (30 ppb/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 to coastal communities. Critical remaining questions in this regard include the following:

- 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?

For these reasons and those discussed below, the hydrogen sulfide system in the lake is a canary in the coal mine when it comes to assessing health of the Salton Sea 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.

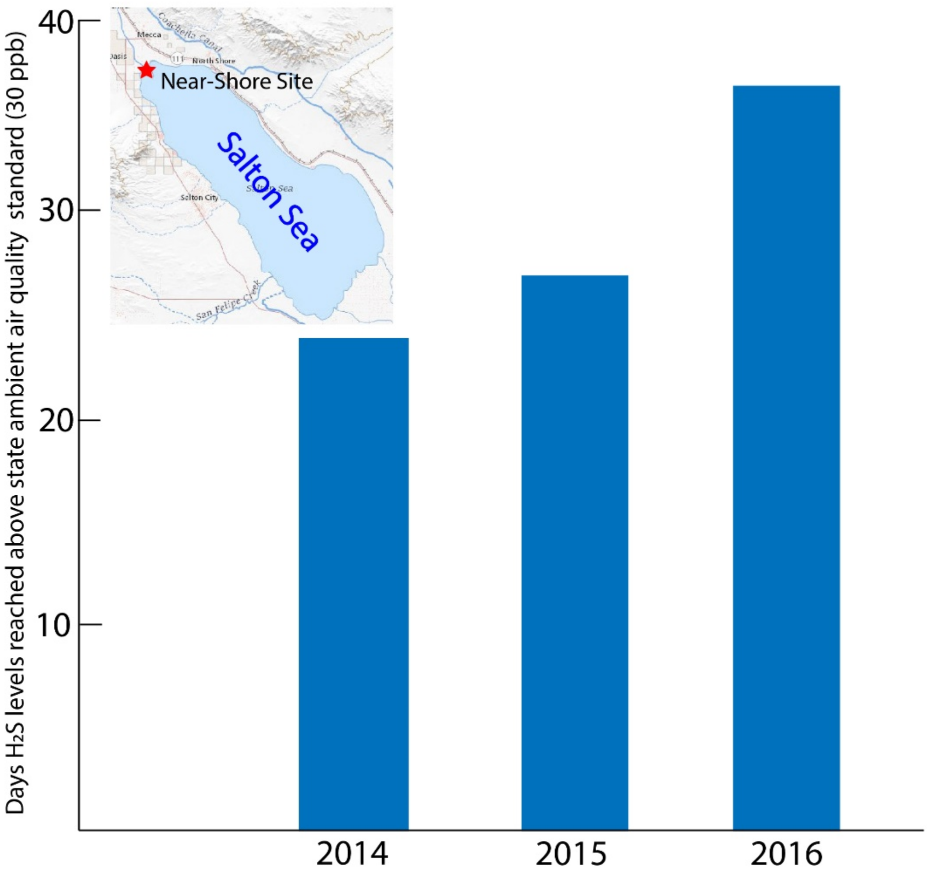

Figure 3.2. The number of days in the years 2014-2016 when hydrogen sulfide (H_2S) levels surpassed state ambient air quality standard of 30 ppb at the Near-Shore air quality monitoring station near the Salton Sea (inset). These events are linked to hydrogen sulfide production in the lake and regional wind patterns and result in widely distributed 'rotten egg' odors during the summer. Data from the public records of the South Coast Air Quality Management District.

During the late summer, strong winds from the south resulting from Santa Ana cyclones, monsoons, as well as surges from the Gulf of California exacerbate 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 a 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 explain the formation of a gypsum crust on shorelines of the Salton Sea (Figure 3.4a), but the mechanism of formation of these crusts is currently unknown. We do know that the salty crusts have formed recently and rapidly (Figure 3.4b). These crusts offer both negative and positive possibilities for lake chemistry and ecology and dust impacts on surrounding communities but have not been studied.

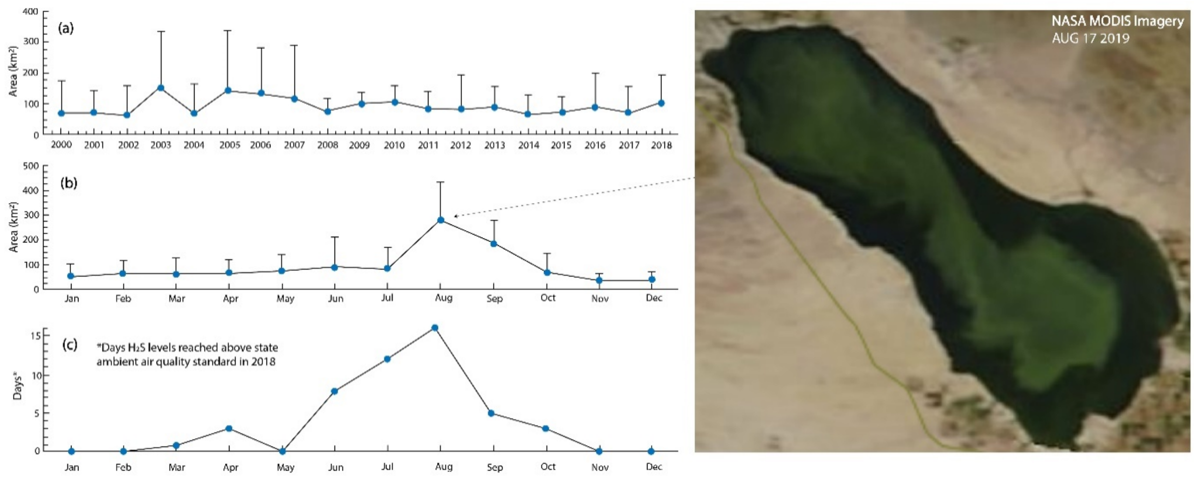

Figure 3.3. Gypsum bloom area in the Salton Sea from 2000 to 2018 presented as annual (a) and monthly (b) averages (adapted from Ma et al., 2020). Inset shows NASA MODIS satellite image of widely distributed gypsum bloom on August 17, 2019. The area of gypsum bloom is related to the concentration and distribution of hydrogen sulfide in Salton Sea water. The monthly trend for days when H_2S concentration exceeds state ambient air quality standards (>30 ppb) at the Near-Shore site is shown in (c). Data for (c) are from SCAQMD public records for 2018 and show peaks in the late summer months of August and September.

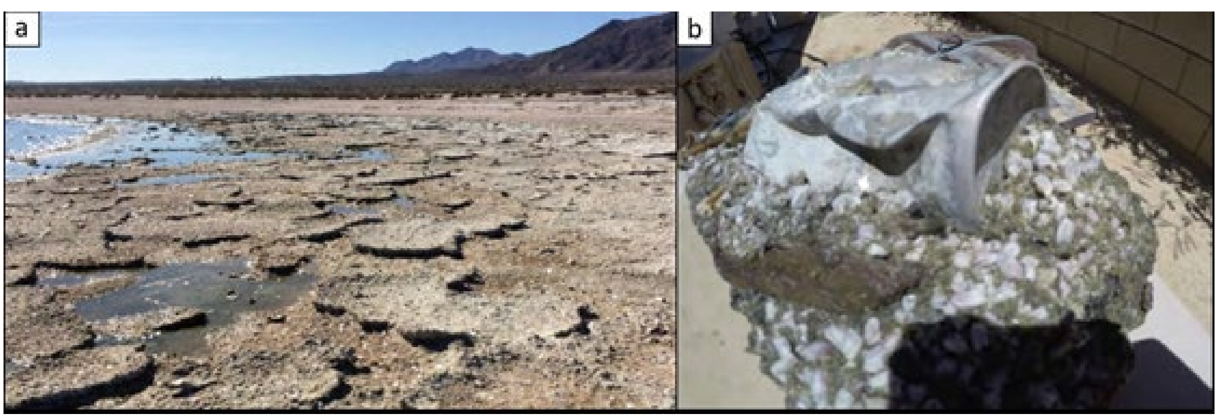

Figure 3.4. **(a)** Salt crust capping exposed playa areas and extending beneath the water line along the receding shoreline of the Salton Sea at Desert Shores, Riverside County. **(b)** The incorporation of recent debris (in this case a beverage can) suggests rapid and recent formation of these salt crusts.

Accumulation of toxic metals and their potential widespread remobilization as dust

Trace metals and other chemicals (e.g., pesticides containing organic and sulfur compounds) 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. While dissolved metals enter the closed lake via rivers at nontoxic levels, through evaporation and redistribution controlled by oxygen levels, the trace metal concentrations increase in certain regions of the lake. The dissolved metals are then 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 (Figures 3.5, 3.6). The net result is that the metals flow into the Salton Sea, but there is currently no path out other than by dust once the bottom sediments are exposed as the lake shoreline recedes.

These bottom sediments are enriched in toxic trace metals and harmful pesticides, which have been accumulating since the last century (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 (see Chapter 6). Importantly, with further drops in lake level, the sediments with the highest toxic trace metal concentrations (Figures 3.5 and 3.6) 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 (see Chapter 2), vast areas of the lake bottom depicted in Figures 3.5 and 3.6 already have molybdenum and selenium concentrations higher than levels acceptable for daily human intake (Vyskočil and Viau 1999; Wilber 1980). Therefore, the associated flux of dust transport will lead 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 will result in harmful levels.

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 (Figures 3.5 and 3.6), 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). If the current water policy continues, there will be more dust, and that dust will be more toxic.

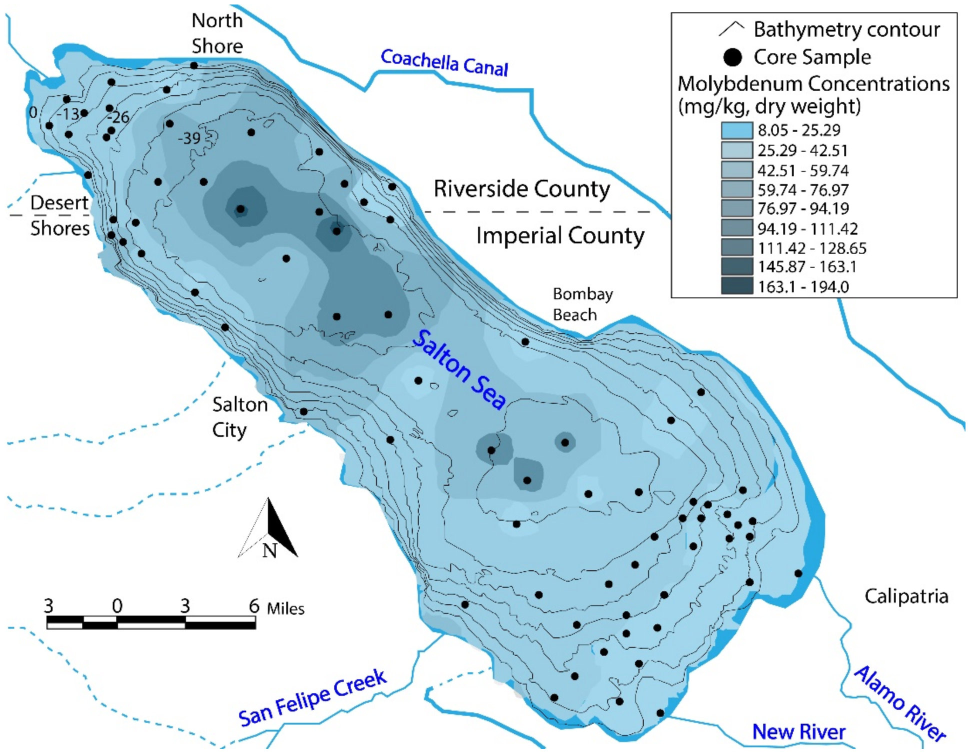

Figure 3.5. Bullseye pattern for molybdenum concentration in bottom sediments of the Salton Sea (adapted from Vogl and Henry, 2002); bathymetry contours with 2m intervals are adapted from Watts et al. (2001). Because water level has decreased in the last two decades, the bathymetry map is for conceptual understanding only. Other toxic metals (e.g., selenium in Fig. 6) show a similar pattern related to persistent and seasonal patterns of oxygen and hydrogen sulfide availability in the lake waters.

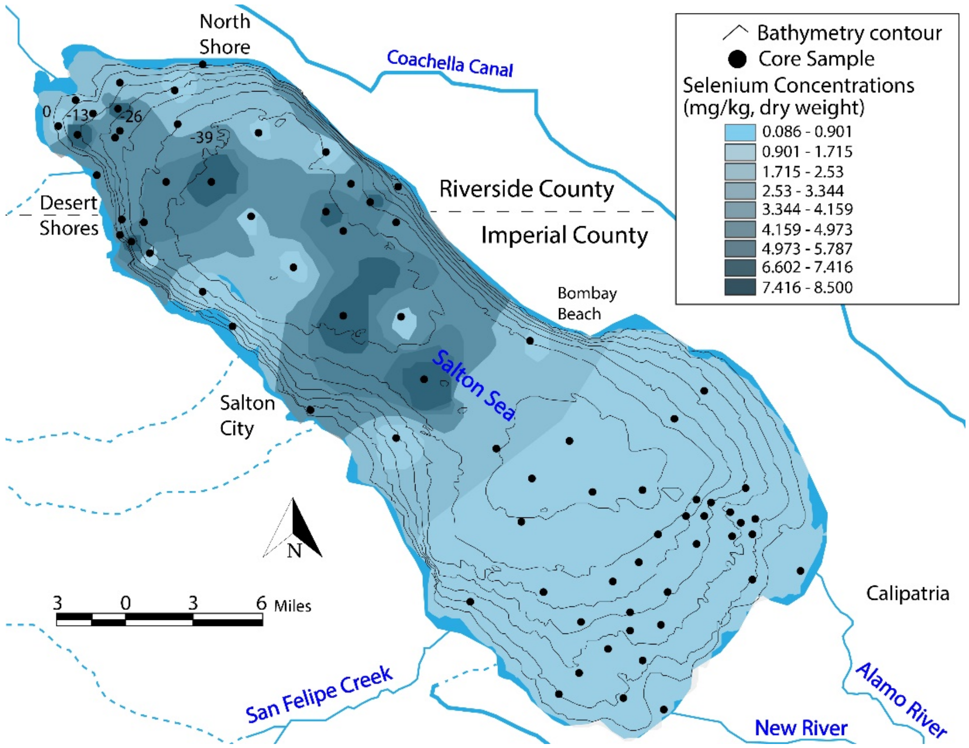

Figure 3.6. Bullseye pattern for selenium concentration in bottom sediments of the Salton Sea (adapted from Vogl and Henry, 2002); bathymetry contours with 2-meter intervals are adapted from Watts et al. (2001). Because water level has decreased in the last two decades, the bathymetry map is for conceptual understanding only. Note the similarities with molybdenum, reflecting similar responses to water chemistry. Many other metals show analogous patterns—specifically, the bullseye enrichments in the basin center. These sediments, if exposed, pose the greatest threat.

Historically, selenium with its toxicity has been the primary metal of interest in studies of the Salton Sea. 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—very small amounts (Rudnick and Holland, 2005). The natural selenium content of most soils lies between 0.1 and 2 mg/kg. 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). Over the decades, this constant influx of selenium to the lake has made its way into the sediments and 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 both temporally and spatially with future reductions in water level and increases in salinity and temperature. One prediction with increasing temperature through climate change and increasing salinity is more frequent, widespread, and persistent episodes of oxygen loss in the water column and thus hydrogen sulfide release events resulting in immediate deleterious effects on the Sea’s ecosystem. This changing chemistry, from the previous oxygen-poor conditions, 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 to local ecosystems, communities, and agriculture from remobilization of selenium, molybdenum, arsenic, and pesticides at toxic levels

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 wind-blown dust. Key toxic metals of interest are molybdenum and selenium, among others. These have been found in significant levels 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 nearby communities of 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. Even though trace amounts of selenium are necessary for cellular function in many organisms, including humans, it is toxic to humans in minute amounts above 0.055 mg/kg/day (Aldosary et al. 2012). Chronic exposure can trigger lung malfunction (i.e., dyspnea, asthma, and cough), as well as various other disorders (Jaishankar et al. 2014). It is the rate of delivery as dust not just the concentration in that dust that 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 have already caused an ecological crisis in the aquatic food chain (Hamilton 2004). Scientists found that in 1996, a severe Type-C botulism outbreak killed over 15,000 pelicans and associated fish-eating birds. It was shown that 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. Further, selenium introduced as dust and volatile gases continues to be released 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. Although beneficial in ecosystems (e.g., molybdenum is in the enzyme that fixes nitrogen into soils), high molybdenum content transported through dust can negatively impact 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). Even though the 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 the above highlights for selenium and molybdenum, related literature cites other toxic 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). The biogeochemical cycling of elements in the Salton Sea will continue to change as the lake shallows.

Potential outcomes via three possible Scenarios

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 under three potential scenarios of lake evolution in the face of changing water management.

A. Scenario 1: Business-as-usual, lake level declines dramatically

Water levels will continue to decrease, which will increase the salinity of the water column, 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 in past research.

B. Scenario 2: Mitigation, such as wetland restoration and dust suppression that divert water to the lake

The benefits of this approach include: (1) continued immersion of the center of the lake where the toxic metals are most concentrated and (2) introduction of buffer zones that could reduce fertilizer and metal transport into the lake. Research is needed to determine the optimal design of these buffer zones and the lake level that would most effectively mitigate against dust production from the most contaminated bottom sediments.

C. Scenario 3: Water importation, where water from the ocean or local freshwater sources are brought in to stabilize and possibly increase lake levels

This Scenario could be the most effective in 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. Further, models are needed 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. For example, preliminary model results predict that the addition of substantial freshwater and saltwater would both lead to dissolution of the gypsum 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.

Future research needs

Action is required immediately to fully assess the present 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. 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 detail in light of recent changes and future plans in the region. Essential new data will be integrated into first-of-their-kind quantitative models to help us predict the outcome of the three possible remediation Scenarios. Specific research goals focus on three topics:

1. **Evolution of water column and sediment chemistry:**

- Model and measure the salinity and ionic composition effects on oxygen solubility and the physical properties (e.g.., density and temperature) of the Sea's waters to predict the related consequences of water management policy.
- Monitor oxygen and hydrogen sulfide 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 their sensitivity to changing water levels.
- Characterize metal enrichments in the sediments of the central Sea. Track the potential for selenium remobilization using specialized natural tracers (e.g., selenium isotopes; Johnson et al. 1999; Stüeken 2017).

2. **Airborne release of hydrogen sulfide and transport of toxic dust:**

- Monitor airborne hydrogen sulfide levels in surrounding communities and work with atmospheric circulation modelers to predict regional propagation of frequent hydrogen sulfide in air masses.
- Assess health and life-quality risks to surrounding communities linked to more frequent, persistent, and likely more concentrated hydrogen sulfide release from the Sea.
- Work with the community of air quality researchers to introduce sulfide detection in Salton Sea's waters and surrounding regions as input parameters in models designed to forecast sulfide 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.

3. **Health impacts to nearby communities:**

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

Summary

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. 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.

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Dust mitigation at the southern region of the Salton Sea---Photo credit Jonathan Nye

CHAPTER FOUR

Air Quality Issues at the Salton Sea

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Highlights:

- Airborne dust fluxes at sites close to the Sea are already in the high range of values observed at Owens Basin before mitigation efforts.
- A large fraction of the dust at sites closest to the shore of the Salton Sea is associated with emissions from the lakebed and sea spray.

Introduction

Air quality around the Salton Sea, located between the Imperial and Coachella valleys of California, is impacted by emissions from the surrounding arid lands, urban and other anthropogenic emissions upwind, emissions from the newly exposed playa (i.e., lakebed), 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 air quality standards. National and State 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 µm in aerodynamic size ($PM_{2.5}$) or up to 10 µm in aerodynamic size (PM_{10}). PM are 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 compositions, 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: by wind blowing over the dry desserts, large bodies of water, by breaking of waves, forming “primary PM”, or from forming in the atmosphere through atmospheric oxidation reaction of gaseous pollutants, leading to “secondary PM”. Not all gaseous pollutants are reactive and immediately harmful, however. For example, greenhouse gases such as methane and carbon dioxide are long-lived pollutants that, once emitted, can remain in the atmosphere for decades and pose 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. These Scenarios include 1. Business as usual with increased exposure of the lakebed in the next decades, to levels greater than 400 km^2 by 2038 (lake water level less than ~ -255 ft), due to loss of water input to the lake, increased loss to ground water, and/or through evaporation; 2. Wetland creation and dust mitigation projects with some additional exposure of the lakebed in the next decades to a steady-state lakebed exposure level of ~400 km^2 by 2038, with lake water level at ~ -255 ft; 3. Maintaining water in some areas of Salton Sea by water importation. This chapter introduces the major classes of atmospheric pollutants: direct PM emissions from the playa and the Sea, emission of reactive gases that can form secondary PM, and the emission of greenhouse gases. Emissions of each pollutant class are then discussed in the context of the three Scenarios and finally, remaining critical scientific research questions are highlighted.

Atmospheric Pollutants

When considering the 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 are highlighted in Figure 4.1. These pathways include 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), ammonia (NH_3)), and emissions of unreactive, greenhouse gases (e.g., carbon dioxide (CO_2) and methane (CH_4)).

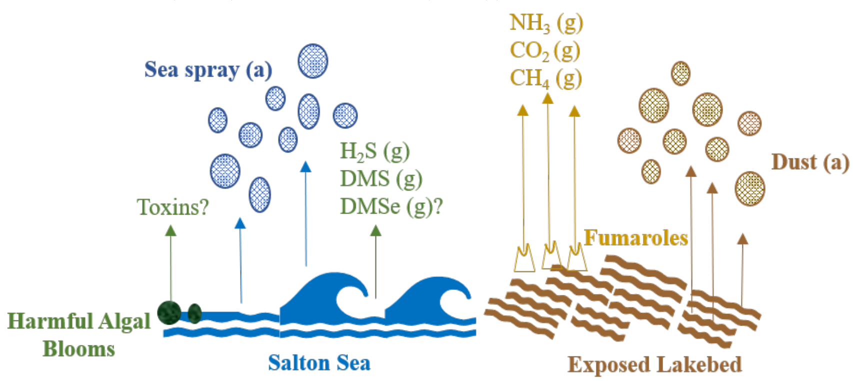

Figure 4.1. Diagram depicting major sources of gas-phase (g) and aerosol-phase (a) pollutants at Salton Sea.

Direct Particulate Matter emissions

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). PM emissions have gained interest 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 Salton Sea (IID et al., 2017), until recently composition of PM was unknown and therefore, it was unclear what the contribution of different sources to PM loading in the region was. Absence of knowledge on the chemical composition or size distribution of the dust in the area were also limiting our understanding of the human health impacts of dust. In a study in 2015, 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 elements with an anthropogenic source such as cadmium, the EF is higher 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. 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.

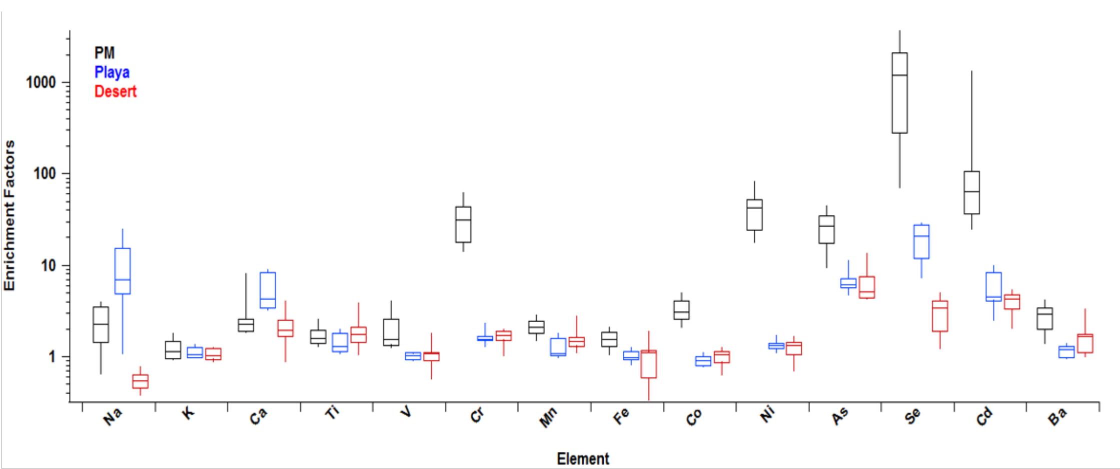

Figure 4.2 Elemental enrichment factors determined for particulate matter, playa, and arid desert lands. Box and whiskers depict 10th, 25th, 75th, and 90th percentile values, the horizontal lines show the median. Figure from Frie et al., 2017.

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), Se) were concentrated more uniformly among the submicron particles (Figure 4.3). This result is expected since mechanical processes for primary PM formation generate larger particles, whereas PM components that are formed from secondary atmospheric oxidation processes are concentrated on submicron particles. Since selenium 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, which is discussed further in later sections.

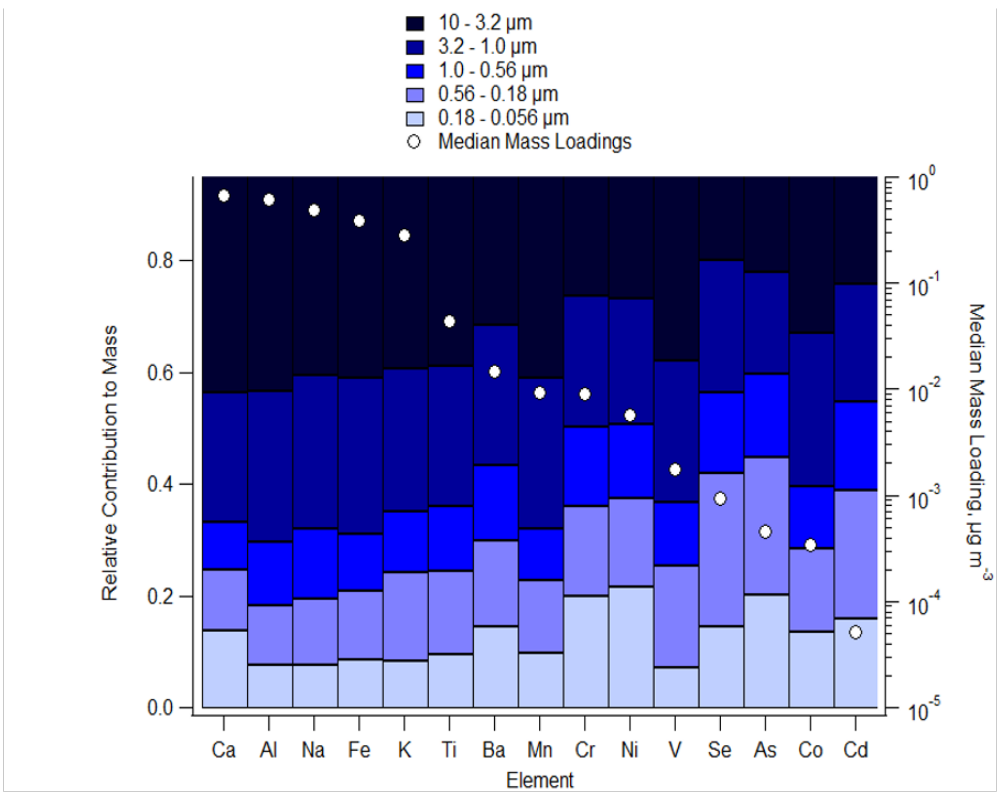

Figure 4.3. Size segregated elemental composition of particulate matter. Figure from Frie et al., 2017.

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 PM_{10} 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 PM_{10} (Frie et al., 2017) while the playa sources contributed by up to ~10% to PM_{10} concentrations while contribution of playa sources to Na concentration of PM_{10} was significant at 40-70% (Frie et al., 2017).

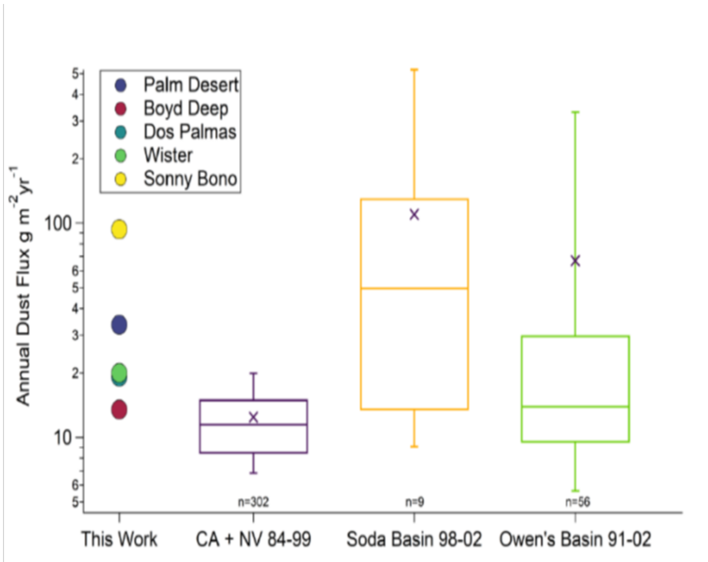

Figure 4.4. Estimates of annual dust flex at several sites around the Salton sea as well as several historic records in southwest US. Box and whiskers depict 10th, 25th, 75th, and 90th percentile values, the horizontal lines show the median and crosses show the mean. Figure from Frie et al., 2019.

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 km^2 of playa being exposed, dust fluxes were higher than the historical median values in the Southwest US. Even at Owens Lake before mitigations when ~260 km^2 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 was determined to be in exceedance of the 24-hr average national standard for PM_{10}, prompting the local air pollution control district to establish a monitoring network of PM_{10} surrounding the lake. In the following years and after establishing the State Implementation Plans, the Department of Water Resources was ordered to mitigate dust emissions by implementing a variety of dust control measures on ~127 km^2 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 PM_{10} exceedance value was at 280 ⌈g/m^3, substantially reduced from 1,087 ⌠g/m^3 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 not the other two sulfate-based salts (Frie et al., 2019). The stability of the Sea's unique crust, however, is not really well understood.

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 current influence of playa emissions on local PM and the potential impacts on human health, there is the need for continuing such measurements to examine how dust concentrations, composition, and size change with time because the exposed lakebeds in the future may not have the same physical and chemical characteristic as the currently exposed areas. As the Sea recedes, it exposes new sediments and playa. Once the salted crust over the sediments is eroded, potential for generating dust from the sediments, potentially with very different composition and higher concentrations of toxic elements, increases (Vogel & Henry, 2002). This aspect was further discussed in Chapter 3. Additionally, dust events are sporadic and episodic; 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 the 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. 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 gas emissions

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 dimehtylsulfoniopropionate (DMSP) that are chemical markers of algae activity. They result in high rates of transfer of gaseous DMS to the atmosphere--rates that are 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 with oxygen and water to form other compounds.

The Colorado River and the sediments it carries are known to be high in selenium. 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 selenium, 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, this compound oxidizes and forms secondary PM, which was 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 DMSe 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 H_2S, DMS, and DMSe 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.

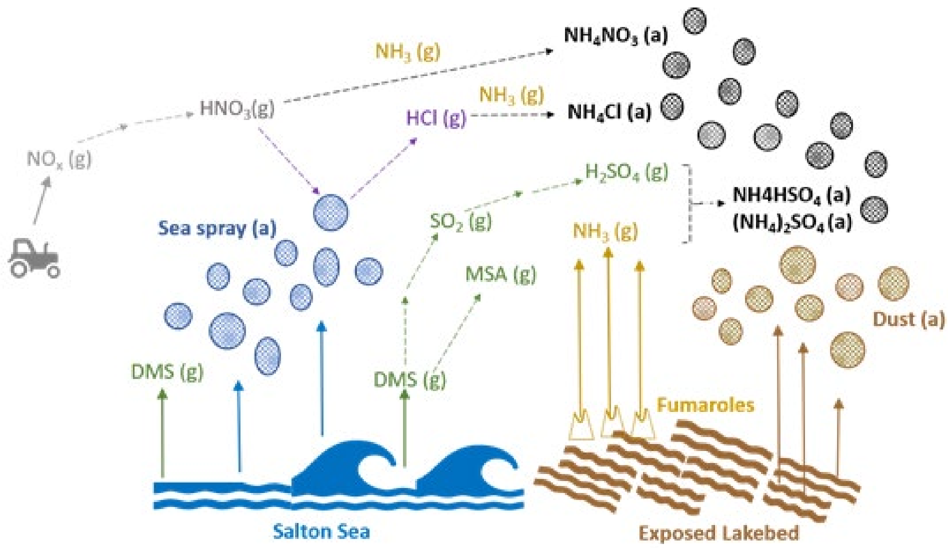

Figure 4.5. Diagram depicting chemical interactions of various reactive gas-phase (g) and aerosol-phase (a) pollutants at Salton Sea. Solid arrows show emissions; dashed arrows show chemical reactions.

Greenhouse gas emissions

Previous studies have examined release of concentrated plumes and diffuse seepage of CO_2 and CH_4 from the main seep field of the Salton Sea geothermal system, namely the Davis-Schrimpf field, at the south-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 m^2 area, daily emission rates of CO_2 and CH_4 were estimated to be 9,410 kg CO_2/day and 44.5 kg CH_4/day, respectively, with only 25% of the emissions originating from the vents (Mazzini et al., 2011). These emission rates translate to 3841 MT CO_2 /yr (i.e., metric ton of equivalent CO_2, assuming global warming potential of 25 for CH_4), which is equivalent to CO_2 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 CO_2 and CH_4 from the Salton Sea geothermal system are likely higher than the current estimates since additional emissions of CO_2 and CH_4 are expected from areas outside the Davis-Schrimpf field site and along the Salton Trough.

Microbial Emissions

An emerging area of research is called aerobiology, or the study of the movement in air of "bioaerosols," including 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. From Figures 4.1 and 4.5, these bioaerosols make up some fraction of the aerosol phase emissions of sea spray from the Salton

Sea and the dust emissions from the exposed playa. In addition to bioaerosol particles, compounds produced by microorganisms can be picked up and transported as aerosols.

As the Salton Sea becomes smaller and more saline, which is predicted in all scenarios, but most extreme in Scenario 1, the environment and ecosystems in and around the Sea will experience changes and decline in quality. 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 restoration strategies.** The changes in the microbiology of the Sea and playa will shift the microbial communities that are picked up as bioaerosols.

Emission 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 EPA 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, most likely due in part 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 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 Westmoreland station, likewise see a summertime shift towards south and easterly winds (Figure 4.6, bottom).

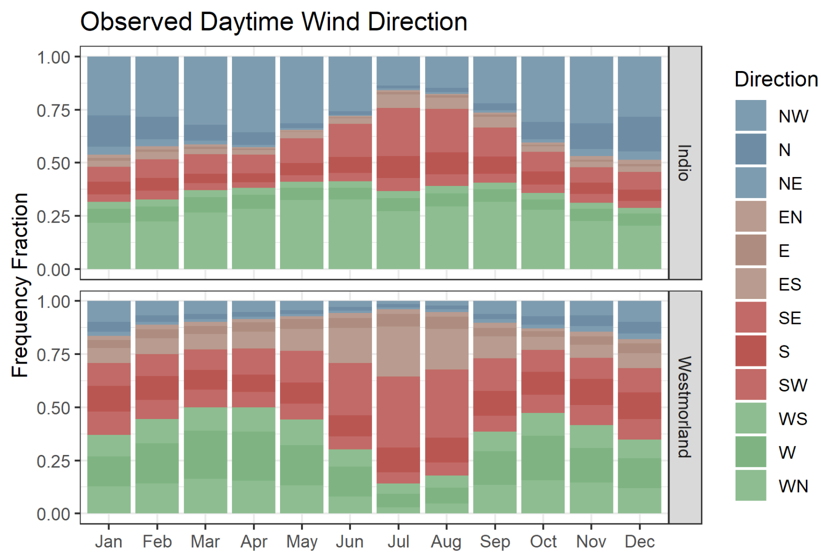

Figure 4.6. Frequencies of mean daytime wind direction at Indio (Coachella Valley) and Westmoreland (Imperial Valley) stations based on data archived through EPA Air Quality System network (EPA AQS, https://www.epa.gov/aqs).

Diurnal patterns of winds during strong dust events 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 in which at least half of the local air quality monitoring stations reported daily PM_{10} concentrations that were at least one standard deviation above the station norm, shows that a large fraction of these regional dust event days was characterized by midday winds blowing from the south (Figure 4.7, top). Based on these observations, **exposure to PM_{10} during these types of Coachella Valley dust events will disproportionately include dust that may have originated 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 – a similar analysis of winds measured at the Westmorland station during Imperial Valley dust events shows some morning winds from the south, with afternoon and evening winds dominated by winds from the west.

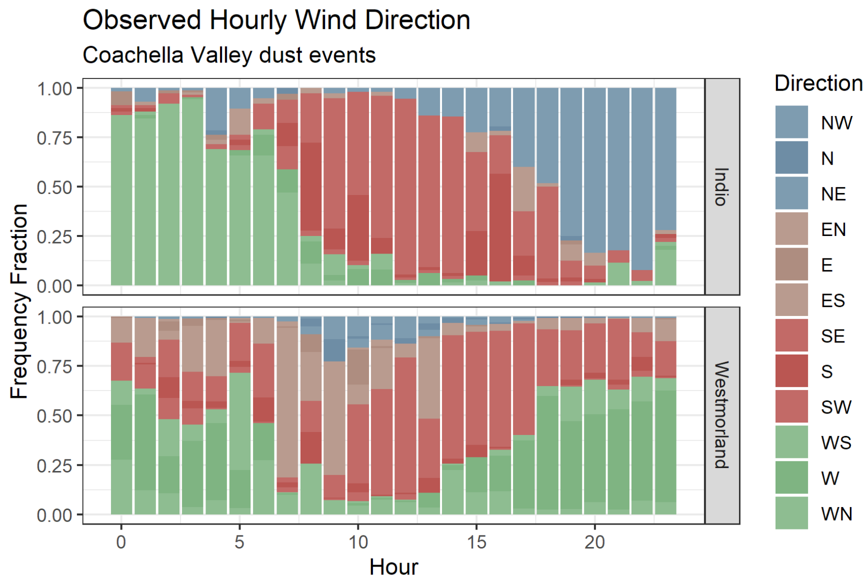

Figure 4.7. Hourly wind speed frequencies for regional dust event days only, defined as days during which at least half of all local stations (in the Coachella Valley or Imperial Valley for the Indio and Westmorland stations, respectively) exhibit daily PM_{10} values exceeding the station mean by at least one standard deviation.

Future of Atmospheric Emissions

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. Under Scenario 1, it is expected that more than 400 km^2 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 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 2nd Scenario, at least 400 km^2 of lakebed is expected to be exposed by 2038, therefore, many of the atmospheric emission implications of Scenario 1 still apply. The only significant difference is that the most toxic sediments towards the center of the Salton Sea will most likely remain submerged, and therefore, hazards related to dust emissions from these sediments are reduced.

The best outcome for air quality is expected to be achieved under Scenario 3 where dust mitigation efforts restore/maintain water levels in the Sea. Depending on the extent of the exposed lakebed compared to Scenario 1 or 2, 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 will likely not be increased compared to the current levels.

Research Gaps and Opportunities

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 below:

- 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 different types of elements like selenium, chemical ionic species, and organic compounds of PM needs to be measured.
- 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.

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Air quality monitoring equipment. Photo Credit - Emma Aaronson.

Wetlands at the southern Shoreline. Photo credit—Jonathan Nye.

CHAPTER FIVE

Ecology of the Salton Sea and surrounding environments

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Highlights:

- While wetland habitat restoration may benefit certain species of birds, current plans to restore the sea do not address the core problems limiting ecosystem functioning.

- The Salton Sea ecosystem faces collapse due to excessive nutrients, rising salinity, and declining water levels, likely resulting in undesirable outcomes for recreational activities, the regional economy, and public health.

Introduction

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, its margins, including riparian zones and the increasingly exposed playa, as well as the agroecosystems bordering on 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.

Aquatic Primary Production

Primary producers in the Salton Sea include a number of different 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 that form the base of the Salton Sea food web are supported by an overabundance of abiotic nutrient inputs resulting in high levels of activity and productivity. These nutrients are primarily supplied to the sea via agricultural runoff and untreated sewage originating from Mexico, which creates a highly eutrophic aquatic ecosystem. The resultant high rates of primary production have led to the subsequent die-off of aerobic organisms, like tilapia (Beman et al. 2005, Chaffin and Bridgeman 2014, Heisler et al. 2008) as primary producers die and sink into the water column consuming oxygen during their decomposition. In addition, certain species of algae produce toxins (Reifel et al., 2001; Tiffany et al. 2007a; Tiffany et al. 2007b) and are often referred to as harmful algal blooms or HABs.

Harmful algal blooms are signs of polluted waters that occur from coastal 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, for example pelicans.

Other HAB consist of species of cyanobacteria, primitive photosynthetic organisms, like *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 Salton Sea (Anderson et. al 2007). Organisms like this not only produce toxins, but also create conditions whereby their biomass causes anoxic events (see Chapter 3 on the biogeochemistry of the Salton Sea for a more detailed discussion of microbial metabolism in the water column). 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).

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 pathways, 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 (see Chapter 3).

Major ecosystems adjacent to Salton Sea

The Salton Sea is closely connected 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.

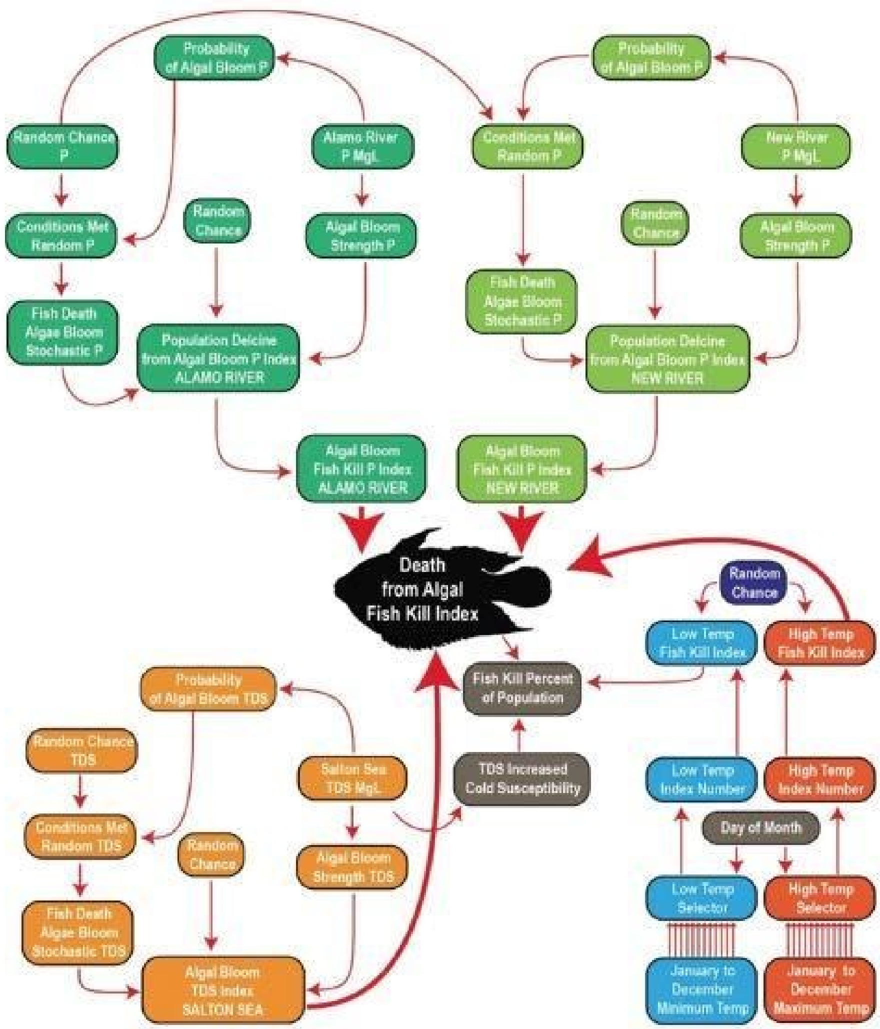

Figure 5.1 . Diagram showing the variables resulting in fish kills. The extent and severity of fish kills are the result of four interconnected variables: Algal blooms and phosphorus cycling from the Alamo River (dark green), Algal blooms and phosphorous cycling from the New River (light green), Algal blooms and total dissolved solids in the Salton Sea (orange/yellow), and seasonal temperatures (blue/orange). (Kjelland, M. E., & Swannack, T. M., 2018)

Agricultural interfaces

High temperature agricultural systems, exemplified by 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). A majority of the United States winter vegetables are grown in fields of the Imperial Valley south of the Sea, while 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 greatly elevated (Oikawa et al. 2015b; Lu et al. 2017).

High temperature agricultural systems can be locations of unusually high nitrogen (N) 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 have demonstrated that modifying fertilization and irrigation practices in a high temperature environment can reduce losses of N 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 changes like this 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 NOx model predictions. These emissions are associated with standard management practices for summer forage crop – 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 region of the Imperial Valley CA 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).

Wetlands

The landmark paper of Shuford et al. (2002) described the importance of Salton Sea's wetlands on the migratory and resident birds of North America. Since that time, however, increasing salinity and nutrient overloads have caused ecological disasters including major fish kills and avian diseases. Today, wetlands surrounding the northern and southern shorelines where the Whitewater, New, and Alamo rivers drain into the Sea are potential low-tech habitats supporting some of the remnant populations still able to take advantage of the area (Figure 5.2).

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. Coastal 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 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 endangered 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.**

Figure 5.2. A wetland near the Salton Sea. (Photo credit to Irfan Khan. Copyright © 2019. Los Angeles Times. Used with permission).

The 2018 Salton Sea Management Plan (2018) 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 engineered habitats will prove sustainable in the short term (2-5 years) or long term (>10 years). (Taken *from the LA Times article).*

A recent LA Times article quotes US Fish and Wildlife Service biologist Tom Anderson who commented on naturally forming wetlands on the New River delta. “My recommendation is that folks start managing the flows of runoff and leave a lot of these wetlands alone,” Anderson said. “They’re doing a fine job of suppressing dust and producing entirely new thriving ecosystems at no cost to taxpayers.”

Microbes can affect air quality---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 described in Chapter 4, as the Sea recedes due to reduced water inputs in all scenarios, it exposes additional playa and increases atmospheric dust levels. 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, that 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 aeolian microbial community can have an impact on functioning of local and global ecosystems, potentially impacting human health.

Aquatic food web structure

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

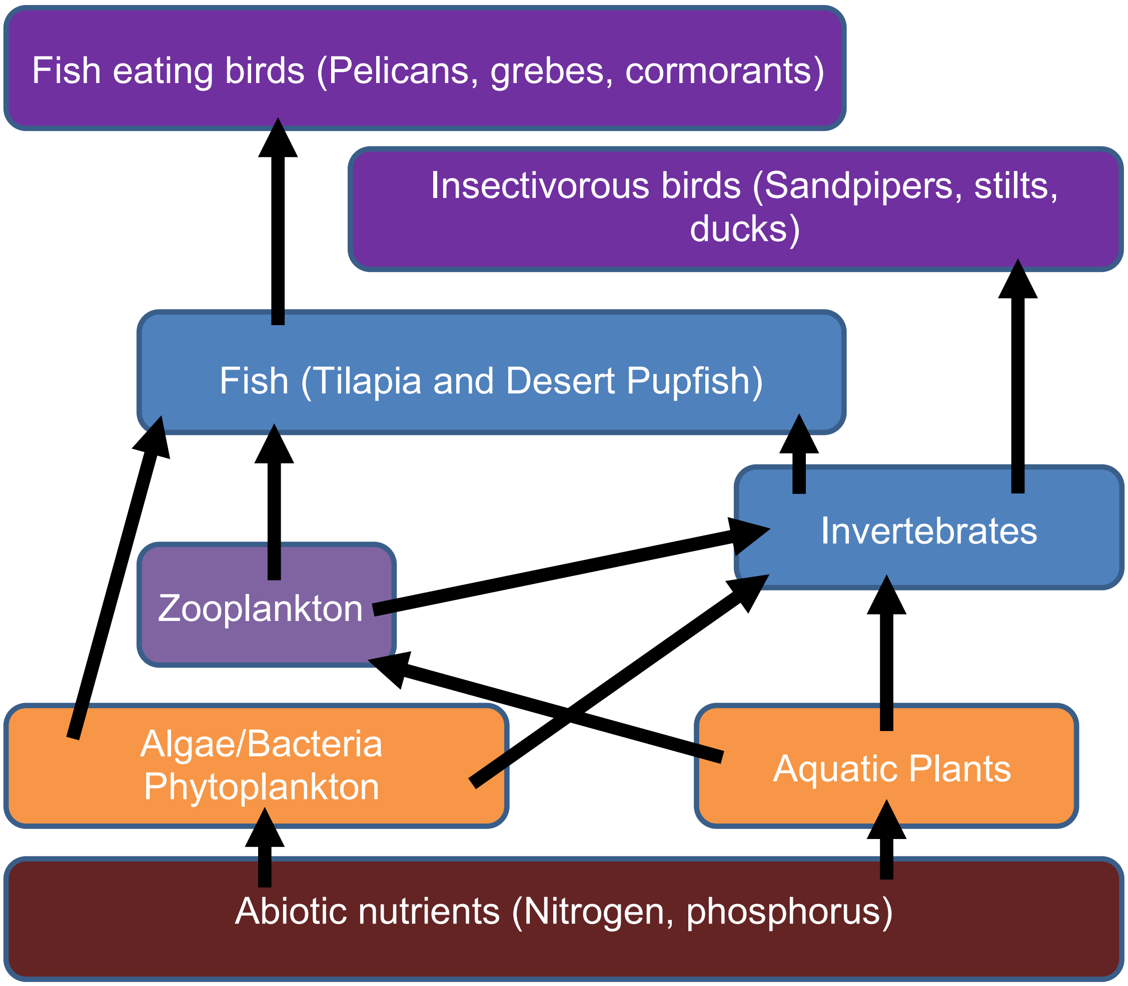

Figure 5.3. A simplified food web showing the species relationships.

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).

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).

Figure 5.4. The desert pupfish in its ideal habitat. (Copyright Minden Pictures, used with permission).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 reserve. The insectivores largely feed 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.

Fish eating birds are highly susceptible to fluctuations in populations of their prey, resulting in piscivorous bird populations fluctuating as well (Hurlburt et al. 2009). Piscivores include pelicans, gulls, cormorants, terns and many others, typically migrating from marine and other saline lakes (Lyons et al, 2018). Lyon et al.'s 2018 study of Caspian Terns (*Hydroprogne caspia*) shows that these birds congregate near the shore-based 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; Upadhay et al. 2018).

Ultimately, 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. It is only with sustained effort that we can maintain habitat suitable for birds, fish, and other organisms in the sea. The way to guarantee the continued presence of these valued organisms is by maintaining habitat by controlling salinity, oxygen levels, and temperatures. While we may not be able to control rising temperatures and the increased frequency of heat waves due to global climate change, the state has the ability to control the freshwater inputs into the sea to maintain a healthy food web that benefits not only the fish and birds, but the people living nearby.

Scenario Effects

While different potential scenarios will impact different organisms differently, the linkages between organisms and interspecies relationships are more complicated than the simplistic food web presented above (Figure 5.5). 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 in this system, 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 our proposed scenarios, naturally created wetlands may have greater potential for supporting wildlife than expensive built habitat.

- 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?

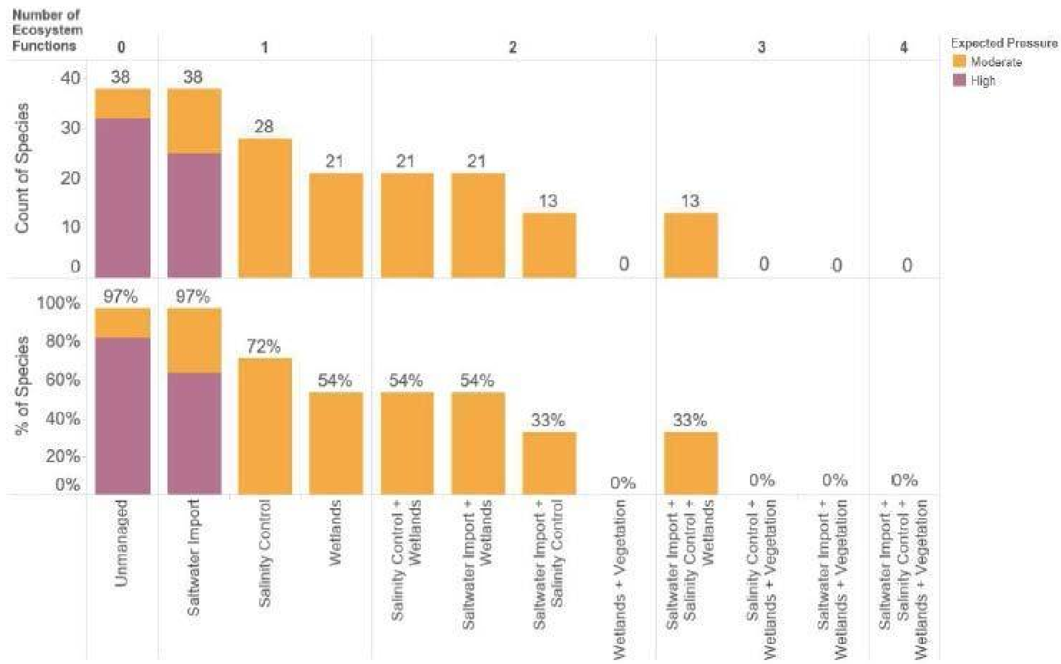

Figure 5.5. Calculation of expected pressures on ecosystem functioning of the Salton Sea. Different mitigation strategies have different expected pressures on species. Combining different mitigation strategies decreases the expected pressures on species. Figure from Forney (2018) with permission.

Further Research Needs

Scenario 1 - Business as usual

In the scenario that lake levels decrease at current trends (Scenario 1, business as usual) the results will likely be devastating to the majority of larger organisms living in and near the sea. With oxygen levels decreasing, hydrogen sulfide levels rising, increased salinity and high temperatures, the lake will become uninhabitable for tilapia. While desert pupfish have specific adaptations for conditions like these, they are unable to sustain these conditions for longer periods of time, rendering the Sea impossible to traverse for individuals traveling between breeding habitats. 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.

Under Scenario 1 with decreased flow input and declining lake level, we know the salinity will increase to levels precluding the survival of fish species. It is also assumed that as the Sea shrinks in size, HAB will increase in prevalence.

- Will there be changes in the organisms at the base of the food chain, in particular will phytoplankton producing toxins be enhanced?
- When will the endangered pupfish go extinct? 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?

Scenario 2 - Partial Mitigation

In the case where lake levels decrease but remain stable at -255 ft (Scenario 2) it is likely we will observe similar effects as Scenario 1, though to a lesser degree. If enough freshwater enters the lake to keep salinity levels in check, and therefore 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 Scenario 2 will result in similar effects to Scenario 1 for larger organisms such as the disappearance of fish and piscivorous birds. Microorganism and insect community composition on the other hand would likely reflect what we see in other very salty aquatic ecosystems, such as Mono Lake, where a prevalence of brine shrimp and flies support insectivorous birds. Under scenario 2 reaching -255 m and holding steady, it may be possible to prevent complete ecosystem collapse.

- How much water needs to be delivered, and where, and when, 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?

Scenario 3 - Water Importation

Scenario 3, in which lake water levels are sustained and managed via importation, presents the best possible case for the survival and stability of fish and bird populations. However, the way lake levels are sustained will matter in determining the Sea's community composition. Saltwater importation may result in increased salinity that can result in the extirpation of tilapia despite maintained lake levels, resulting in similar trophic cascades and disappearance of fish-eating birds described in Scenarios 1 and 2. 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. However, even with freshwater introduction as proposed in Scenario 3, it is not guaranteed that the aquatic food web can be sustained as climate change may result in temperatures and oxygen availability incompatible with fish and birds. Under scenario 3, water will be delivered either by purchase or from the Gulf of California.

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

Concluding Statement

Either way the management of the Salton Sea develops over the coming decade, 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 SSMP is going in the right direction. An independent assessment of ecosystem functioning in its broadest sense is an important component for Salton Sea's future.

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Water collecting in the in the North Shore Yacht Club above the Salton Sea. Photo credit—Jonathan Nye

CHAPTER SIX

Health Disparities, Pulmonary Health, and the Salton Sea

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Highlights:

- The Salton Sea impacts on the health of the community involve several factors, including potential direct impacts of aerosols generated at the exposed lakebed, and contaminants from the geochemistry and agricultural activity, but it also includes secondary impacts from the depressed economy and limited health care access.

- Mitigation strategies at present are focused mainly on dust generation at the exposed lakebed, and scenarios in which Salton Sea retreat is reduced may have an important benefit; however, the factors with greatest impact on health in the region remain to be directly identified or addressed by policy.

Introduction

The United States national average of Primary Care Physicians (PCP's) is 68 per 100,000 people in rural areas and 84 per 100,000 people in urban areas (Petterson et al., 2013). By contrast, the region surrounding the Salton Sea only has 21 PCP's in Imperial County at the southern end, and 31 PCP's in Coachella Valley at the northern end, which qualifies this region as a Medically Underserved Area (MUA). This deficiency in access to health care in the community is further exacerbated by the detrimental effects of occupational and environmental exposures to the people who live in the region.

Coachella Valley and Imperial County also face additional socioeconomic barriers. For example, while California's average poverty level is 12.8%, 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).

According to the 2010 US Census, there are 130,000 people living within 15 miles of the Salton Sea, with another 650,000 directly affected by the dust (Johnston, 2019). These areas around the Salton Sea already face many socioeconomic disparities with potential impacts on health, including linguistic isolation, lack of education, lack of funding and health profession shortages, some of which likely exaggerate ongoing health disparities.

	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	

[7] Coachella Valley populations beyond 2035 County projection estimated at 1% annual growth rate.

Table 6.1. From the Pacific Institute, showing the current and projected populations that will be affected by the Salton Sea dust. (Cohen, 2014)

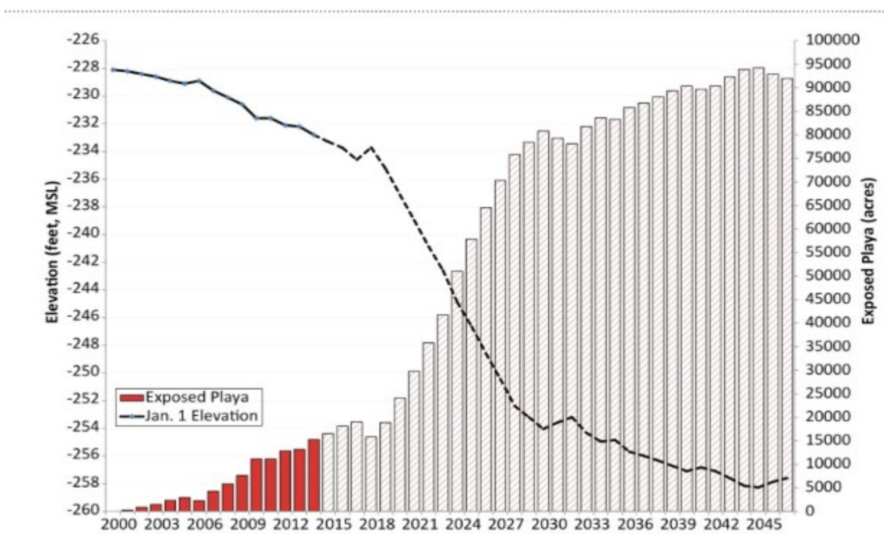

Figure 6.1. From the Pacific Institute, historic and projected Salton Sea elevations and exposed playa, relative to January 1, 2000. Figure from Cohen, 2014.

Respiratory Health Crisis

The drying of the Salton Sea is exposing the surrounding playa and increasing levels of ambient aerosol dust (Figure 6.1). 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 US 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 off of the Mexico-US 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 off of 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 ($\mu g/m^3$). They also regularly exceed federal standards of 150 $\mu g/m^3$ in a 24-hour period. These excesses often occur during dust episodes lasting multiple days, as shown in Figure 6.2. These excesses are expected to lead to increased mortality, with previous work showing that increases of 100 $\mu g/m^3$ in PM_{10} can be expected to produce a 16% increase in death rate (Pope et al 1992). Occupational exposure to PM_{10} has been linked to COPD, Organic Dust Toxic Syndrome (ODTS), bronchitis, pneumoconiosis, rhinitis, and asthma (Cohen, 2014). PM_{10} can furthermore serve as a carrier for pollen allergens, further exacerbating allergic asthma in the area and increasing health risks.

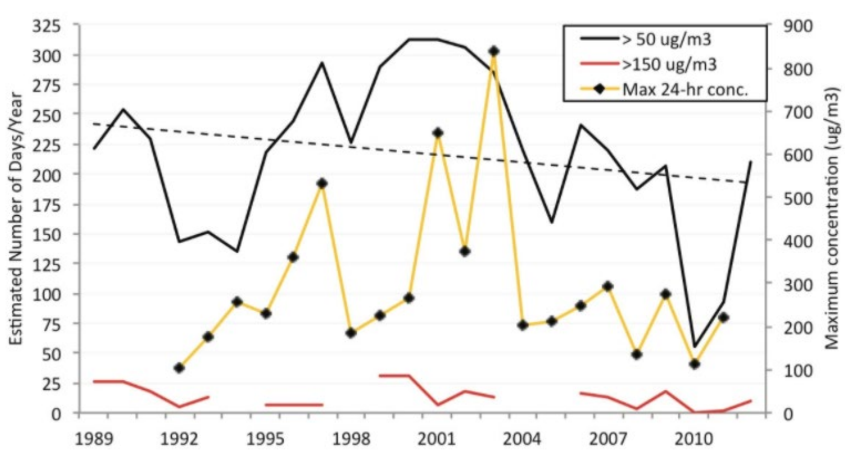

Figure 6.2. Number of days of exceeding daily PM_{10} state and federal standards in the Salton Sea Air Basin. From Pacific Institute publication (Cohen 2014).

Living further away from the exposed area reduces the risks of long term respiratory conditions; however even though 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 6.3). Additionally, the acreage being impacted by the dust particles is increasing exponentially 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.

There is still work to be done in identifying possible connections between dust particulates and their components to the respiratory symptoms seen in the area. 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, which is known to further exacerbate allergic asthma (Frie et al., 2017). 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, though this has been mainly studied 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). However, these compounds may be largely sequestered in the bottom sediments (Schroeder et al, 2002), and therefore might not be currently present at significant levels on emissive playa surfaces.

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.

An Already 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, there are already present inadequacies in asthma management among Hispanic Americans, the predominant local population. High uninsured rates contribute to these vulnerabilities: one third 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.

A significant percentage of people that are identified 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 County and Coachella have the highest rates of English learners in public schools with 43.8% and 53.6% respectively (California Department of Education, 2019) pointing toward communication obstacles which adversely affect health care quality. Potentially due to these reasons, it has been noted that 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.

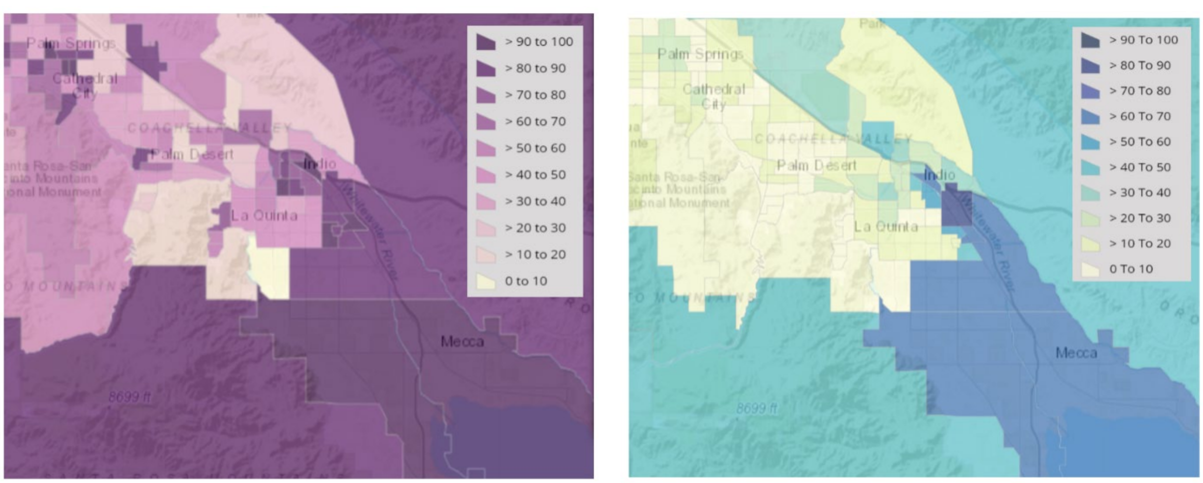

Figure 6.3. Coachella Valley poverty percentiles (left) and pollution burden percentiles (right). Adapted from the CalEnviroScreen 3.0 Overall Results and Individual Indicator Maps provided by the OEHHA (Faust and August, 2017).

The Agricultural Industry and 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 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 (Kambara 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 themselves as part of agricultural activity.

Associated Impacts on Mental Health

There is also the issue of the effects on mental health and the existing difficulties in care. As recently as 2019, 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 (Kambara 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 disparity that may be exaggerated by health effects of the pollution and decreasing property value.

Current Research

There are several ongoing interdisciplinary research projects at the University of California, Riverside involving researchers in the BREATHE Center (https://breathe.ucr.edu/) and the Center for Health Disparities Research in the UCR School of Medicine (https://healthdisparities.ucr.edu/). For example, 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. A second project is studying spatial patterns of aerosol and pollutant transport to determine population exposures. A third project seeks to identify elemental and microbial sources of aerosol particles and their sources in and around the Salton Sea such as topsoil, drying lakebed or marine organisms.

A fourth study utilizes 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. There is less known about the combinatorial effects of pollution, particulates and biological components from the area, so future studies will examine these effects in collaboration microbiologists on the BREATHE team. The overall goal of these studies is to determine the 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 in hopes it will lead to better diagnosis and treatment of pulmonary disease in the region.

The Future: Scenarios and Ongoing Research Needs

This discussion has been largely based 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.**

In the context of the three Scenarios 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, there are many unknowns, as 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, there are several ongoing research needs that are still critically important for understanding the main environmental hazards and their impact on health. **One area where detailed 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, 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, then it could drive a more targeted and appropriate strategy for mitigating the health impacts in this region.

Since 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 hoped that the discussion in this report will begin to provide the necessary focus on the key issues affecting health in the region.

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Igneous features and a geothermal power plant by the southern end of Salton Sea. Photo credit— Mike Mckibben

Geothermal power plant operating in the early morning. Photo credit— Jonathan Nye

CHAPTER SEVEN

Lithium and other geothermal mineral and energy resources beneath the Salton Sea

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Highlight:

- The ability of the region's geothermal industry to develop new non-traditional mineral and energy resources in the Salton Sea geothermal field has great potential for the Salton Sea to become a world-class producer of lithium and other critical metals for the U.S. and the world.

Introduction

The State of 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 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.

Overview of current Salton Sea geothermal 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, 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 414 MW (California Energy Commission, 2019). 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 (Scenario 1), 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 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.

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 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. Earlier in 2020 CalEnergy, the operator of ten of the existing geothermal plants at the SSGF, announced that it will spend up to US$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.

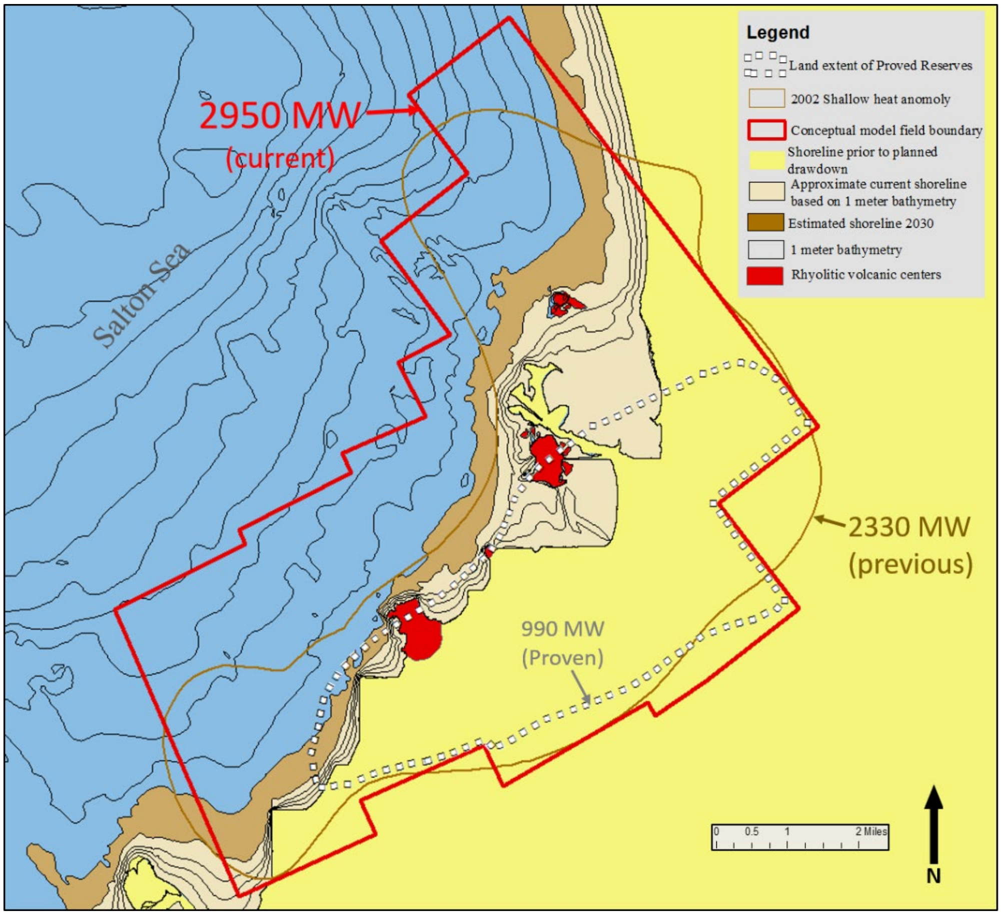

Figure 7.1. Outline of previous Salton Sea geothermal reservoir limit based on the shallow heat anomaly shown in brown, with the new boundary based on the new conceptual model shown in red. Proved reserves are shown by the dotted white outline. Light brown is the area, and reserves, that has been exposed by the receding sea to date, and the darker brown area is the additional area that will be exposed before a project could be completed. Directional drilling could extent the area by ½ mile from pads on the exposed lakebed. Figure 14 from Kaspereit et al. (2016), reproduced with permission.

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 (1) by making hydrogen via electrolysis of clean water, and (2) by pumped storage.

Brine chemistry and strategic metals extraction

Discovered in the early 1960's 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).

Table 7.1. Representative flash-corrected chemical compositions of geothermal reservoir fluids in the Imperial and Mexicali Valleys (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
SiO_2	>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
NH_4	330	NA	NA	NA	6
Cl	157,500	131,000	9,370	11,668	7,758
Br	111	NA	31	NA	NA
CO_2	1,580	30,000	2,400	NA	186
HCO_3	NA	NA	NA	221	NA
H_2S	10	>47	180	NA	1
SO_4	53	NA	4	51	66
TDS	26.5%	25.0%	1.6%	2.2%	1.3%

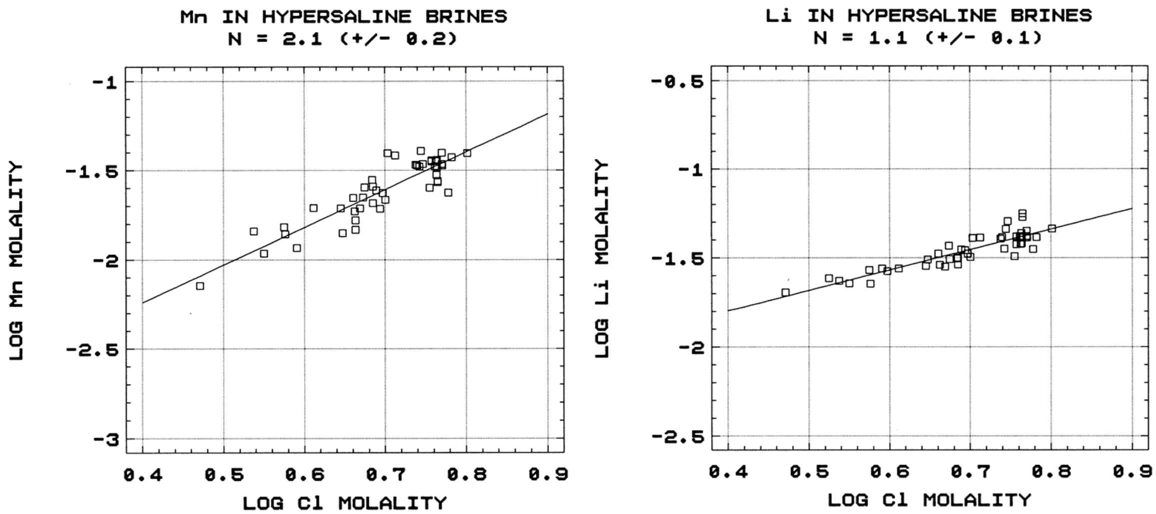

Figure 7.2. Variation of dissolved manganese (Mn) and lithium (Li) metal content (in molality: moles of metal per kilogram of brine) as a function of the brine's chlorinity (dissolved chlorine molality) in the Salton Sea Geothermal Field reservoir brines. Adapted from McKibben and Williams, 1989, including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

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 average Li content in the rocks is 40 ppm compared with >200 ppm in the brines (Table 1), indicating that the bulk of the Li resource in the geothermal field presently resides within the brines rather than the rocks. This is similar to the case for other valuable metals such as Mn, Zn and Cu (McKibben and Hardie, 1997).

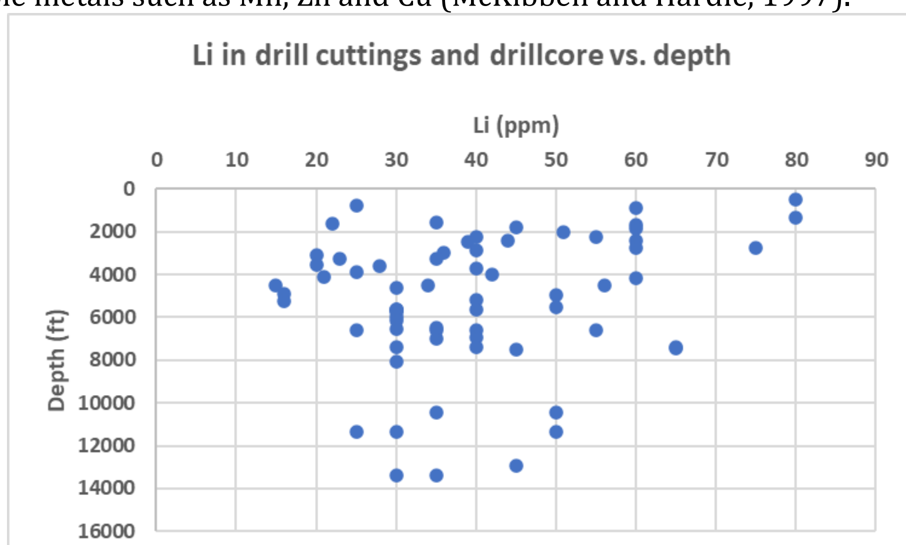

Figure 7.3. Variation of lithium (Li) metal content (in parts per million) versus depth for cuttings and core from several drill holes in the Salton Sea Geothermal Field. Based on

unpublished spectrographic data provided to S. D. McDowell, collected in 1971 by D. E. White, L. J. P. Muffler and H. Bastron, USGS.

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 SSGF contains a conservatively estimated 10^{13} kg of hypersaline brine. With a density of 1.0 at 300^{o}C, this corresponds to a total of 11 km^3 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 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 in Table 7.2.

Table 7.2. Total brine metal reserves in the Salton Sea Geothermal Field (SSGF) relative to global production (in metric kilotons), U.S. import reliance and U.S. production (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

It is clear that any significant production of Mn, Zn and Li from the SSGF brines could make the US 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. 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 Li 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. Therefore, the additional circuit needed to extract the metals from these brines would have minimal environmental impacts compared to opening a new lithium hard rock mine (using sulfuric acid) or a new salt lake brine lithium operation (with high salar water loss).

The World Bank (2020) estimated 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 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. 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 US, but also would reduce environmental consequences of traditional mining operations in other locations.

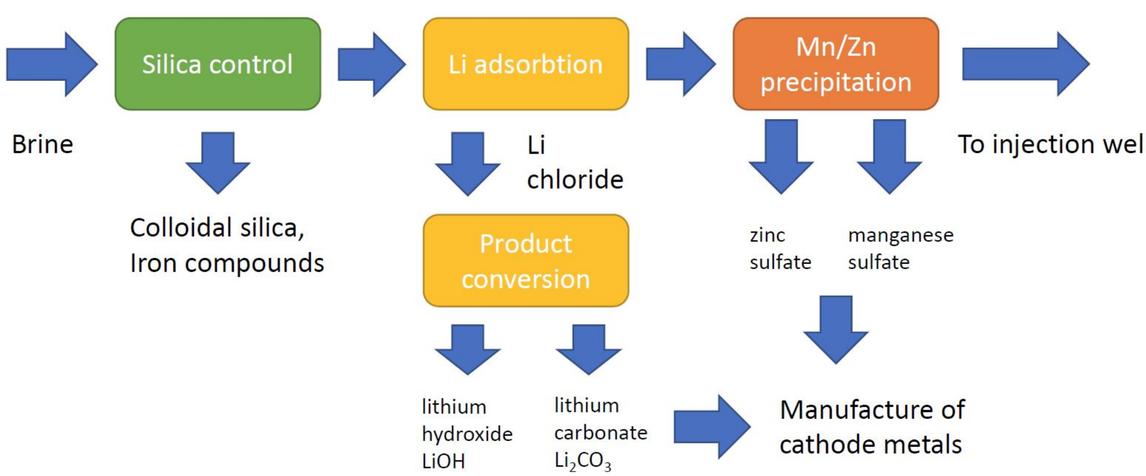

Figure 7.4. Scheme for extracting lithium and other valuable chemicals from Salton Sea geothermal brines. Mn/Zn removal can precede that of Li. Adapted from Harrison (2010a).

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).

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)

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

relative to U.S. annual consumption (USGS Mineral Commodity Summaries, 2020).

It is evident by comparison with Table 2 that lithium production from the SSGF (17 to 40 ktpa) could easily meet the USA's current demand (2 ktpa) and eliminate its import reliance, as well as supply a significant fraction of the current global production (77 ktpa). 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 the World Bank (2020) and 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.

The need for flexibility in electric power production at the SSGF

As mentioned earlier, 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 wells 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. The SSGF has the potential to play an important role in providing this essential service to the local community while developing additional revenue streams. This could be achieved by (1) taking advantage of the terrain surrounding the Salton Sea to build pumped storage facilities, and (2) using the electricity generated for electrolysis to produce hydrogen, as well as osmosis to produce deionized water, and cascading the thermal effluent to produce hot and chilled water for district heating or cooling (Shnell et al., 2018; Elders, et al., 2018).

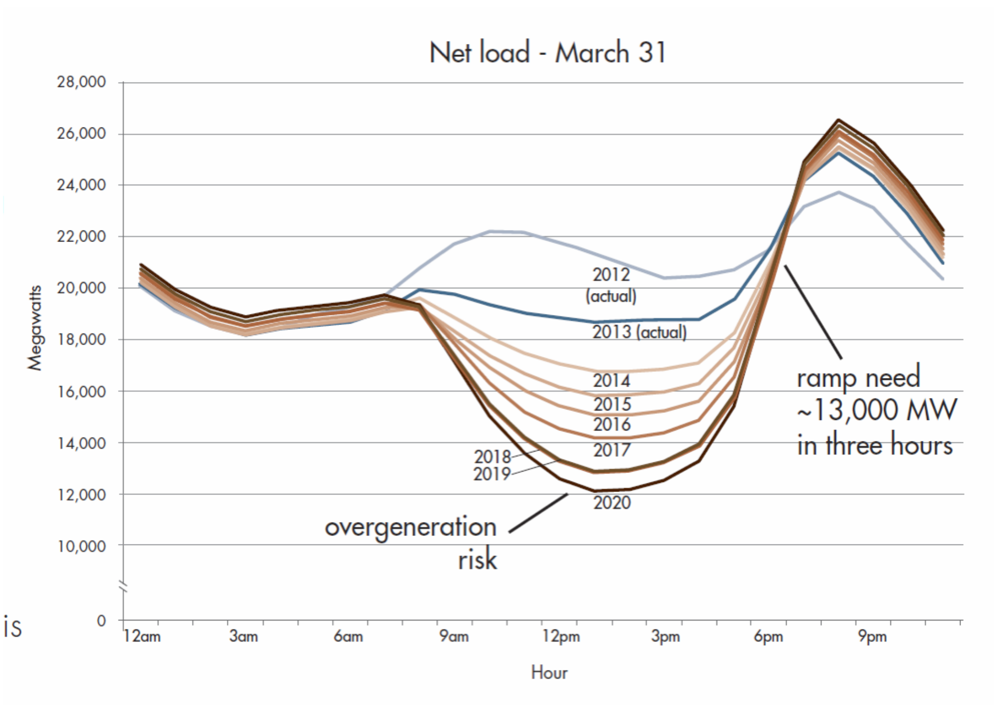

Figure 7.5. Projected daily electricity demand, minus wind and solar generation, on a typical spring day in California. There is a risk of overgeneration in the middle of the day and early afternoon, followed by a steep ramp where an additional 13 GWe is needed (Source: California Energy Commission,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

Pumped Storage at the Salton Sea

We propose therefore an investigation of the feasibility and economics of building large, pumped storage plants that use the waters of the Salton Sea and the electricity 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 times, the geothermal 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 during the ramp in demand.

For example, if the upper reservoir was sited in a basin in the hills west of Desert Shores, 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 integrated 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.

Cascading use of geothermal brines

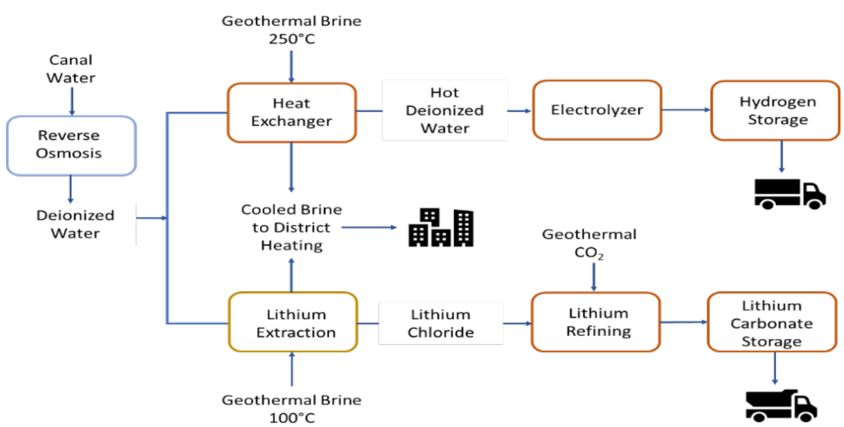

Figure 7.6. Conceptual design of lithium and hydrogen extraction from Salton Sea geothermal brines at temperatures of 250^{o} and 100^{o}C. From Elders et al., 2019. Direct conversion of Li chloride to a Li hydroxide product would be more advantageous for battery manufacture.

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 ~300°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 ~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:

- Utilization of geothermal electricity and heat in alkaline or PEM electrolyzers
- Utilization of geothermal heat in thermochemical processes and hybrid cycles
- Direct hydrogen production through separation of hydrogen molecules from geothermal gas vents

Potential employment and economic impacts

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 made an estimate of employment numbers associated with construction and maintenance of lithium extraction facilities, as well as anticipated revenue and county tax receipts (Table 7.4).

Table 7.4. Anticipated revenue, county tax receipts, and employment figures associated with construction and maintenance of lithium extraction facilities. 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		
Procurement	$918M	**Lease Holder Royalties**	$4.5M per year
Construction Management	$72M		
Construction (Disciplines)	$702M	**Imperial County Taxes**	$20M per year
	$1,800M		
Cost of Production		**Annual Revenue**	
Annual Cost of Capital (20%)	$360M		
Annual Operating Expense ($4000/t)	$360M	vs	(90,000t x $10,000/t)
	$720M		$900M

GHG emission reduction compared to conventional metal extraction, pumped storage and hydrogen production.

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 CO_2 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 in the context of three Salton Sea preservation/reclamation Scenarios

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 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.

Future Opportunities

In order 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 at the SSGF to construct lithium batteries 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 US 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.

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Desiccated fish carcass on the shore of the Salton Sea. Photo Credit –Dana Swarth

Exposed shoreline of the Salton Sea. Photo Credit –Dana Swarth

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