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MAY 2006

ISBN No. 1-893790-12-6

ISBN-13: 978-1-893790-12-4

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The Future of the Salton Sea With No Restoration Project

Michael J. Cohen and Karen H. Hyun

A report of the

PACIFIC INSTITUTE

May 2006

Prepared with the support of
The Salton Sea Coalition & Imperial Visions
The U.S. Geological Survey Salton Sea Science Office
and the Compton Foundation

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Acknowledgements

This report could not have been completed without the assistance and support of many people.

The Salton Sea Coalition & Imperial Visions, the U.S. Geological Survey Salton Sea Science Office, and the Compton Foundation generously provided funding for this report.

Valuable comments, recommendations, and suggestions on earlier drafts were provided through reviews by Doug Barnum, Eric Connally, Dale Hoffman-Floerke and DWR staff, Chris Holdren, Kathy Molina, Jennifer Pitt, Theresa Presser, John L. Scott, Jim Setmire, Mike Walker, and Nils Warnock. We gratefully acknowledge their insights and their time. New and remaining errors are solely our own.

Ian Hart carefully edited multiple drafts of this document, demonstrating prodigious patience and attention to detail.

Doug Barnum, Scott Hein, Al Kalin, Mike Morgan, Bob Miller of Southwest Birders, Harry Ohlendorf, and Aharon Oren graciously allowed the use of their photographs. Uncaptioned photographs taken by Michael Cohen.

Brian Cohen patiently created the maps.

We also thank the following people for their advice, information, and suggestions:

Lisa Benvenuti, Summer Bundy, Fred Cagle, Pat Chavez, Dan Cohen, Jack Crayon, Kim Delfino, Ginna Green, Thomas Haltom, Robert Jellison, Armin Munévar, Cheryl Rodriguez, Carla Scheidlinger, Chris Schoneman, Rey Stendell, Tom Turini, Miguel Velasco, Laura Washburn, Paul Weghorst, and Bruce Wilcox.

Cover

Photograph by Al Kalin, taken on a windy February 15, 2006 from next to the New River facing east across its delta. Adjacent is a photograph taken by Al Kalin in the same place on a calm day.

Executive Summary

The Salton Sea lies on the brink of catastrophic change. The amount of water flowing into the Sea in the next twenty years will decrease by more than 40%, causing its surface elevation to drop by more than 20 feet, rapidly shrinking its volume by more than 60%, tripling its salinity, and exposing more than 100 square miles of dusty lakebed to the desert's blowing winds. These changes will cause four major impacts:

1. Human health in the Imperial and Coachella valleys – currently home to more than 400,000 people and growing quickly – will be harmed by the estimated 33% increase in the amount of fine windblown dust in the basin. The Imperial Valley already suffers from the highest childhood asthma hospitalization rate in the state; the growing number of retirees living in both valleys are especially susceptible to poor air quality.
2. Air quality in these two valleys – which already fails to meet state and federal air quality standards – would get much worse, increasing the cost of bringing these areas into compliance.
3. Air quality-related litigation and state liability will increase. California has assumed ultimate responsibility for managing only those lands exposed due to a recent set of water transfers, constituting about half of the estimated 134 square miles exposed in 30 years. Responsibility for managing any dust blowing off the other 60 or so square miles will rest with the individual property owner. However, there is no clear way to determine which lands will be exposed due to the water transfers and which will be exposed due to other actions. Total air quality management costs at Owens Lake have exceeded $400 million. Costs at the Salton Sea could be higher.
4. Many – if not most – of the hundreds of thousands of birds that currently use the Sea will lose their roosting and breeding habitats and their sources of food. The Sea's fish will be almost entirely gone within a dozen years. Those birds that remain will suffer from disease and the reproductive deformities and failures that plagued the Kesterson National Wildlife Refuge twenty years ago. Some of the endangered and threatened species that use the Sea may be able to find other habitats, but others could suffer significant population losses.

Background

The Salton Sea is California's largest lake, a huge, shallow body of water more than 228 feet below sea level, in one of the hottest deserts in the state. As shown in Figure ES-1, the Sea lies in a broad depression between the agricultural fields of the Coachella and Imperial valleys, about 135 miles southeast of Los Angeles and about 90 miles northeast of San Diego.

Figure ES-1. The Salton Sea basin and southern California.[1]

The tremendous scale of the Sea adds to its complexity, and the difficulty of finding a viable solution. The Sea currently runs almost 35 miles long, and 15 miles at its widest point, covering about 365 square miles. It has the largest surface area of any lake in California, yet is barely 50 feet at its deepest point. The Sea is 1/3 saltier than the ocean, and, fed by the fertilizers running off of neighboring fields, sustains incredible levels of biological productivity. Until recently,

1 Image ISS004-E-6119.JPG taken January 10, 2002, courtesy of Earth Sciences and Image Analysis Laboratory, NASA Johnson Space Center, available at http://eol.jsc.nasa.gov.

the amount of water entering the Sea was roughly balanced by the amount of water evaporating from its broad surface. Stabilizing the Sea at its current salinity would require the removal of more than four million tons of salt each year, assuming flows to the Sea do not change.

But they will change. Under a set of agreements signed in 2003, the Imperial Valley has begun to transfer water to San Diego County, ultimately reducing flows to the Salton Sea. Other actions, including actions in Mexico, will also reduce the amount of water flowing to the Sea, by 45% or more in the next 30-40 years. These changes will dramatically decrease the size of the Salton Sea and the quality of its water.

In September, 2003, the California legislature passed a set of laws that implement the 2003 water agreements and provide a 15-year reprieve for the Sea. The legislation offers the prospect of more than $300 million of restoration funds, but it does not guarantee a long-term restoration project for the Salton Sea. California's Resources Agency will submit a Salton Sea Ecosystem Restoration Plan and related documents to the state legislature by December 31, 2006. The cost of any long-term restoration plan will almost certainly exceed a billion dollars. Although various private-public partnerships have been suggested, funding and implementation of any restoration plan is far from certain, especially given the lack of consensus on a preferred alternative.

Objective of Report

The objective of this report is to describe likely future conditions at the Salton Sea if no restoration project is implemented, over a period of 75 years. Because of the uncertainties inherent in any such projection, this study focuses on general trends, rather than specific year-by-year annual projections. The scope of this report is limited to discussion of future trends in hydrology, water quality, biological resources, and air quality, largely within the confines of the current shoreline of the Salton Sea itself.

Under no circumstance should this report be construed as an endorsement by its authors, funders, or any of its reviewers, of a future with no restoration project for the Salton Sea.

Future Conditions

From now through the end of 2017, changes at the Salton Sea will be gradual. Its elevation will drop about five feet in the next 11 years and its salinity will increase by about a third. The combination of poor water quality, infestation by parasites, and slowly rising salinity could eliminate most of the Sea's fish, and many of its larger invertebrates, by 2017. A five-foot drop in elevation translates into the exposure of more than 26 square miles of land that currently is under water. Although dust and salt have been seen blowing off of recently exposed land, the percentage of exposed land that will generate dust during the region's frequent wind storms has not been quantified. If an estimated 40% of these lands generate dust, an average of 17 tons of fine dust could be added each day to the basin's already poor-quality air within 11 years.

Starting in 2018, the rate of change at the Sea will increase dramatically, as shown in Figure ES-2. (The width of the lines in the graph connote the uncertainty and variability in the projections.) These rapid changes, caused by an abrupt decrease in the amount of water flowing into the Sea, will cause the surface of the Sea to drop 20 feet in the 10 to 12 years after 2017, shrinking the Sea's volume by more than 60% and tripling its salinity. The impacts of these rapid changes will be catastrophic for wildlife, including the loss of all fish in the Sea within a couple of years, the loss of breeding and roosting habitat for birds, widespread disease, and possibly the hideous deformities that plagued birds at Kesterson 20 years ago.

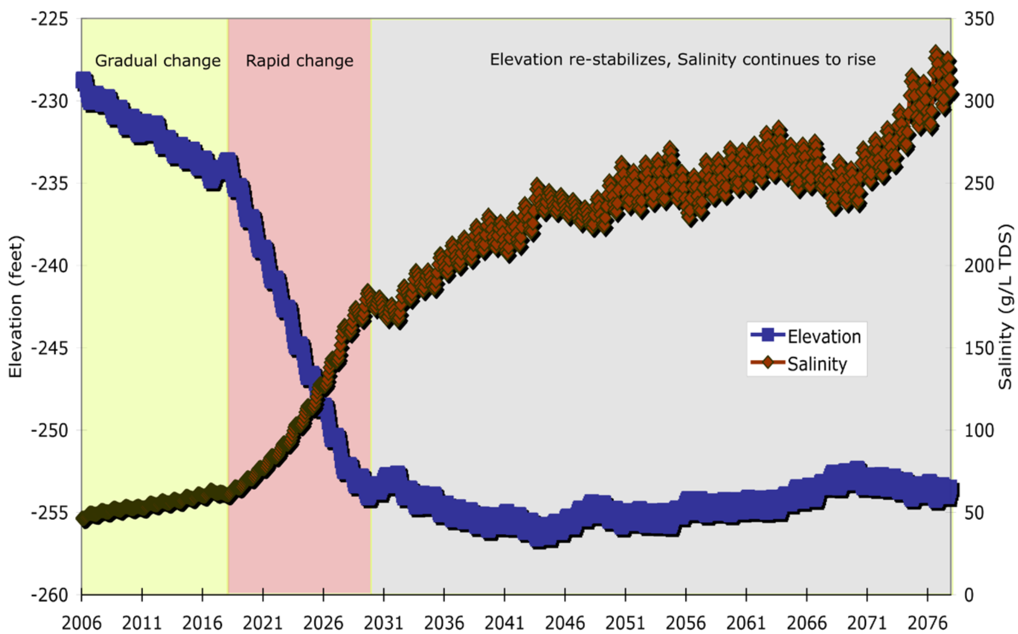

Figure ES-2. Elevation and salinity of the Salton Sea, Jan. 2006 – Dec. 2077.

Ultimately, the Salton Sea's surface will drop to about 255 feet below sea level, about 27 feet below its present elevation. At that elevation, the Sea will be approximately 29 miles long, but its average depth will be only 14 feet. At those proportions, if the Sea were 100 yards long, it would be only 1/3 of an inch deep. The future Sea will continue to be very productive biologically, but aside from brine shrimp and flies, very high salinity (>200 g/L TDS) will cause this productivity to come from algae and bacteria. In about 30 years, the Sea will often be a dense green, orange, or red algal/bacterial soup; far from dead, but a very different lake.

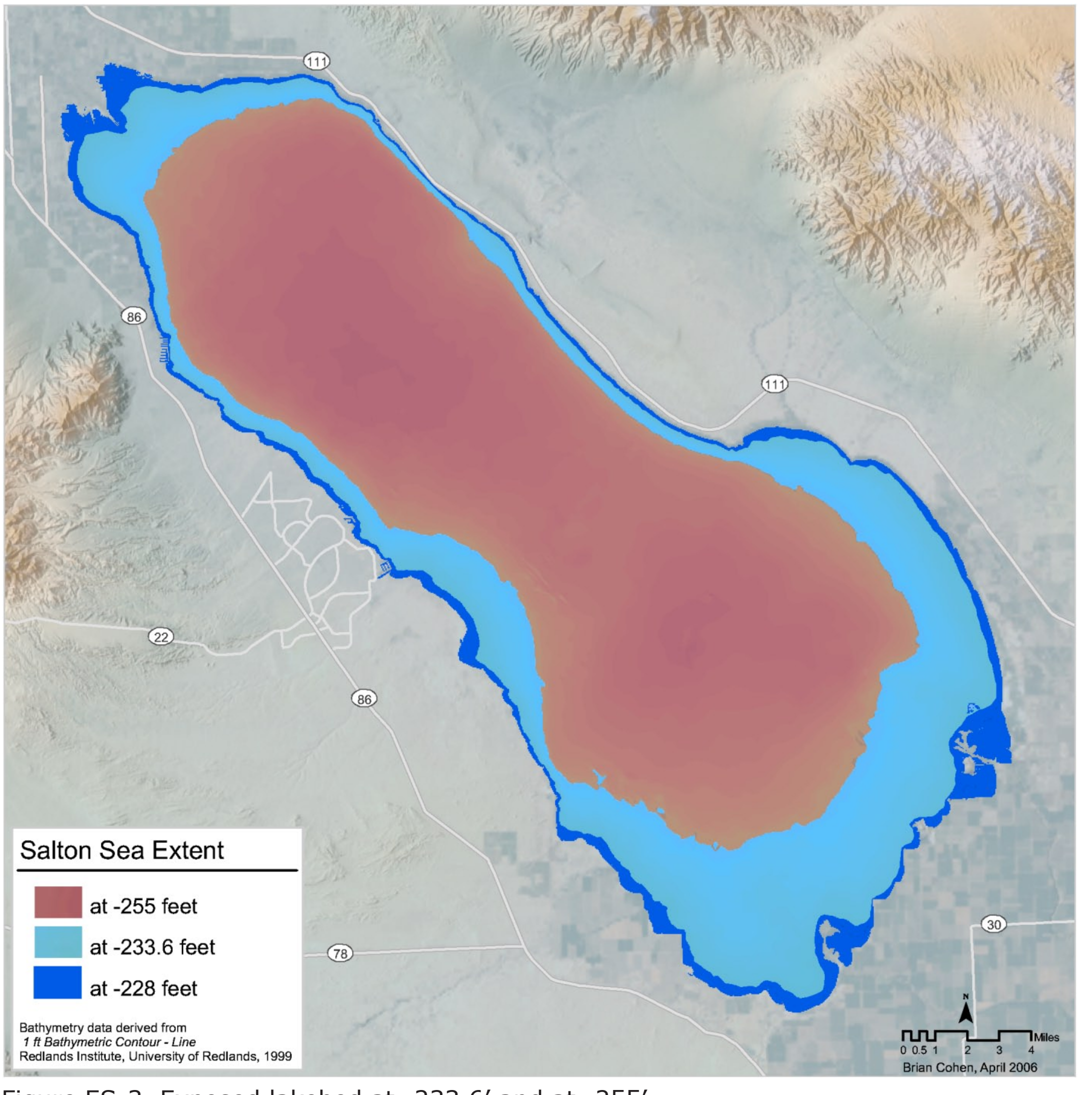

Figure ES-3. Exposed lakebed at -233.6′ and at -255′.

As the Sea's salinity continues to climb, brine shrimp and fly populations will shrink, reducing food resources for the tens to hundreds of thousands of birds that will feed on these organisms. Currently, the Sea's abundant food resources and its variety of roosting and breeding habitats attracts hundreds of species of birds, often numbering in the hundreds of thousands of individuals. The future loss of these food resources and the loss of habitat as the Sea recedes will eliminate the ecological value of the Salton Sea for most of the birds that currently use it. The loss of this critically important breeding habitat and refueling stopover for migrating birds will be felt throughout western North America. Those birds that remain will be decimated by various diseases, and will also suffer from reduced breeding success, due to elevated concentrations of contaminants in their food.

Air Quality and Human Health

As the Salton Sea's elevation drops, it will recede 4-5 miles from its current southern shoreline, exposing more than 134 square miles of lakebed – an area five times the size of Washington, D.C., and nearly three times the size of the City of San Francisco. Winds blow throughout the Salton Sea basin, generating large dust storms that harm human health. Air quality in both the Coachella and Imperial valleys already fails to meet state and federal standards. Childhood asthma hospitalization rates in Imperial County are the highest in California, and three times the state's average. Exposing 134 square miles of salty lakebed could increase the amount of blowing dust in the basin by a third, harming tens of thousands of children, the elderly, and others with breathing problems. The local $1.5 billion agricultural economy will suffer from the blowing dust and sand, as will those seeking to enjoy the extensive recreational opportunities throughout the region.

California has accepted ultimate responsibility for managing the dust blowing off lakebed exposed due to California water transfers, but not from lakebed exposed due to other actions. Determining which actions exposed which lands will probably be very contentious, especially given the expected costs, in both dollars and in water, necessary to manage this land. For purposes of comparison, dust management costs at Owens Lake already exceed $400 million. It is not clear how much land under the Salton Sea will generate dust once it is exposed, nor is it clear how much it will cost to manage dust blowing off of this land.

Conclusion

Without a restoration project, the future Salton Sea will change dramatically. Many of these changes will carry exorbitant costs, in terms of human health, ecological health, and possibly agricultural production. As California and Congress decide whether and how to move forward with restoration of the Salton Sea, the high cost of funding a Salton Sea restoration project must be weighed against the catastrophic long-term costs of doing nothing.

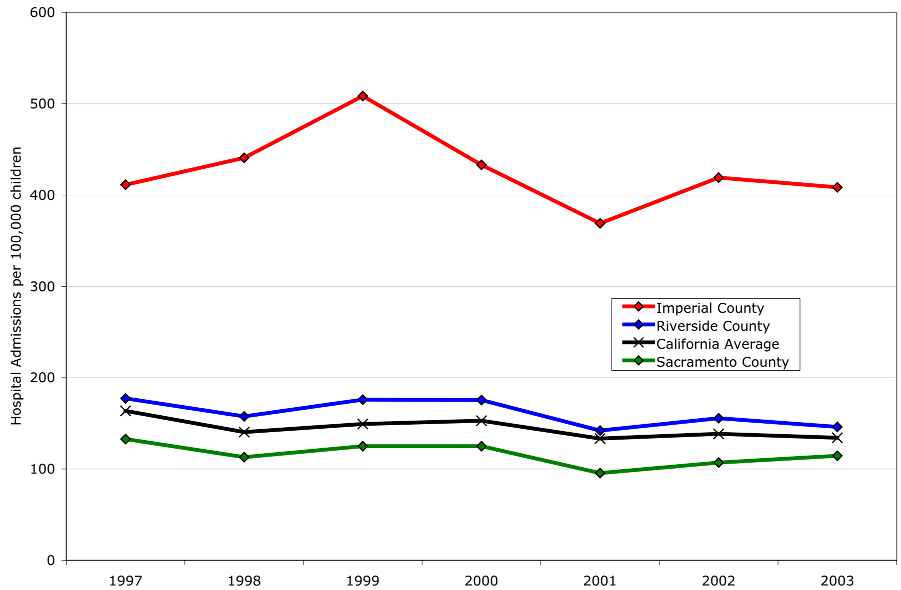

Figure ES-4. Children's hospitalization rates for asthma, by county.

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Introduction

Southeastern California's Salton Sea has been described as "one of the most important bird areas in the Western Hemisphere."[1] The Sea sits at the crossroads of human health, the Pacific Flyway, water politics, recreation, and economic development, raising its present visibility even as its future grows cloudier. In September 2003, protecting the Sea became the linchpin of legislation implementing California's Quantification Settlement Agreement (QSA), which quantifies and reallocates some of California's share of the Colorado River. The legislation provides a 15-year reprieve for the Sea, and the prospect of more than $300 million in transfer-generated restoration funds, but it does not provide a long-term solution.

Several local organizations, most notably the Salton Sea Authority and the Imperial Group,[2] have proposed long-term restoration plans for the Sea. Meanwhile, the State of California's Resources Agency proceeds with its multi-year Salton Sea Ecosystem Restoration Program,[3] which will submit a suite of restoration project alternatives and related documents to the state legislature by December 31, 2006. The cost of any long-term restoration plan will almost certainly exceed a billion dollars. Although various private-public partnerships have been suggested, funding and implementation is far from certain.

The tremendous size of the Salton Sea adds to the difficulty of finding a viable solution. The Sea has the largest surface area of any lake in California, yet its maximum depth is only 50 feet. Some 1.3 million acre-feet of water[4] flow into the Sea each year, roughly balancing the amount that evaporates from its broad surface. Stabilizing the Sea at its current salinity would require removing more than four million tons of salt each year, assuming inflows to the Sea remained constant.

But that is not going to happen. California has begun to transfer water from the Imperial Valley to San Diego County. Since the Sea depends on agricultural drainage from the Imperial Valley, this transfer means that inflows to the Sea have begun to decrease, shrinking the Sea and making it saltier. Shrinking the Sea will ultimately expose tens of thousands of acres of lakebed, potentially leading to dust storms that could rival those at Owens Lake (site of a $400 million dust abatement program). The environmental, human health, and socio-economic impacts of the water transfer will resonate throughout California and the West.

The Salton Sea has been changing ever since it first formed a century ago. The Sea will change more rapidly in coming years, primarily because of a reduction in the amount of water flowing into it. Future conditions at the Sea will be very different from historic and current conditions, whether or not any restoration plan is implemented.

The objective of this report is to describe likely future conditions at the Salton Sea over the 75 year period of the QSA, if no restoration project is implemented. Because of the uncertainties inherent in any seventy-plus year projection, this study focuses on general trends, rather than specific year-by-year annual projections. Sources of uncertainty include: (1) the complexities of the Sea's present physical and chemical processes; (2) the range of possible future actions that could affect the quantity and quality of inflows to the Sea; and (3) the potential impacts of climate change on local and regional run-off, evaporation, and cropping patterns.

This report is not a 'no action alternative' as defined by the National Environmental Policy Act (NEPA) or by the California Environmental Quality Act (CEQA). Such an alternative would include discussion of a much broader range of impacts. Instead, the scope of this report is limited to discussion of future trends in hydrology, water quality, biological resources, and air quality, largely within the confines of the current shoreline of the Salton Sea itself.

Two actions and interventions at the Sea will occur even if no restoration project is implemented: (1) the connection of agricultural drains within the current extent of the Sea, to promote genetic exchange among desert pupfish populations; and (2) monitoring of land exposed as the shoreline of the Sea recedes, to determine the existence and, if necessary, the management of emissive (dust-generating) soils. The specifics of these future actions have yet to be determined, and are included here only in general terms. Nonetheless, they are included in this discussion of the Sea's future, since the State of California has committed itself to undertake these two actions.[5]

Organization of Report

This report describes the future Salton Sea's hydrology, water quality, biota, and the potential environmental and human health impacts of future changes. The next section discusses the methods used to project future trends and conditions at the Salton Sea, followed by a brief description of the Sea's

1 Kimball Garrett, Natural History Museum of L.A. County, quoted in Patten et al. (2003), p. vii.

2 See http://www.saltonsea.ca.gov/ and http://www.imperialgroup.info/saltonsea.php, respectively.

3 See http://www.saltonsea.water.ca.gov/.

4 Enough to support 10 million people, if the quality were better.

5 Quantification Settlement Agreement Joint Powers Authority Funding and Creation Agreement, §9.2. Posted at http://www.crss.water.ca.gov/docs/crqsa/Parts/QSA_ST.pdf

historic conditions and context. The discussion moves on to sections on hydrology and hydrodynamics, water quality, and expected changes in the Sea's biota. The potential for disease and toxicity are then discussed, focusing on impacts to birds. The impact on air quality resulting from the projected exposure of more than 80,000 acres of lakebed is then explored, focusing on impacts to human health. Although this report necessarily focuses on these separate physical and biological factors, they are complex and interdependent and cannot be reduced to simple cases of cause and effect.

The report concludes with general descriptions of possible conditions in 2017, 2047, and 2077 (corresponding to the final year of mitigation flows to the Salton Sea, the final year of the first transfer period, and the final year of the possible transfer extension, respectively) offer a more holistic snapshot than the topic-specific discussions, though the projection of conditions in any specific year is speculative.

Under no circumstance should this report be construed as an endorsement, by its authors, funders, or any of its reviewers, of a future with no restoration project for the Salton Sea.

Methods

This projection of future conditions at the Salton Sea draws from several previous USGS Science Office experts workshops and meetings, most notably a series of meetings in early 1999 that focused specifically on developing a no action alternative, and from a brief synthesis paper by Stephens (1999a) on limnology and fisheries that arose from these meetings. Other sources include:

- Salton Sea-related articles in the peer-reviewed literature, notably *Hydrobiologia* 473 (2002) and *Studies in Avian Biology* 27 (2004);
- general articles in the scientific literature;
- USGS Salton Sea Science Office reconnaissance studies (Shuford et al., 2000; Costa-Pierce and Riedel, 2000);
- Draft reports from the State of California's Salton Sea Ecosystem Restoration Program;
- Presentations at the 2005 Salton Sea Centennial Symposium in San Diego;
- a draft environmental risk assessment of pilot solar evaporation ponds adjacent to the Salton Sea (Tetra Tech, 2004);
- reports on these ponds and on Reclamation's pilot enhanced evaporation system at the Sea (Agrarian, 2003a; Weghorst, 2004); and
- published and posted information on current and historic conditions at Mono Lake, the Great Salt Lake, and other hypersaline lakes.

Please see *References* for the full list of sources consulted in this study. Many of these references are available online.[6]

Water quality and quantity projections are key to estimating future conditions at the Salton Sea. This study used projections from the hydrological model (Munévar, 2006) created for the California Resources Agency's Salton Sea Ecosystem Restoration Program, adjusted to reflect actual January 1, 2006 initial conditions. Other modifications include the assumption that high future salinities (>160 grams per liter (g/L) total dissolved solids (TDS)) will depress evaporation rates from the surface of the Salton Sea by 10%, stepping to 14% when salinity exceeds 200 g/L, based on observations made at the Salton Sea enhanced evaporation ponds (P. Weghorst, pers. comm.). Climate change estimates suggest that future evaporation rates could rise by six percent or more given a 5.4ºF (3ºC) temperature increase (Cavagnaro et al., 2006). However, this potential increase would be overwhelmed by the decrease in evaporation due to rising salinity. Although the future Sea generally will be well-mixed, recent California Irrigation Management Information System (CIMIS) wind-speed data indicate that the early summer months tend to have very low winds. Summer evaporation rates are 3.5 to 4 times higher than those in winter. Assuming that present seasonal wind patterns do not change in the future complicates the estimate that high future salinities will depress future evaporation rates, since relatively calm conditions could permit stratification, especially near the river mouths, with low salinity inflows (with their higher evaporation rates) floating atop the higher density, high salinity Salton Sea water. No hydrodynamic modeling was done to estimate these inputs; the general assumption in this report is that the intermittent existence of such lenses would have limited impact on future evaporation rates.

Depressing future evaporation rates increases the future volume of the Sea, decreasing its salinity. The model's salinity projections were also dampened to reflect the range of loadings of total dissolved solids, from the 3.4 million metric tons calculated by Holdren and Montaño (2002) to the 3.9 million metric tons used in the hydrologic model (Munévar, 2006). Although these modifications do not affect the general salinity trends at the Sea, they do decrease maximum projected salinity under the variability condition by approximately 20% (60 g/L) in the final few years of this study, relative to the original model projections. Dampening the rise in salinity could mean that the estimates of future conditions are too conservative, though the general trends

6 See http://www.saltonsea.water.ca.gov/documents/

should not change.

The water transfer agreement itself is scheduled to expire in 2047, although it includes a provision for a 30-year extension. Like the state's process, this report assumes that the 30 year extension is approved by both parties, although such approval is by no means certain.

Background

Physical Geography

Southeastern California's Salton Sea (33° 15' N, 116° W) lies 35 miles (56 km) north of the U.S.-Mexico border, in one of the most arid regions of North America. The Sea is a terminal lake, with a January 1, 2006 surface elevation of 228.9 feet (69.8 meters) below mean sea level. The Sea is a huge body of water - about 35 miles (56 km) long, 9 to 15 miles (14 to 24 km) wide, with roughly 120 miles (190 km) of shoreline. At its current elevation, the Sea has a maximum depth of about 50 feet (15 meters) and average depth of 30 feet (9 meters), a volume of 7.2 million acre-feet[7] (MAF) (8.9 km^3) of water, and a total surface area of about 370 square miles (957 km^2) – more than five times the size of Washington, D.C., and nearly three times the size of San Francisco.

The Salton Sea lies in the Colorado desert, where maximum temperatures in the basin exceed 100° F (38° C) more than 110 days each year; temperatures drop below freezing only in unusual years. Annual precipitation on the Sea averages less than 3 inches (7.6 cm), while net evaporation rates from the Sea's surface exceed 66 inches (175 cm)/year (Munévar, 2006). The Sea's watershed (see Figure 1) encompasses some 8,360 square miles (21,700 km^2), extending from San Bernardino County south through Riverside and Imperial counties and into the Mexicali Valley, in Baja California, Mexico, but more than 85% of the Sea's inflows come from the drainage from fields irrigated with imported Colorado River water (Cohen et al., 1999). The lowest point of the Sea lies more than 278 feet (84.7 m) below sea level, the second lowest point in the United States. The Salton Sea is a terminal lake - water that flows into the basin has no exit aside from evaporation.

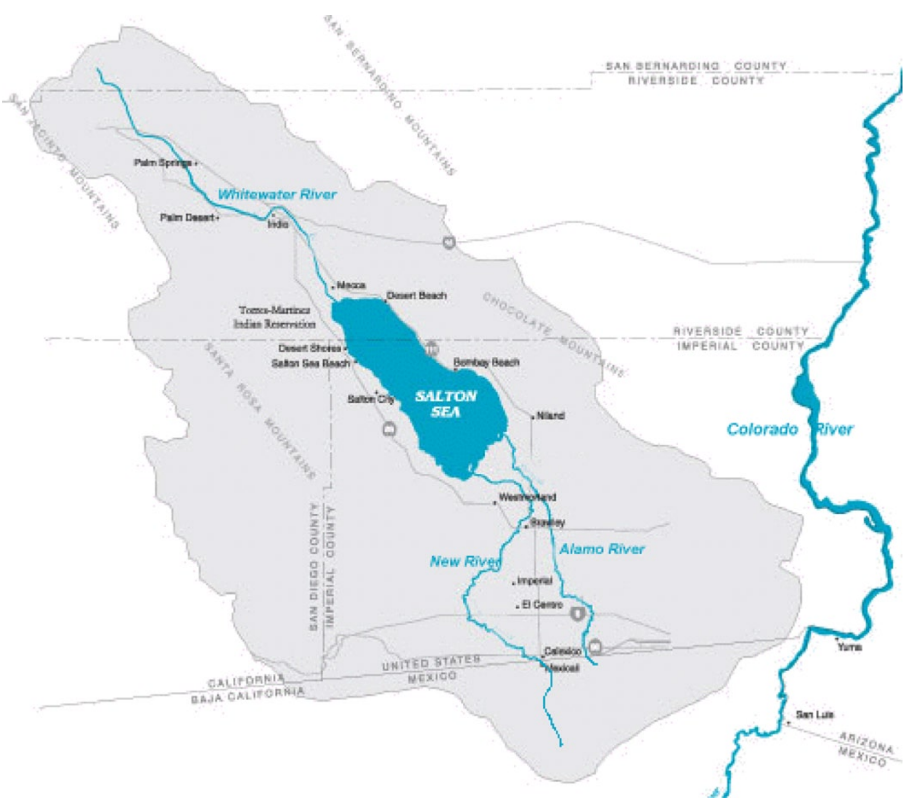

Figure 1. The Salton Sea watershed.[8]

7 By convention, large volumes of water in the western United States are measured and allocated in acre-feet. One acre-foot equals 325,851 gallons or 1,233 cubic meters; one cubic km equals 810,700 acre-feet.

8 Source: Salton Sea Ecosystem Restoration Program. Map posted online at http://www.saltonsea.water.ca.gov/documents/watershed.cfm.

Origins

The Salton Sea lies in the northern arm of the former delta of the Colorado River (Sykes, 1937) in a large, seismically-active rift valley that was once the northernmost extent of the Gulf of California (Redlands, 2002). Before 1900, the river periodically emptied northwest into the Salton Sea basin, forming a water body known as Lake Cahuilla to a size several times that of the current Sea (de Buys, 1999). The Sea itself formed in 1905, a result of unanticipated Colorado River floods eroding an unprotected diversion and following an irrigation canal toward the Imperial Valley. At that time the river was approaching its easternmost meander, and so may well have returned west and north toward the Salton Sea, even without the irrigation diversion (de Buys, 1999). The Salton Sink quickly filled with the river's flows, to a maximum elevation some 30 feet (9 m) higher than its current level, dissolving some of the salts stranded by evaporated former lakes. Even after the river itself was dammed and channelized, its waters continued to flow through the Imperial Valley via canals and fields and drainage ditches, and ultimately into the Sea itself. This drainage has sustained the Sea for a century, as shown in Figure 2. Without it, the Sea would evaporate in about a dozen years.

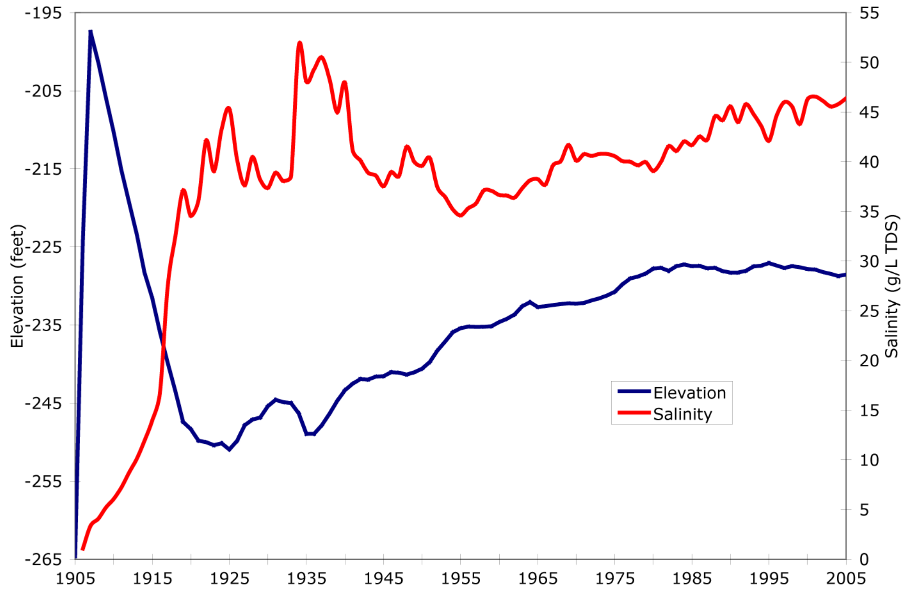

Figure 2. Historic elevation and salinity of the Salton Sea.[9]

Hydrology

Currently, about 1.3 million acre-feet (1.6 km^3) flow into the Salton Sea each year. About 80% of these inflows come from the Imperial Valley, 7.4% from Mexico, 8.6% from the Coachella Valley, and the remainder from direct precipitation and local run-off (Cohen et al., 1999). The Sea reaches its maximum annual elevation from March through June each year, dropping about a foot (0.3 meter) to its minimum elevation in October and November, reflecting irrigation practices in the Imperial Valley (Figure 3).

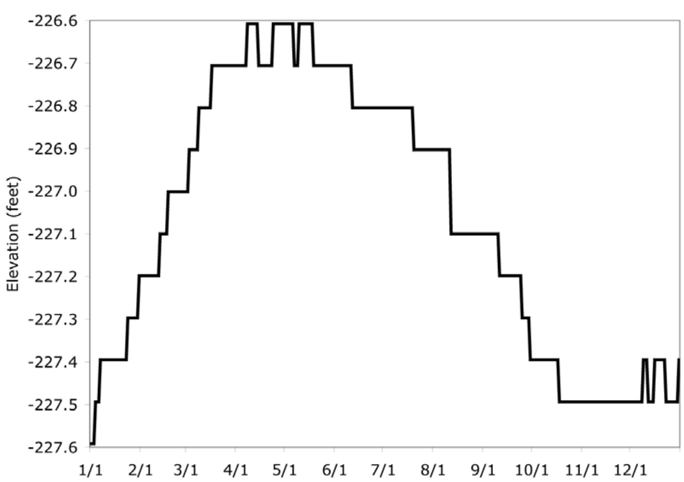

Figure 3. Daily Salton Sea elevation, 1995. Source: USGS

Water flows into the Salton Sea from the Alamo (~46% of total inflows) and New (33%) rivers in the Imperial Valley, from the Whitewater River (5.6%) in the Coachella Valley, from irrigation drains discharging directly to the Sea (10%), and from direct precipitation and ephemeral washes draining the nearby mountains (Cohen et al., 1999). Alamo River water contains a blend of surface and sub-surface agricultural drain water, as well as a small volume of municipal effluent (~11-19 thousand acre-feet per year (KAF/y)). New River water contains a blend of agricultural drainage and municipal effluent from Mexico (~20%), and agricultural drainage and a small volume of municipal effluent (~8 KAF/y) from the Imperial Valley.[10] Surface drain water, also known as tailwater, has higher concentrations of nutrients and pesticides, and lower concentrations of salts and minerals such as selenium, than does sub-surface drain water (also known as tilewater). Small (<15 KAF/y) volumes of groundwater from the alluvium bordering San Felipe Creek and from the Imperial Valley also flow to the Salton Sea, slightly offset by outflows (<1 KAF/y) into the over-drafted Coachella Valley aquifers (Munévar, 2006).

Water Quality

The salinity of the Salton Sea is currently about 46.5 g/L, roughly 33% saltier than ocean water. At this salinity, the Sea contains approximately 450 million metric tons of salts. An estimated 3.4 (Holdren and Montaño, 2002) to 4 (Munévar, 2006) million metric tons of salts enter the Salton Sea each year. Because the Salton Sea lacks an outlet, many of the various contaminants entering the Sea concentrate there. However, as much as a third of the Sea's external salt load precipitates out of solution each year, primarily as calcite and gypsum, reducing the rate at which the Sea's salinity increases (Amrhein et al., 2001).

Although the Sea's rising salinity is often reported as the cause of an impending ecological collapse, salinity is but one of several critical water quality factors affecting life in the Salton Sea. The Sea's inflows also contain elevated levels of nitrogen, phosphorus, and selenium, as well as traces of other contaminants such as pesticide residues (Setmire et al., 1993). The Salton Sea's nutrient-rich inflows have created eutrophic to hyper-eutrophic conditions, with characteristic high biological productivity, low water clarity, and very low concentrations of dissolved oxygen, fostering the production of hydrogen sulfide and ammonia, and causing periodic massive fish kills and noxious odors (Setmire et al., 2000).

9 Sources: Tostrud, 1997; USGS Station 10254005; R.Thiery, CVWD; C. Holdren, Reclamation; J. Crayon, CDFG; IID.

10 California Regional Water Quality Control Board - Colorado River Basin Region staff report, available at http://www.waterboards.ca.gov/coloradoriver/saltonseawatershed.htm

Although the Sea's relatively high salinity may be stressing some of its organisms, other factors – such as the periodic venting of accumulated hydrogen sulfide and ammonia from the bottom – cause many of the large-scale fish kills at the Sea. Disease claims thousands of birds each year, a number that has been increasing each decade since the 1970s (Friend, 2002). These problems are discussed in subsequent sections of this report.

Ecology

The Salton Sea is an unusual, complex system. Its sulfate concentrations, fed primarily by Colorado River water, are several times higher than those in the ocean. Biological and chemical processes currently decrease selenium and phosphorus concentrations well below what would be expected from the volumes entering the Sea each year, while producing large volumes of hydrogen sulfide and ammonia in deeper, anoxic waters. The Sea boasts a diversity of micro-organisms, many of which are new to science, and prodigious levels of primary productivity, at times attracting literally millions of birds. Unlike the many dry lakebeds and salt playas in the interior West intermittently fed by storm run-off and flood flows, the Sea enjoys a perennial water source, in the form of large volumes of agricultural drainage. The high nutrient and contaminant loads carried by this agricultural drainage distinguish the Salton Sea from the Laguna Salada and other ephemeral lakes in the region.

The Salton Sea has an unusual, short food web, where grazing fish generally feed upon worms and other invertebrates consuming detrital organic matter on the lake bottom. These invertebrates, and formerly the fish, provide an abundant food source for a very high abundance and diversity of birds. In 1999, the Sea boasted one of the world's most productive fisheries (Cohn, 2000), though fish populations subsequently plummeted by more than 95%, due in part to the longer and more frequent periods of very low oxygen concentrations found in the Sea, and in part to their high parasite loads. In recent years, declining fish and invertebrate populations have also diminished populations of the birds that feed on these organisms.

More than 50 species of special status birds (threatened, endangered, or species of concern) have been observed at and around the Sea, including the endangered brown pelican, more than 90% of the North American population of eared grebes, 23-30% of the entire North American breeding population of white pelicans, about 40% of the U.S. population of the endangered Yuma Clapper Rail, and up to half of the world's population of mountain plovers (Shuford et al., 2002). The Sea boasts the second-highest diversity of birds in the country, and extraordinary numbers of birds. It hosts the largest known breeding populations of several species, tens of thousands of shorebirds congregate there, and millions of eared grebes have been seen feeding upon its invertebrates (Patten et al., 2003).

Air Quality

Both the Coachella and Imperial valleys suffer from poor air quality, with very high concentrations of small particulate matter. Many practices and actions impair air quality in the basin, including agriculture and the desert surroundings more generally. This poor air quality causes health problems, especially in children. Imperial County's childhood asthma rates, as measured by hospital discharge records, are the highest in California, and roughly three times the state average.[11] Dust storms periodically swirl off of exposed Salton Sea lakebed, adding to the high volumes of dust already in the basin.

Black-necked stilts, gulls, and white pelicans at the Salton Sea. Courtesy of D. Barnum.

11 County data from California Office of Statewide Health Planning and Development, Healthcare Quality & Analysis Division, Healthcare Information Resource Center, available at http://oshpd.ca.gov/HQAD/hirc.htm.

Future Conditions

William DeBuys (1999, p. 223) writes in *Salt Dreams* that "In low places consequences collect." The Salton Sea, whose surface lies more than 228 feet below the level of the ocean, reflects the water uses in the Colorado River basin, capturing the agricultural and municipal residues accumulated by the river along its course. The Sea reflects the conditions not only in its watershed, but in the Colorado River basin more broadly. Those conditions will change in the years ahead, and as they change, so too will the Sea.

The volume of water flowing into the Salton Sea, less the volume of water lost to evaporation, determines the Sea's elevation and extent, while the quality of those inflows influences the Sea's physical and biological chemistry, and the abundance and diversity of the biota that depend upon the Sea. Recent and projected actions will dramatically decrease the volume of water flowing into the Sea in the next several decades – potentially by more than 40%. The quality of that water will also change, with greater concentrations of salts and selenium, but lower concentrations of nitrogen and phosphorus. As the volume of the Sea declines due to decreasing inflows and high evaporation, concentrations of salts and other contaminants will rise dramatically.

Over the long term, climate change could have significant global impacts (IPCC, 2001). Summer temperatures in the Salton Sea basin could rise by 4-11°F (2-6°C) over the course of this century (Hayhoe et al., 2004; Cayan et al., 2006). Precipitation generally decreases in California in these scenarios (Hayhoe et al., 2004), though the spatial resolution of these estimates do not permit an estimate of trends specifically for the Salton Sea basin. Evaporation off the Sea's surface could increase 4.5-6% or more due to rising temperatures (Cavagnaro et al., 2006), directly affecting the size of the Sea itself and indirectly affecting the volume of agricultural drainage flowing into it. Ultimately, however, the magnitude of changes occurring under such future climate scenarios would result in dramatic physical and institutional changes throughout California and the West (and the world), refuting the assumptions of institutional stability inherent in this study.

The single most notable factor decreasing inflows to the Sea is the implementation of California's Quantification Settlement Agreement of 2003, and particularly its water conservation and transfer agreement between the Imperial Irrigation District (IID) and the San Diego County Water Authority (SDCWA).[12] The transfer agreement calls for an annual increase in the volume of water effectively moved from the Imperial Valley to San Diego, from 10 KAF in 2003 to almost 200 KAF in 2020.[13] A related agreement will move water from the Imperial Valley to the Coachella Valley, rising from 4 KAF in 2008 to 103 KAF in 2026. Through the year 2017, the QSA includes the delivery of 'mitigation water' to the Sea, to offset the direct impacts of decreased inflows due to the transfer. The delivery of the mitigation water ceases at the end of 2017. The water transfer agreement itself is scheduled to expire in 2047, although it includes a provision for a 30-year extension. In addition to the clear and quantifiable impacts of the QSA, other planned actions will further decrease inflows below recent historic volumes (see Table 1).

Table 1. Planned Changes Affecting Inflows[14]

Action	*Reductions in Inflow by Year 2026 (af/yr)*	*% of pre-QSA flows*
QSA / IID Transfer	303,000	23.3
Entitlement Enforcement	59,120	4.5
Mexicali Wastewater Treatment Plant Operations	22,500	1.7
Mexicali Power Plant Operations	10,700	0.8
Reduced Colorado River flows to Mexico	10,700	0.8
Total	**-406,000**	31

Some of these changes, especially the quantity of water transferred out of the Imperial Valley, will occur gradually over time; others, such as "Entitlement Enforcement" and "Reduced Colorado River flows to Mexico," are already being realized. Initially, these decreased inflows may be offset by other changes, such as fluctuations in local precipitation events and Colorado River flows. Eventually, though, the impacts will be significant, particularly upon the conclusion of mitigation water deliveries to the Salton Sea at the end of 2017.

12 See http://www.crss.water.ca.gov/crqsa/index.cfm for the text of these agreements.

13 See Appendix B for the QSA delivery schedule.

14 Entitlement Enforcement refers to the QSA-imposed cap on the first three priorities of Colorado River contractors in California, of 3.85 million acre-feet in normal years. Under this cap, IID and CVWD face an annual average reduction (relative to historical use) of 59,120 acre-feet, to ensure that total use of these first three priorities remains at or below 3.85 MAF. Reduced Colorado River flows to Mexico includes reduced availability of surplus Colorado River water and a reduction in the volume of over-deliveries at Morelos Dam, as well as continued deliveries of Colorado River water to Tijuana via the Colorado River Aqueduct (pursuant to Minute 310 of the International Boundary and Water Commission).

In addition to the clear and quantifiable actions listed in Table 1 are other possible actions and changes that are likely to occur by the year 2078.[15] Such changes include the construction of regulatory storage projects along the lower Colorado River that reduce over-deliveries to Mexico, as well as the possibility that shortage conditions may be imposed, reducing deliveries to Mexico below normal treaty obligations.[16] Either of these changes would be likely to reduce the volume of New River water crossing the border and eventually flowing into the Salton Sea. Projecting the frequency, magnitude, and impacts of these and other changes over more than 70 years is highly uncertain. Nonetheless, ignoring these changes would distort projections of the Sea's physical and biological characteristics. The actions and changes potentially affecting inflows in the next 70 years include (but are not limited to):

- Construction of new regulatory storage facilities in the U.S.
- Declaration of shortage under the 1944 Treaty with Mexico
- Population growth and conversion of agricultural land to urban uses in the Coachella, Imperial, and Mexicali valleys
- Climate change impacts on evaporation and evapotranspiration rates
- Climate change impacts on precipitation
- Increased water efficiency in agricultural and municipal uses
- Implementation of Total Maximum Daily Load (TMDL) programs
- Implementation of the Colorado River basin states' 'Intentionally Created Surplus' program for the Colorado River[17]

For the sake of consistency and comparability, this report relies upon the hydrologic variability projections and scenarios developed by the Salton Sea Ecosystem Restoration Project Advisory Committee's Inflows/Modeling working group (Munévar, 2006), modified as described in *Methods*. The working group adopted a model that randomly samples from a broad range of possible future inflows, to reflect the variability and uncertainty of future inflow conditions. The variability model also incorporates direct climate change-driven increases in evaporation from the surface of the Sea. The impacts of climate change on direct precipitation on the Sea are much less certain; in any case, even a doubling of current precipitation would amount to less than seven percent of future evaporation. For the period 2003-2077, the variability model projects mean (of 1000 traces) annual inflows to the Sea to be 795 KAF; for the period 2018-2077, after the delivery of mitigation water ceases and the water transfer has largely ramped up to its maximum volume, mean annual inflows to the Sea decrease to 717 KAF (median: 730 KAF), a reduction of some 45% from current volumes.

Other planned and probable future actions will affect the quality of the water flowing into the Sea. The means by which water to be transferred is conserved in the Imperial Valley will affect water quality, decreasing nutrient loadings while increasing the concentration of salts and selenium. Development and implementation of the Regional Water Quality Control Board's TMDL program for the Salton Sea watershed for various pollutants[18] will generally improve the quality of water flowing into the Salton Sea. However, projected population growth in the Imperial and Mexicali valleys may increase pollutant loadings – especially phosphorus – in the New and Alamo rivers.

Evaporation is the only exit for the waters entering the Salton Sea, leaving behind formerly suspended and dissolved solids. Yet the measured rate of increase of the salinity of the Salton Sea has been much lower than would be expected based solely on the volume of salts that enters the Sea each year. This lower rate of increase is due to the precipitation of salts. In January, 2001, a Salton Sea Science Subcommittee experts workshop (Amrhein et al., 2001) estimated that 0.33 to 1.5 million metric tons of salts precipitate out of the Sea's water column each year, primarily in the form of calcite ($CaCO_3$) and gypsum ($CaSO_4 \cdot 2H_2O$). The upper end of this range suggests that roughly one-third of the salt load entering the Sea each year does not contribute to the Sea's rising salinity. Amrhein et al. (2001) report previous findings that sediment samples had 24% calcite by weight on average, and 6.9% gypsum by dry weight on average, supporting the assumption that these compounds are precipitating. Calcite and gypsum can also be seen on lands formerly covered by the Sea (see cover image). Higher salinities in the future will decrease solubility and increase the rate of salt precipitation,

15 The 75-year project period of the Salton Sea Ecosystem Restoration Program ends in 2077.

16 Article 10 of the 1944 Treaty states, "In the event of extraordinary drought …, the water allotted to Mexico under subparagraph (a) of this Article will be reduced in the same proportion as consumptive uses in the United States are reduced."

17 The Colorado River Basin States proposal to create "System Efficiency, Extraordinary Conservation and Augmentation Projects" is at http://www.usbr.gov/lc/region/g4000/strategies/SevenBasinStatesPreliminaryProposal.pdf Section 4.

18 Listed pollutants include suspended sediments, nutrients, salt, and selenium, among others. See www.swrcb.ca.gov/rwqcb7/tmdl.html and related links.

though the exact nature of these changes has not been determined. Holdren and Montaño (2002) report that the Sea is also currently super-saturated with several silicate and phosphate minerals; the latter may be creating a phosphorus sink in the Sea.

Uncertainties regarding the future interaction of these processes, and their impact on future precipitation rates, challenge efforts to project the increase in the Sea's salinity. The methods chosen by the State of California to satisfy its QSA-related air quality mitigation responsibilities at the shrinking Sea create additional uncertainty. As discussed further in *Air Quality*, various methods have been proposed to address potential air quality impacts. Proposals include applying agricultural drainage water to exposed lakebed (directly or via irrigation of vegetation planted to minimize the emission of dust). This would decrease the volume of water flowing directly into the remnant Sea, shrinking it further.

Hydrology

The Salton Sea will shrink in the future. Its elevation will drop, its surface area and volume will decrease, and its shoreline will contract, exposing tens of thousands of acres of currently submerged lakebed. Through the end of 2017, because of the required delivery of mitigation water, these changes will occur gradually. Starting in 2018, with the cessation of mitigation water deliveries, the rates of these changes will increase markedly (Figure 4). The Sea will react quickly to these declining inflows, rapidly receding from its current shoreline. On January 1, 2003, the Sea's elevation was -228.6'. By January, 2018, its elevation will have fallen five feet. In the following 10 to 12 years, its surface elevation could fall another 18 to 20 feet.

Figure 4 depicts three general trends for the elevation of the Salton Sea. (The width of the projected elevations connotes uncertainties associated with this projection.) In the first, the elevation of the Sea decreases gradually, as the delivery of mitigation water attenuates the impacts of the QSA transfers and other unrelated actions reducing inflows to the Sea. At the tail end of this period, an increase in the volume of mitigation water generates a temporary increase in the Sea's elevation. The termination of mitigation water deliveries at the end of 2017 leads to a rapid decrease in the Sea's elevation, marking the second period. Note that the Sea's surface elevation drops roughly 20 feet (6 m) in the 10 to 12 years after 2017. In the final period, the surface elevation of the Sea gradually achieves a new dynamic equilibrium, balancing inflows against seasonally varying evaporation, within the broader context of a decrease in evaporation due to rising salinity and a rise due to projected climate change. Note that intra-annual changes will continue, in response to inflows and to the difference in evaporation rates between winter and summer, which can vary by a factor of four.

Table 2 lists several key characteristics for the Sea in future years, based on these projections. The variability in the model precludes specific annual projections. Instead, the table lists elevations within the range of possible values for specific years, denoting uncertainty by indicating the approximate year when the elevation and related values will be seen. Conversely, at the end of the study period, the related values are approximate.

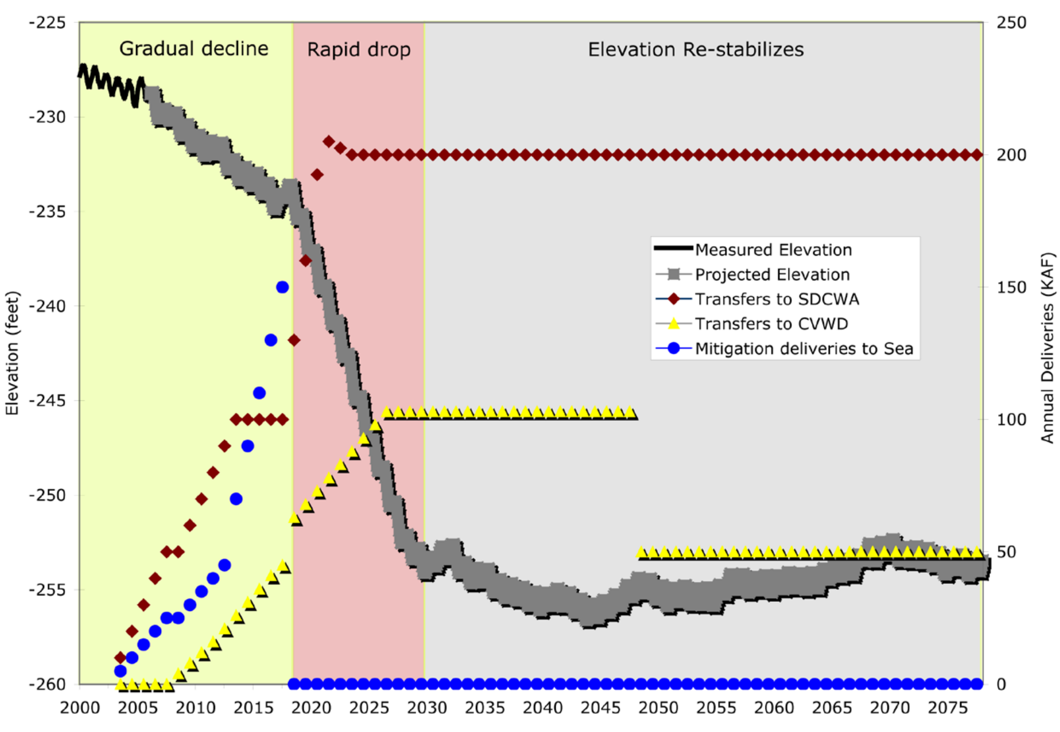

Figure 4. Surface elevation, Jan. 2000 - Dec. 2077.[19]

19 Measured data for Dec. 1999-Sept. 2004 from USGS Station 10254005, Salton Sea nr Westmorland, reported in USGS, annual, *Water Resource Data for California. Part 1. Volume 1. Surface Water Records*. Data for Oct. 2004-Dec. 2005 are provisional, per USGS. Projections for Jan. 2006 onward derived from model projections provided by A. Munévar.

Table 2. The Size of the Salton Sea.[20]

Date	Elevation (feet)	Extent (acres)	vs 2003 extent	Max. depth (feet)	Avg. depth (feet)	Volume (KAF)	vs 2003 volume
Jan.31, 2003	-228.4	237,956	--	49.6	~ 30.6	7,319	--
Jan.31, 2006	-228.8	236,786	99.5%	49.2	~30.4	7,224	98.7%
c. 2018	-233.6	220,963	93%	44	~28	6,124	84%
c. 2029	-254	154,600	65%	24	~14	2,287	31%
c. 2044	-256	148,000	62%	22	~14	1,984	27%
2078	~ -253	~156,000	~66%	~ 25	~ 15	~2,364	~32%

As shown in Table 2, the total volume of the Salton Sea decreases even more rapidly than its elevation. From 2018 to 2030, the volume of the Sea will shrink by more than 60%, even while it continues to receive additional loadings of salts, selenium, nutrients, and other contaminants. Concentrations of these contaminants could roughly triple during this period of transition. Even in 30 years, after the Sea's elevation re-stabilizes based on reduced inflows and prevailing evaporation rates, it will still be California's largest lake, slightly larger in surface area than Lake Tahoe (though with only about 2% of Tahoe's volume). The Sea will still be a massive body of water, though it will be shallow, with dramatically different water quality and biota, as discussed in the following. Figure 5 shows the changing size of the Salton Sea in future years.

Effects of receding shoreline

As the shoreline recedes, tributaries will extend to the Sea. The discharge of some of the smaller drains, however, will likely be insufficient to maintain a perennial connection with the diminished Sea in future years. For example, there are currently ten agricultural drains discharging directly to the Sea west of the New River, with a current combined annual discharge of approximately 15 KAF/y, or roughly 2 cubic feet per second (cfs) (0.057 m³/sec) each on average. Future conservation and efficiency practices will further diminish these flows. The rivers and larger direct drains will continue

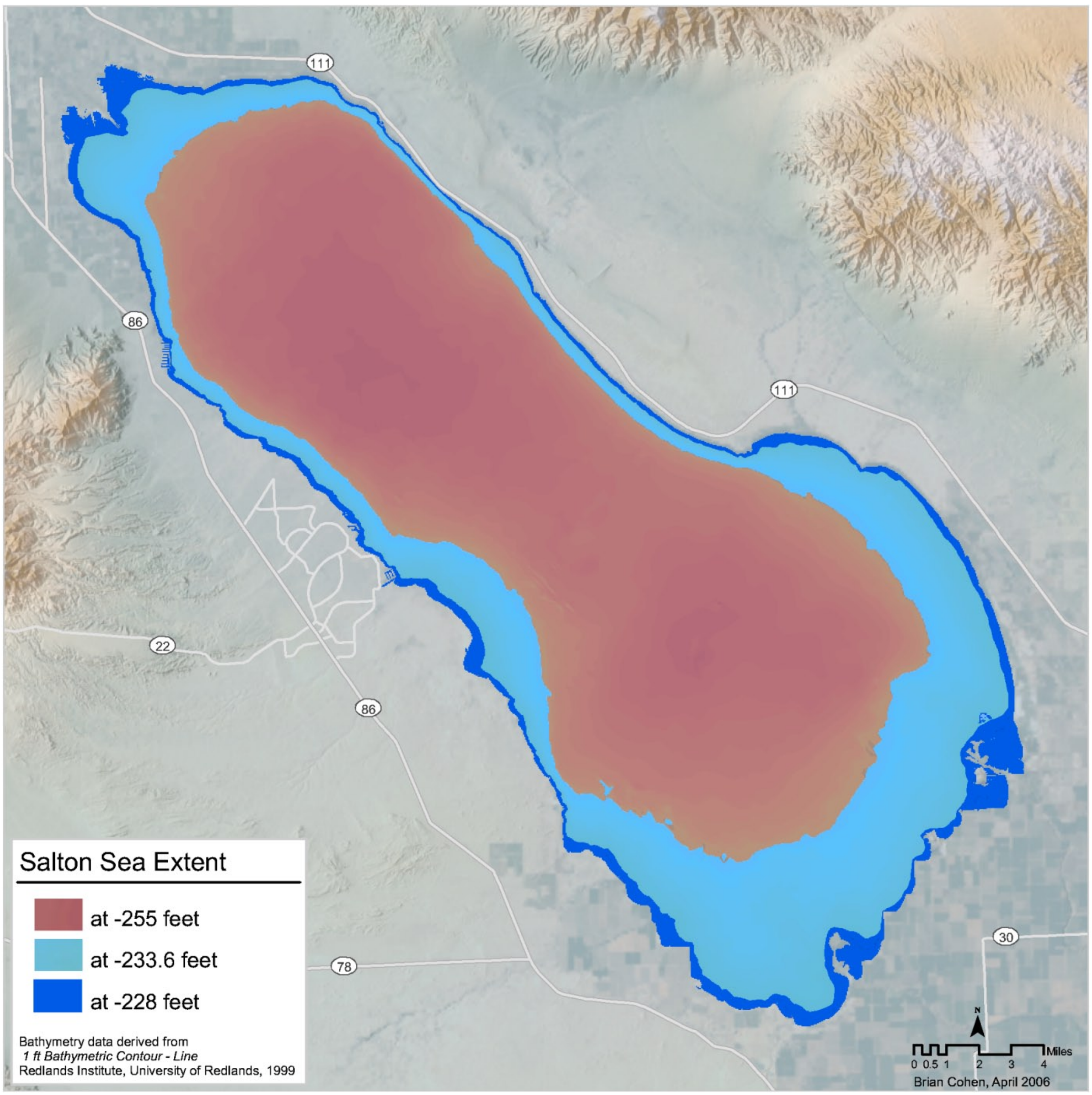

Figure 5. Exposed lakebed at -233.6′ and at -255′.

20 Using Reclamation's Salton Sea Elevation-Area-Capacity table, developed by P. Weghorst.

to support emergent and riparian vegetation (predominantly saltcedar), while the smaller drains that lose connection to the Sea would likely support small, potentially ephemeral, wetlands.[21] The larger drains will form new deltas where they discharge into the receding Sea; the rivers will continue to discharge high loads of sediments, extending their deltas as the Sea recedes.

To facilitate drainage, IID currently dredges and removes vegetation from the New and Alamo river channels and the larger direct drains. At the higher elevations, IID expects that the river channels and some of the drains will always require periodic dredging to remove accumulated silt, regardless of the Sea's elevation (B. Wilcox, pers. comm.). Such activities would continue as the rivers and drains extend, until channel elevation falls below the level necessary to maintain drainage. Below this point, the abundance of saltcedar and emergent vegetation would increase. When the Sea's surface drops to -240' (in roughly 15-16 years), the New and Alamo rivers would run roughly another four miles (6 km), not including expected meanders, if they continue to run along their existing sediment fans. Depending on the extent of dredging and channel management, the gradual slopes and high sediment loads carried by the New and Alamo rivers could create broadly meandering channels.

Discharge from the rivers themselves will continue to be high, especially relative to the volume of the Sea. Mean annual discharge near the mouth of the Alamo River from 1991-2003 ranged from a low of 440 cfs (12.5 m^3/sec) (on the day after Christmas) to a high of 1163 cfs (32.9 m^3/sec) (on April 19). The water transfer will presumably reduce the variability of these flows by reducing the tailwater component, while tilewater flows should remain roughly constant. Even if the future flows of the Alamo River decrease to 336 cfs (9.51 m^3/sec), the minimum value recorded in this 13 year period, the resulting estuarine area in the Sea will be quite large. In 30 years, once the Sea's elevation has stabilized, the projected average inflows of about 720 KAF/year will represent roughly 33% of the Sea's total volume. In comparison, Mono Lake's annual inflows represent less than 10% of its total current volume. As the Sea shrinks, its internal currents and sediment transport will differ markedly from present conditions, as described in *Hydrodynamics* and in *Turbidity*, below.

Hydrodynamics

The Sea is a large, shallow body of water, with currents and mixing driven primarily by wind energy. The Salton Sea's currents, long- and short-period waves, sediment transport dynamics, and mixing regimes drive many of its physical and biological interactions, including dissolved oxygen concentrations, nutrient cycling, sediment deposition, the distribution and abundance of plankton and other biota (Watts et al., 2001). Currents also drive aesthetic considerations, such as the accumulation of fish carcasses after a large-scale die-off. The Sea's currents form a strong counterclockwise gyre in its southern basin; these currents move up to four times as rapidly as those in the northern basin (Cook et al., 2002). Figure 6 clearly shows this southern gyre.

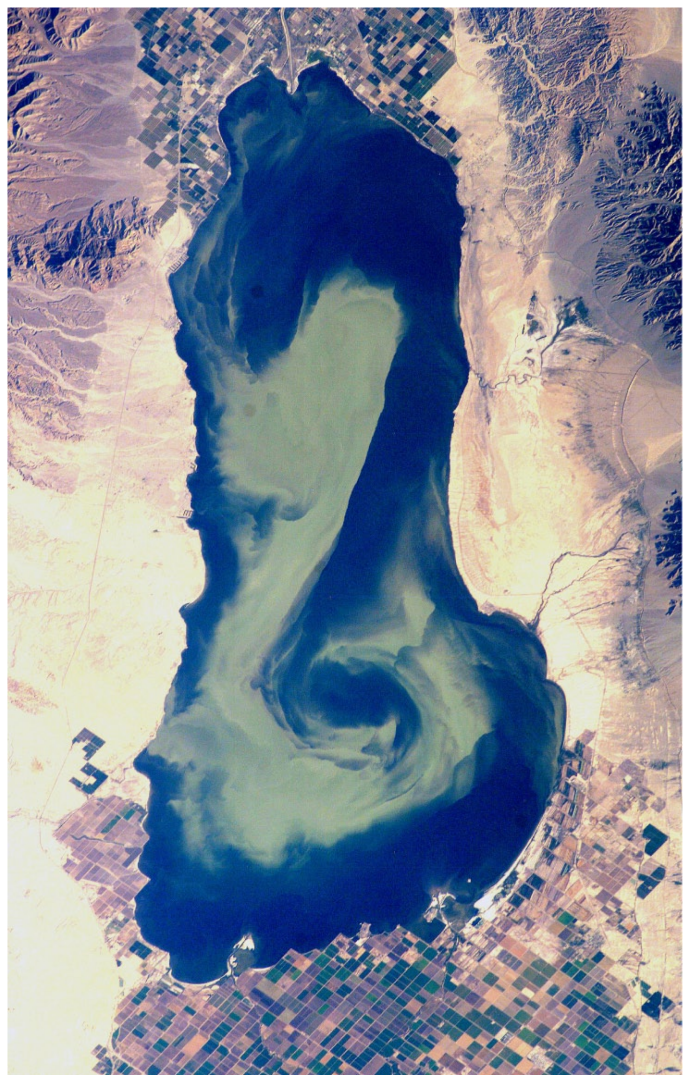

Figure 6. Currents in the Salton Sea, July 4, 2004.[22]

21 When the salinity of the Sea reaches 90 parts per thousand (ppt) (99 g/L) or lower (in 15-17 years), it presumably will prevent endangered desert pupfish from moving between their various drain and creek habitats. To promote the exchange of genetic material between desert pupfish populations, IID will connect individual drains, in consultation with the U.S. Fish & Wildlife Service and the California Department of Fish & Game (IID, 2003). The design of such connections has yet to be determined (C. Roberts, pers. comm.), but would alter drain flow patterns, and could (indirectly) link all of the drains to the Sea.

22 Image ISS009-E-13810.JPG courtesy of Earth Sciences and Image Analysis Laboratory, NASA Johnson Space Center,

Thermal stratification affects many biological, chemical and physical processes in the Sea, such as oxygen concentrations, nutrient cycling, and movement of micro-organisms (Tammert et al., 2005). Currently, the Sea experiences prolonged, persistent periods of thermal stratification, when, instead of being uniform and well-mixed, the temperature of the Sea varies with depth (Watts et al., 2001; Palmarsson and Schladow, 2005). The persistence of this temperature gradient varies with depth and location. Holdren and Montaño (2002) report temperature differences between the top and bottom of the water column of as much as 16°F (9°C) during the summer. During periods of stratification, dissolved oxygen may be prevented from mixing into lower, cooler, denser portions of the Sea. The byproducts of anaerobic respiration (notably hydrogen sulfide and ammonia) may be confined to these lowest depths, until a wind event of sufficient energy mixes the entire water column, releasing the accumulated hydrogen sulfide and ammonia that have been trapped at the bottom of the Sea (Tiffany et al., 2005b).

The depth of mixing is largely a function of wind speed and the distance over which the wind blows across the surface of the Sea (the wind fetch); as the Sea shrinks, the fetch will decrease, diminishing the amount of wind energy transferred to the Sea. The Sea's long NW-SE axis currently extends about 35 miles (56 km), paralleling the path of the basin's strongest winds (Watts et al., 2001). This distance will diminish to about 29 miles (47 km) as the Sea's elevation falls to about -255'. However, the Sea's average depth and total volume will decrease much more rapidly in future years than will its maximum length. As the fetch to volume ratio increases in future years, the Sea will be mixed more frequently and more uniformly, and for longer periods during the year (Schladow, 2005). When the Sea's elevation re-stabilizes in about 35 years at an elevation of about -255', its maximum length relative to 2003 will have decreased by about 20%, its volume will have decreased by 70%, and its maximum depth will have decreased by more than 50%.

By 2021, as the Sea's depth decreases to less than 40 feet (12 m), stratified conditions will likely be weak and infrequent (Schladow, 2005). As the Sea's depth and volume rapidly decrease after 2021, the Sea will likely be well-mixed throughout most of the year, suggesting that the lakebed will be exposed to higher concentrations of dissolved oxygen, reducing production of hydrogen sulfide and ammonia (Schladow, 2005). Even as the Sea's salinity increases beyond 300 g/L in about 60 years, despite the increased density of this hypersaline water it is likely that the Sea's long fetch will transfer sufficient wind energy to mix the Sea fully and frequently, given its limited depth (<18'). However, modeling of these future conditions was not performed as part of this study, so these estimates of future mixing have not been quantified.

At present, waves and currents transport fine sediments, associated organic matter, and selenium to the deepest parts of the Sea, where these materials accumulate, effectively removing them from the water column and the food web (Schroeder et al., 2002; M. Anderson, 2005). In the future, the decreasing depth of the Sea and its more frequent mixing suggest that sediment resuspension and transportation will occur, at least occasionally, throughout the Sea (M. Anderson, 2005). Greater mixing of the sediments, and higher concentrations of dissolved oxygen along the lakebed, will tend to remobilize the organic material sequestered there (Schroeder et al., 2002). These conditions would also tend to remobilize the selenium that has accumulated in the top foot (30 cm) of the Sea's sediments (Vogl and Henry, 2002; M. Anderson, 2005).

These expected changes will dramatically alter future nutrient and selenium cycling. Much of the organic material and selenium now sequestered in the Sea's sediments, as well as some of the other trace materials found there, could be re-introduced into the Sea's water column and food web pathways. After more than 50 years of effectively sequestering these materials in its depths, the massive internal nutrient and selenium loadings driven by the Sea's new hydrodynamic regime would likely offset any reductions in external loadings, greatly increasing concentrations of these materials in the water column.

Water Quality

As part of the Salton Sea Science Subcommittee's discussions regarding a no action alternative, Stephens (1999a) compiled a table projecting the impacts of increasing salinity and decreasing depth on salient water quality characteristics of the Salton Sea, and their subsequent biological effects and impacts.

available at http://eol.jsc.nasa.gov. CIMIS hourly wind speed records for stations near the Salton Sea in the week prior to this date show a maximum wind speed of 16 mph, for one hour only, insufficient to mix the Sea to the bottom. As discussed below in *Hydrogen Sulfide*, this suggests that the conditions in the photograph may be an algal bloom, rather than the 'green tide' that follows irruptions of hydrogen sulfide.

Table 3. Water Quality Changes at the Salton Sea

Water constituent or characteristic	Drivers		Effects & Uses	
	Increased salinity	Decreased depth	Biological effect	Use of Salton Sea
Temperature	Increased thermal capacity; water slower to warm in summer and slower to cool in winter	Potential increases in summertime temperatures; decrease in winter minimum temps.	Wide temperature fluctuation may be restrictive to some species	May restrict sport fishery. Effects on avian resources not known
Dissolved oxygen	Decreased solubility	Increased mixing of atmospheric oxygen in near-surface water and suspension of oxygen-demanding materials from bottom	Reduces number of oxygen-breathing organisms. May increase number of sulfate-reducing bacteria and organisms that can utilize atmospheric oxygen	Restrict fishery, possible increase in odor due to sulfides, would decrease fish abundance for birds
pH	Decreased buffer ability as calcium carbonate solubility is reduced, causing pH to rise	Not known	Wide pH fluctuation may be restrictive to some species. Photosynthesis may cause wide variation in diel pH due to lack of buffering	
Turbidity	May decrease solubility of some organic substances, increasing the turbidity	Increased turbidity due to suspension of bottom materials	Reduced light penetration for photosynthesis, particularly for benthic algae	Adverse effect to aesthetics, restrict sport fishery, could cause surface algal scum as algal blooms more surface dominated
Nutrients (nitrogen, phosphorus)	Causes changes in biological community and may greatly change the interaction of nutrients in algal and animal groups	Greater rate of mobilization of nutrients released from bottom sediment	Algal blooms increased; greater oxygen demands from decaying algae; greater secondary production by zooplankton	Odor problems; restrict fishery and avian populations at lower salinity but could increase avian use at high salinity of zooplankton dominated by brine flies & shrimp
Trace elements	Generally reduces toxicity of some due to common ion interaction	Increased mobilization from sediment to oxidized water column may increase availability, particularly for Se	Effect on biota uncertain. While toxicity may be reduced due to salt effects, oxidation may make some elements more available	At lower salinities, increased trace element availability could decrease abundance of fish and birds

Source: Reproduction of Table 1 in Stephens (1999a).

These and other water quality changes are discussed in detail below.

Salinity

The Sea's salinity will gradually increase to about 60 g/L by about 2018, will spike above 180 g/L by about 2030, and then will gradually rise to more than 300 g/L by the end of the study period.[23] Although projections of future biota often assume that salinity is the major determinant of species diversity, distribution, and abundance, other factors, such as biological, physical, and chemical interactions, may play a more important role (Williams, 1998). Salinity's influence may be indirect, complicating predator-prey interactions and adding stress in environments with poor water quality (Williams, 1998).

The Salton Sea is a terminal lake. The various salts that wash into it tend to concentrate in its waters, though the rise in salinity has been tempered by the precipitation of some of these salts, particularly calcite and gypsum (Amrhein et al., 2001). Holdren and Montaño (2002) calculate historic annual loadings of total dissolved solids to the Sea of 3,434,000 metric tons/year, less than the 3,958,320 metric tons/year projected by the Salton Sea Ecosystem Restoration Project Advisory Committee's Inflows/Modeling working group

23 Model runs that ignore the dampening effects rising salinity has on evaporation rates and that assume the precipitation of salts remains constant as salinity increases project that the salinity of the Sea would exceed 390 g/L in 70 years, well above saturation for NaCl.

(Munévar, 2006). Wardlaw and Valentine (2005) recently estimated internal salt loadings, from brines concentrated in the sediments, to be 1-10% of external loadings. Such loadings are well below the estimated 15-44% precipitation rates of the inflowing dissolved solids (Amrhein et al., 2001). As the Sea's salinity rises, these internal salt loadings will decrease, while precipitation rates will increase.

Measurements of the Sea's salinity have been made regularly, though differences in data exist due to sampling location, season, and analytical precision (Figure 7). As shown in Figure 7, the Sea's salinity generally trends upwards. Maximum annual values are recorded in November, when lake elevation is at its lowest (Watts et al., 2001). Samples taken near inflows, and especially those taken near or between the New and Alamo rivers, tend to be lower than the Sea's actual average salinity (Amrhein et al., 2001).

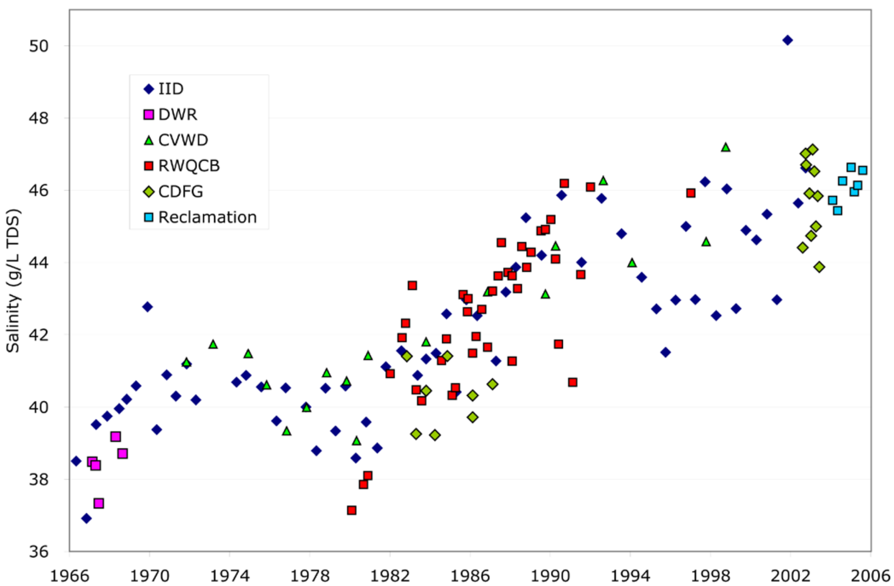

Figure 7. Reported Salton Sea salinities 1966-2006, by agency.[24]

Current salinity of the Salton Sea is approximately 46.5 g/L, 33% saltier than the ocean. However, the relative concentration of major ions in Salton Sea water differs from that in ocean water, as shown in Table 4. Sulfate concentrations in particular are roughly four times higher in the Salton Sea than in ocean water, affecting future salt composition, as well as productivity of sulfate-reducing bacteria. High sulfate concentrations in the Sea, as well as in the pilot evaporation ponds adjacent to the Sea (Agrarian, 2003a), suggest that the future Sea will also be sulfate-dominated, rather than an alkaline, carbonate system such as Mono Lake. This will affect the abundance and distribution of the Sea's future flora and fauna (Herbst, 2001), as described below.

24 Data through 1998 compiled by R. Thiery, CVWD; subsequent years from reporting agency.

Table 4. Major ion concentrations, Salton Sea vs. ocean water.[25]

	(percent)						
Location	g/L	Cl	SO_4	Ca	Mg	Na	K
Sea near Test Base	~44	1.78	1.06	0.10	0.15	1.36	0.02
Sea near Niland	~44	1.79	1.03	0.09	0.14	1.24	0.06
Ocean water	~35	1.9	0.27	0.04	0.14	1.05	0.04

Through the end of 2017, because of the delivery of mitigation water, the increase in the Sea's salinity will occur relatively gradually. This mitigation water is raw Colorado River water, with much lower salinity (currently about 0.73 g/L) than the agricultural drainage it replaces (about 2.5 g/L). Starting in 2018, with the cessation of mitigation water deliveries, salinity's rate of change will increase markedly (Figure 8). The rapid decrease in the Sea's volume and the continued high salt loadings explain the Sea's very swift rise in salinity after 2017.

As shown in Figure 8, salinity will roughly triple in the 10 to 12 years after 2017, dramatically changing the Sea's physical processes and its biota, and possibly its hydrodynamics. These dramatically higher concentrations will rapidly precipitate calcite and gypsum out of solution near the inflows of the rivers and drains, causing these salts to accumulate on the lakebed in or near what will be some of the Sea's most productive areas. Although bacteria will likely colonize these salts (see *Micro-organisms* and Figure 23), the salts will discourage other organisms. Falling elevations will initially decrease the depth to these precipitated salts within the otherwise productive benthos of estuarine areas, and ultimately will expose them entirely, potentially exposing dust-generating surfaces (see Figure 20).

Surface lenses

Watts et al. (2001) report stratified conditions at the Sea after a 10-day windless period, in which lower salinity (17 g/L) water floated atop the higher salinity (41 g/L) water of the Sea itself, 10 km NNW of the mouth of the Alamo River. As the Sea grows increasingly saline in the future, the relatively fresh (2.5 - 4 g/L), less dense agricultural drainage flowing into the Sea could float atop the significantly denser water of the Sea, creating a less saline lens. The formation and persistence of this lens requires calm or very light wind

25 Source: Agrarian (2003a).

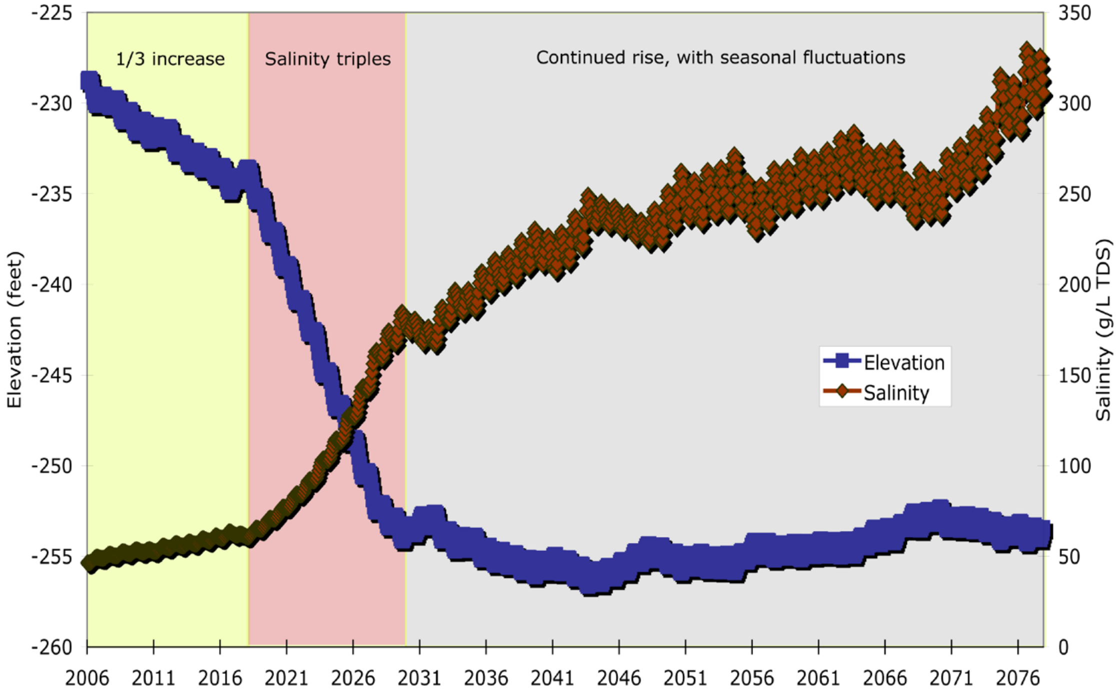

Figure 8. Future salinity trends at the Salton Sea.

conditions: wind-driven waves and currents will mix the inflows into the main body of the Sea. As shown in Table 5, average daily wind speed adjacent to the Sea occasionally measured less than 5 mph[26] for extended periods. Assuming that current wind patterns continue, for a period of days and perhaps weeks, the size of this lens could expand to cover a significant portion of the Sea's surface, especially in the south basin where most of the inflows occur. These lenses would likely have a salinity gradient, rising from the mouths of the rivers to the edge of the lens. Such conditions occur to a limited extent at Mono Lake, where creek inflows (with peak snowmelt discharge generally less than 400 cfs) occasionally create stratified layers with typical salinity of 65-70 g/L extending several kilometers over the lake, the remainder of which has a salinity of 85-95 g/L (R. Jellison, pers. comm.).

Table 5. Frequency of Calm and Light Air Days at the Salton Sea.[27]

	Salton Sea West - CIMIS #127			Salton Sea East - CIMIS #128		
Year	Total Number of Days with Avg. Daily Wind speed <5 mph	Maximum Number of Consecutive Days with Avg. Daily Wind speed <5 mph	Number of 10+ Consecutive Day Periods with <5 mph winds	Total Number of Days with Avg. Daily Wind speed <5 mph	Maximum Number of Consecutive Days with Avg. Daily Wind speed <5 mph	Number of 10+ Consecutive Day Periods with <5 mph winds
2000	129	24	2	155	19	3
2001	120	10	1	199	31	5
2002	144	16	2	188	16	6
2003	148	13	5	190	25	5
2004	128	10	1	204	17	3
2005	139	21	3	173	26	3

In less than 23 years, the Sea's volume could decrease by 70% (see Table 2). Given the large volume of annual inflows relative to the Sea's total volume, this large, less saline lens atop the Sea's dense saline waters could dramatically impact the Sea's hydrodynamics, aquatic organisms, and the birds foraging at the Sea. This lens will disappear as the Sea mixes, eliminating the plankton and invertebrate (and possibly fish) populations that colonize this ephemeral, brackish habitat from the rivers and drains.

Inflow projections suggest that about 30 years from now, the elevation of the Sea will stabilize at -255', with a volume of about 2,130 KAF.[28] If the Sea did not mix for a month, projected inflows from sources in the southern part of the lake would represent about 8% of the volume of the Sea's south basin, sufficient to create a lens covering the entire south basin to a depth greater than a foot. This lens would be similar to the drainage water that feeds it, including the water's high selenium concentrations.

If wind conditions permit large low-salinity lenses to form intermittently atop the Sea, intra-annual fluctuations in salinity will be rapid and dramatic as these lenses mix with the underlying Sea water. The degree of isolation between the north and south basins will also determine the existence and strength of any salinity gradient between the two areas. If the much higher inflows in the south end

26 "Calm" and "light air" conditions on the Beaufort scale, presumably insufficient to mix the Sea's surface.

27 Source: Average daily CIMIS data for stations 127 and 128, available at http://www.cimis.water.ca.gov/cimis/welcome.jsp

28 Projections ignoring all potential variability impacts, as well as climate change impacts on direct evaporation rates, indicate that the Sea would stabilize at about -250', with a volume of about 2,930 KAF.

tend to circulate there, rather than mixing uniformly to the north, the north basin could become more saline than the south.

Salt Formation

Both calcite ($CaCO_3$) and gypsum ($CaSO_4 \cdot 2H_2O$) currently precipitate out of solution at the Salton Sea (Amrhein et al., 2001). For instance, frequent maintenance at the enhanced evaporation test site was required because of the gypsum that precipitated in the intake lines and especially within the evaporation fans (Weghorst, 2004). At the pilot solar evaporation ponds, gypsum formed more than 72% (by weight) of the precipitated salts at salinities below roughly 300 g/L (Agrarian, 2001), suggesting that it will be the prevalent salt formed by the Sea for the next 60-70 years. As salinity exceeds about 70 g/L in the future and gypsum precipitation rates increase, calcium will be depleted from the water column by these salts (Oren, 2000). At the pilot solar ponds, concentrations of dissolved calcium decreased by more than 75% as salinity increased from about 44 g/L to more than 300 g/L (Agrarian, 2001).

At the pilot solar evaporation ponds (Agrarian, 2003a) and at the pilot enhanced evaporation ponds (Weghorst, 2004), Salton Sea brines precipitated a mixture of halite (simple table salt - NaCl) and bloedite ($Na_2Mg(SO_4)_2 \cdot 2H_20$) at about 300 g/L TDS. The solar evaporation pond with a salinity of ~350 g/L precipitated as much as an inch of salt per month in some months, though precipitation rates were much lower in winter (Agrarian, 2003a). Crusts formed on the surface of pilot ponds when salinity exceeded about 360 g/L (specific gravity of 1.254), dramatically reducing evaporation rates (Agrarian, 2001). Such salinities are not expected at the Salton Sea in the next 75 years, though they could occur in isolated pools and bays.

Temperature

In the future, the temperature of the Salton Sea will vary less than it does now, due to more frequent mixing and the buffering effects of rising salinity. Estuaries, however, could experience greater variability. Water temperature has several important chemical and biological implications. As water temperature rises, the solubility of oxygen decreases, while the rate of oxidation increases, imposing a greater oxygen demand on a reduced supply (Dunne and Leopold, 1978). Hot summer temperatures tend to alter plankton communities, often favoring blue-green algae. On the other hand, cold temperatures can stress tilapia and brine shrimp, leading to mortality in winter months.

Water temperatures in the Salton Sea currently range from 48-100°F (9-37°C) (Brauner and Sardella, 2005). Holdren and Montaño (2002) report that the rivers ran slightly cooler than the Sea itself in 1999, ranging from about 86°F (30.5°C) in late August to a low of 52.5°F (11.4°C) in mid-December; river temperatures will influence estuarine temperatures. In future decades, as the volume of the Sea decreases by 70%, its thermal inertia will decrease, making it more susceptible to daily and seasonal temperature fluctuations (Hurlbert, 2002). This variability will be tempered by the increase in salinity, which increases thermal capacity (Stephens, 1999a). Minimum daily air temperatures in the vicinity of the Sea can hover near freezing in December and January; maximum daily temperatures reported for the Brawley weather station have exceeded 116°F (47°C) in July.

The less saline water lenses expected to form intermittently atop the Sea's surface would be especially susceptible to dramatic temperature changes, given their relatively small volume and low salinity. The water clarity of these lenses would probably be extremely limited (see *Turbidity*, below); however, if for some reason their turbidity is low and light penetration is high, they could facilitate the development of a natural salinity gradient solar lake. Under these unlikely conditions, the dense hypersaline water beneath the lens could become extremely hot.

Nutrients

The fertilizers that run off of agricultural fields, supplemented by the phosphates in municipal effluent, promote high productivity in the Salton Sea. Although agricultural run-off will decrease in the future, greater cycling of the accumulated nutrients now in the sediments will maintain the Sea's eutrophic status well into the future.

Inflows to the Salton Sea historically have contained high concentrations of nitrogen and phosphorus compounds, from agricultural and municipal sources. Cagle (1998) reports annual total nitrogen loadings to the Sea of 13,750 tons, with an additional 1,251 tons of total phosphorus loadings. These high nutrient loads have created eutrophic to hyper-eutrophic conditions (Setmire et al., 2000),[29] with extremely high levels of biological productivity and associated low concentrations of dissolved oxygen (Holdren and Montaño, 2002). Although there were no ongoing, detailed sampling programs for the rivers and the Sea during the past 30 years to provide a continuous record of nutrient loadings to the Sea and concentrations within the Sea, several data points in that period suggest general trends. These include a near doubling of nitrogen concentrations in the Sea in the face of relatively constant external loadings. Despite a reported

29 Setmire et al. (2000) note that the trophic state index of the Salton Sea has been calculated at 60-70, at the threshold of hyper-eutrophic designation. The frequency of algal blooms and fish kills at the Sea underscore the Sea's highly eutrophic to hyper-eutrophic classification.

doubling of external phosphorus loadings in this period, phosphorus concentrations in the Sea actually decreased (Holdren and Montaño, 2002).

Nitrogen Dynamics

Schroeder et al. (2002) note that nitrogen concentrations in the Sea are only about 5% of what would be expected given inferred nitrogen loadings over the past half century; much of this discrepancy can be explained by relatively high nitrogen concentrations in the Sea's sediments. Holdren and Montaño (2002) found that nutrients discharged into the Salton Sea from agricultural runoff (external loadings) were currently greater than diffusion out of bottom sediments (internal loadings) by an order of magnitude. However, as the Sea shrinks and the water column becomes more frequently and uniformly mixed, sediments rich in nitrogen could be re-suspended and exposed to higher concentrations of dissolved oxygen, possibly re-dissolving the nitrogen and increasing its availability in the water column (Schroeder et al., 2002). Additionally, the loss of the Sea's current sediment accumulation zone, due to the Sea's reduced depth and volume, will resuspend the organic materials that have accumulated in the Sea's central portions over the past decades, dramatically increasing internal nutrient loadings (M. Anderson, 2005).

Phosphorus dynamics

Sedimentation, chemical precipitation (Stumm and Morgan, 1981; Holdren and Montaño, 2002), and biological uptake (Riedel et al., 2001) can explain phosphorus sequestration in the Salton Sea. Holdren and Montaño (2002) suggest that the formation of hydroxyapatite and fluorapatite create a phosphorus sink in the Sea; as salinity increases at the Sea, the rate of formation of these phosphorus minerals may increase. Such minerals are highly insoluble, indicating that some proportion of the phosphorus in the sediments is irreversibly sequestered (Schroeder et al., 2002). As salinity increases, biological uptake by and sequestration in fish will largely be eliminated, attenuating the increased rate of chemical sequestration (Schroeder et al. 2002).

In coming years, two factors will decrease nutrient loadings to the Sea from agricultural sources in the Imperial Valley: the implementation of on-farm and system efficiency improvements and the implementation of Best Management Practices (BMPs) to meet the TMDLs for nutrients and for sediments.[30] Amrhein et al. (2005) note that these BMPs could result in a 13-20% reduction in the annual inputs of biologically available phosphorus to the Sea. Additional reductions will be realized by the construction of new wastewater treatment capacity in Mexicali that discharges outside of the New River watershed. Increased phosphorus loadings due to population growth will at least partially offset these reductions. The Southern California Association of Governments projects that the population of Imperial County (predominantly located in the Imperial Valley) will increase from about 165,000 people in 2005 to more than 230,000 in 2020, and to almost 270,000 in 2030.

Reduced phosphorus inputs to the Sea could diminish the Sea's excessive productivity (Amrhein et al., 2005). However, within about 25 years, the total volume of the Sea will have decreased by more than 65%, so that even substantial reductions in phosphorus inputs on a total volume basis will still result in an increase in terms of concentrations in the Sea (Robertson, 2005).

As the Sea shrinks, nutrient-rich sediments will be re-suspended due to wave action along the shoreline, and more generally due to wind energy. It is not clear how phosphorus and nutrient dynamics will change in the future in response to these changes, but it is likely that internal loadings will supplement the proportionally greater external loadings. As greater mixing increases sediment transport and oxygenation of the sediments, internal loadings could increase in future years. Ultimately, the Sea is already eutrophic: future nutrient concentrations will likely be at least as high as they are currently, and will not limit future biological activity at the Sea.

Turbidity

Turbidity will increase as the Sea shrinks. The Sea's excessive biological productivity decreases the clarity of its waters. Currents suspend and transport organic and inorganic matter, contributing to nutrient cycling but occluding its waters (Schroeder, 2004). Visibility in the Sea is quite low, with Secchi depths[31] ranging from 1.3 to 4.6 feet (0.4-1.4 m) (Holdren and Montaño, 2002). This turbidity limits the penetration of light to the bottom of the Sea, reducing photosynthesis. This limited availability of light could be a greater factor than nutrient availability in determining total primary productivity in the Sea (Gonzalez et al., 2005). As noted above, the projected increase in the frequency and depth of mixing will exacerbate these conditions, introducing more organic and inorganic material into the water column (Stephens, 1999a), further reducing light penetration and photosynthetic activity.

30 See http://www.waterboards.ca.gov/coloradoriver/tmdl/TMDL_Status.htm and http://www.ivtmdl.com/bmp.php for more information.

31 Secchi depth is a measurement of water transparency, using an eight inch (20 cm) disk lowered into water until no longer visible.

Dissolved Oxygen

The trend of future dissolved oxygen concentrations in the Sea is uncertain. The amount of oxygen dissolved in water has important biological implications (Stephens, 1999a). Concentrations below 4 mg/L stress most aerobic organisms; concentrations below 2 mg/L generally are lethal for aerobic life (Williams, 1998). Although dissolved oxygen (DO) is often supersaturated at the surface of the Salton Sea due to photosynthesis (Reifel et al., 2001) and mixing with the atmosphere, concentrations deeper in the water column approach zero, especially during periods of stratification (Setmire et al., 2000; Watts et al., 2001). During the summer, more than 60% of the bottom of the Sea frequently is anoxic, killing or displacing benthic organisms such as pileworms and barnacles (Stephens, 1999a; Watts et al., 2001).

The Sea's low DO concentrations are typical of eutrophic lakes, which experience a rise in surface DO during the day due to photosynthesis and a decrease at night as phytoplankton (and other organisms) use oxygen in respiration. The Sea's thermal gradients exacerbate these low concentrations, restricting the mixing of anoxic deeper waters with the higher DO concentration waters near the surface (Watts et al., 2001). Furthermore, the production of hydrogen sulfide under the anoxic conditions in the sediments tends to strip the remaining oxygen from the lower water column during mixing events (Tiffany et al., 2005a).

As salinity increases, the solubility of oxygen decreases, lowering concentrations of DO (Sherwood et al., 1992). At the future Salton Sea, this will be at least partially offset after about 2021 by increased mixing with atmospheric oxygen, as the Sea grows shallower (Stephens, 1999a). Yet this increased mixing energy could also disturb the Sea's anoxic sediments, increasing biological oxygen demand as organic material is suspended in the water column (Stephens, 1999a). The oxygen demand of metals and metalloids in the sediments, such as iron, manganese, and selenium, could also rise with increased mixing of the water column. While increased mixing should limit the formation and persistence of stratified conditions and an anoxic hypolimnion, these competing factors suggest that the trend of future DO concentrations in the Sea is uncertain.

Hydrogen Sulfide

The magnitude of hydrogen sulfide releases will diminish in the future. Hydrogen sulfide, the source of the rotten egg smell occasionally detected at and around the Sea, is a highly toxic gas capable of killing aerobic life both directly, by preventing cellular respiration, and indirectly, by stripping available oxygen from the water column. In the Sea's anaerobic sediments, sulfate-reducing bacteria produce hydrogen sulfide gas as a byproduct of oxidizing the abundant detrital organic matter found there (Amrhein et al., 2001; Watts et al., 2001). Hydrogen sulfide accumulates under stratified conditions, often reaching high concentrations in the anoxic waters in the middle of the Sea (Tiffany et al., 2005a). In late July 1999, sulfide concentrations measured >5 mg/L at depths of 33-46 feet (10-14 m), sufficient to deoxygenate most of the water in the Salton Sea (Watts et al., 2001). Preliminary calculations suggest that sulfate-reducing bacteria may be generating some 78,000 metric tons of hydrogen sulfide annually at the Sea (Amrhein, 2005). When wind events mix this sulfide-rich layer into the rest of the water column, the sulfide strips available oxygen from the water and dissolved oxygen levels plummet, killing fish, invertebrates, and plankton (Watts et al., 2001; Tiffany et al., 2005b).

In the presence of the relatively higher dissolved oxygen levels in the upper water column, sulfide oxidizes into sulfate, precipitating as gypsum crystals that form 'green tides' that can be detected from space (Tiffany et al., 2005b). These green tides at the Salton Sea have been documented in satellite images (Figure 9) at least as early as August, 1965, and appear to be occurring more frequently, starting earlier in the year and lasting longer (Tiffany et al., 2005b). Such tides, occurring predominantly in mid-Sea locations, signal hydrogen sulfide-induced fish kills at the Salton Sea (Tiffany et al. 2005b).

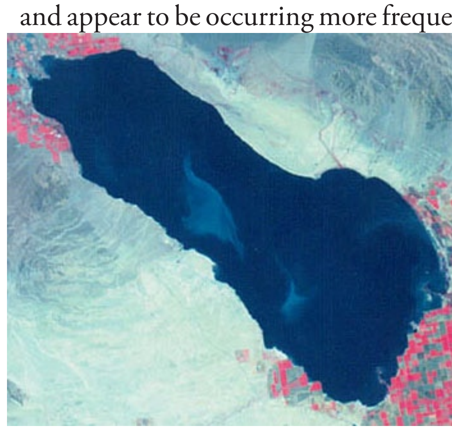

Figure 9. Salton Sea showing 'green tides', June 30, 1992.[32]

Several factors will affect hydrogen sulfide production in the future: dissolved oxygen levels in and above the Sea's sediments; the frequency of mixing of the water column (or, alternatively, the persistence of stratified conditions); availability of detrital organic material; sulfate (SO_4^{2-}) concentrations, and the salinity tolerance and persistence of the sulfate-reducing bacteria. Although primary productivity in the Sea will decrease markedly as salinity rises (see *Micro-organisms*, below), sediments will continue to offer large volumes of accumulated organic material to sulfate-reducing

32 This North American Landscape Characterization image was obtained from the Earth Resources Observation Systems Data Center Distributed Active Archive Center, located in Sioux Falls, South Dakota. This Landsat 4 Multispectral Scanner image was acquired on June 30, 1992 (Path 39 Row 37).

bacteria. Sulfate concentrations are about 10.5 g/L currently, likely at or near saturation with respect to gypsum (Amrhein et al., 2001). They increased by more than a factor of five as salinity approached halite saturation (~300 g/L) in pilot evaporation studies (Agrarian, 2001), indicating that sulfate availability will not limit future sulfide production.

Sulfate-reducing bacteria function well at salinities of 120 g/L (Brandt et al., 2001), and reportedly can tolerate salinities as high as 210 g/L at the Great Salt Lake, though their optimum growth occurred at salinities of 45 g/L and a pH of 6.5-7.3 (Brandt et al., 1999). Brandt et al. (1999) report high densities of such bacteria in the Great Salt Lake, noting that these bacteria's productivity declined linearly from a maximum at about 50 g/L to zero at about 250 g/L. The most salt-tolerant sulfate-reducing bacteria reported in recent years occurred in Africa, growing at NaCl concentrations of about 320 g/L (Oren, 2000), a concentration not likely to be achieved by the Sea for 70 years. Assuming that bacteria with similar salinity tolerances exist in or colonize the Salton Sea suggests that production of hydrogen sulfide will continue at the Salton Sea, declining in a roughly linear fashion, for the next 30 to 40 years. Sulfate reduction will also continue to occur in shallow anoxic sediments in the Sea, though such activity would be much lower than current levels. However, more frequent mixing will limit accumulation of hydrogen sulfide, changing the system to smaller, more regular venting of small volumes of hydrogen sulfide, rather than the current infrequent venting of large volumes.

pH

The Salton Sea is an alkaline lake, with a reported surface pH of 8.2 and a benthic pH of ~7.2 (Holdren and Montaño, 2002). As the Sea's salinity increases, the solubility of calcium carbonate will be reduced, normally causing the pH to rise. However, continued calcium and magnesium loadings in agricultural drainage will maintain future pH in its current range (Schroeder et al., 2002). More generally, extreme fluctuations in marine or salt lake waters are practically unheard of because of the buffering effects of salts (Hurlbert, pers. comm.).

Selenium

Expected changes in hydrodynamics and sediment resuspension suggest that the Sea's current ability to sequester incoming selenium may be lost or dramatically decreased in the future, greatly increasing selenium concentrations in the water column, in aquatic organisms, and in the birds that prey upon them. Coupled with larger volumetric external loadings,[33] selenium will likely pose a considerable risk to birds (Skorupa, 1998).

Selenium, a trace element, occurs in Colorado River water in concentrations of ~2 micrograms per liter (µg/L). Although an essential element at low concentrations, slightly higher concentrations of selenium can be toxic. The threat, best demonstrated at the Kesterson National Wildlife Refuge in California in the early 1980s (cf. Ohlendorf, 1989; Skorupa, 1998), was the accumulation and magnification of selenium concentrations up the foodchain (to 1,000-5,000 times the concentrations in the surrounding water), greatly increasing the incidence of deformed chicks and general nesting failure in birds, as well as the mortality of adult birds (Schuler et al., 1990).

In general, the presence of selenium is a concern because of:

- its ability to bioaccumulate in the food web;
- the narrow range between the concentration that is nutritionally beneficial and that which is toxic;
- its effect on fish and bird reproduction and embryonic development;
- its role in causing immune deficiency; and
- its effect on human health from consumption of contaminated fish and birds. (Fairbrother and Fowles, 1990; Setmire et al., 1993; Cohen, 2005)

The water transfer will lead to an increased proportion of tilewater, with its higher concentration of selenium, flowing into the Sea in future years. The median dissolved selenium concentration of 304 samples of Imperial Valley tilewater taken from August 1994 - January 1995 was 28 µg/L, with a range of 1 - 311 µg/L (Setmire and Schroeder, 1998). The higher end of this range is much more important for assessing potential selenium threats than are the median values. Even a brief spike in selenium concentrations can set foodchain contamination at a higher level than would be expected based solely on the median concentration (Skorupa, pers. comm.[34]).

The Salton Sea's sediments currently act as a selenium sink (Selenium Fact Sheet, undated). The median dissolved concentrations of selenium in Alamo River water was approximately 8 µg/L (Setmire and Schroeder, 1998). Yet selenium concentrations in the water column of the Salton Sea are much lower, ranging from 1.1 - 2.1 µg/L (Holdren

33 Although the total amount of selenium (and other elements) that enters the Sea in future years will decrease, the load relative to the diminished volume of the Sea (e.g., in g/L) will increase.

34 Citing Wilber, 1980. Toxicology of selenium: a review. *Clinical Toxicology*, **17**: 171-230.

and Montaño, 2002). If selenium acted conservatively in the Salton Sea and simply accumulated over time, its concentration would be about 400 µg/L (Schroeder et al., 2002). Anaerobic bacteria may be responsible for removing some of the selenium from the water column, but most is absorbed from the water column by plankton and other organisms and carried to the lakebed when the organism dies (Setmire and Schroeder, 1998). Selenium-rich plankton often float with currents into the slower-moving water in the northern basin, eventually sinking as organic detritus into the sediments there (Schroeder, 2004). Selenium is largely limited to the top foot (30 cm) of the Sea's sediments, where its concentrations range from 0.086 to 8.5 mg/kg; higher concentrations predominantly occur in the northern half of the Sea (Vogl and Henry, 2002).

Selenium concentrations in water flowing in to the Salton Sea already are at levels of concern; future water conservation measures will increase those concentrations. Water conservation measures planned and underway as part of the IID-SDCWA water conservation and transfer project, such as reduction of tailwater drainage and operational losses, could increase selenium concentrations in river inflows by as much as 46% percent in the future (IID, 2002). Selenium chemical load concentrations in the rivers and drains could be greater than 6 µg/L and may exceed 9.25 µg/L (IID, 2002). The federal water quality criterion is currently 5.0 µg/L in freshwater and 71 µg/L in saltwater;[35] a seasonal tissue-based criterion of 5.85 µg/g dry weight is being considered for saltwater fish.[36] Samples of sargo tissue (n=5) taken in the late 1980s had a mean selenium concentration of 12.9 µg/g dry weight (Setmire et al., 1993). More recently, selenium concentrations in tilapia fillet tissue measured 9 µg/g dry weight (Moreau et al., 2006).

Selenium concentrations in some birds and fish are already at levels of concern. Even a minor increase in volumetric loadings could have dramatic impacts (Skorupa, 1998). Increasing concentrations of selenium pose a risk to the biota in the rivers, drains, and fresh- and brackish-water

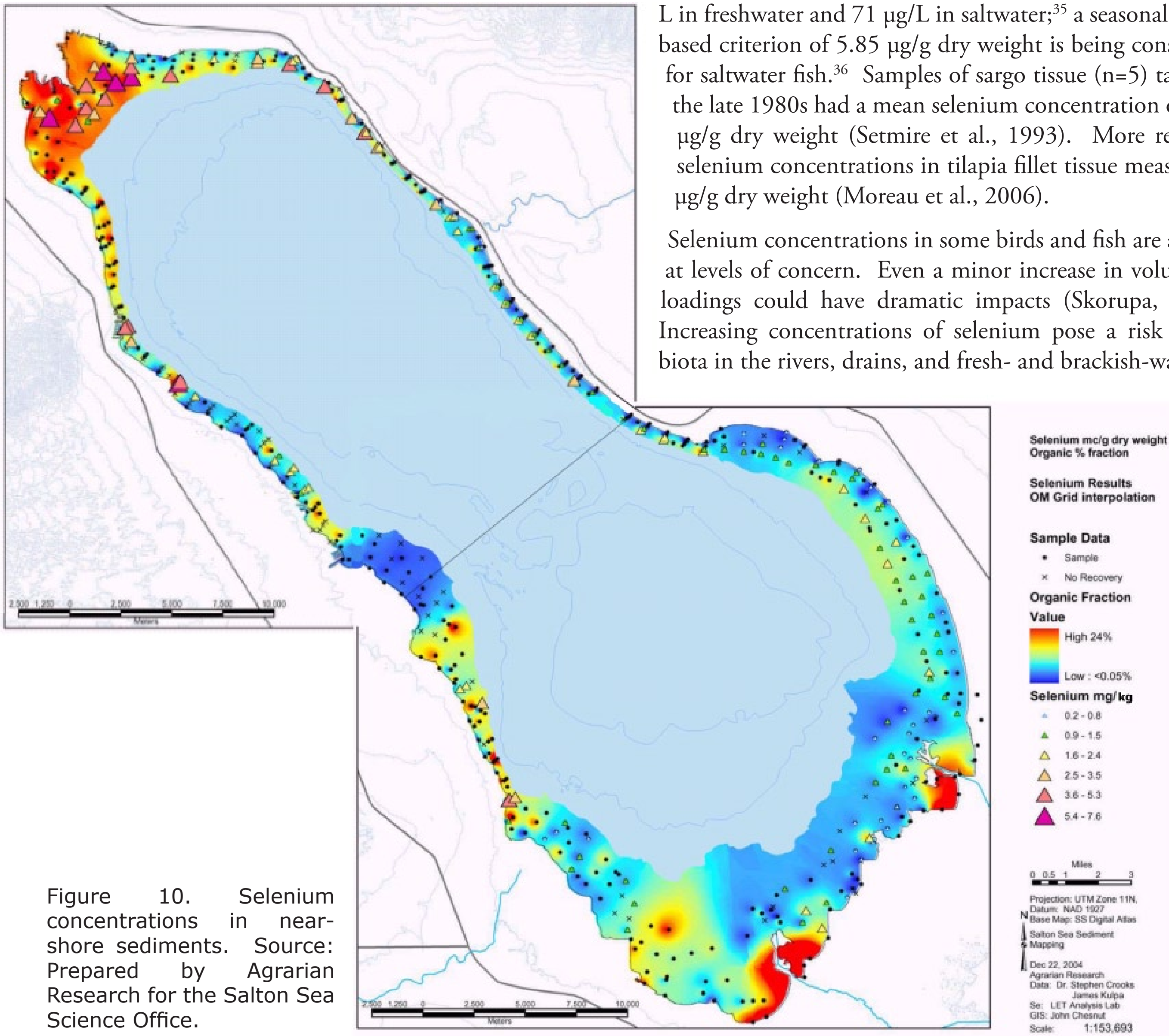

Figure 10. Selenium concentrations in near-shore sediments. Source: Prepared by Agrarian Research for the Salton Sea Science Office.

35 EPA "Water Quality Standards; Establishment of Numeric Criteria for Priority Toxic Pollutants for the State of California," 65 Fed. Reg. 35682, May 18, 2000.

36 EPA "Notice of Draft Aquatic Life Criteria for Selenium and Request for Scientific Information, Data, and Views," 69 Fed. Reg. 75541, December 17, 2004.

wetlands around the Sea, and in the Sea itself, as well as in the ephemeral pools that will form atop exposed lakebed. The primary threat to the biota in the rivers and drains, and the emergent wetlands fed by these, comes from the anticipated rise in selenium concentrations described above. In the future Salton Sea and within the expected ephemeral ponds, the threat comes both from higher volumetric loadings and from the likelihood that selenium in the sediments will re-enter the water column due to increased mixing and sediment transport.

Trace Elements

Although the Salton Sea is the sump for many of the water-borne metals, pesticides, and other contaminants used and applied and present in its watershed, these contaminants are largely absent from the Sea's water column (Vogl and Henry, 2002). For example, if perchlorate, found in Colorado River water, were undiminished in the Salton Sea, it would be present at a concentration of about 14 mg/L. Yet a bacterial or some other process decreases perchlorate concentrations in the Sea below the detection limit of 2.5 µg/L (Holdren, 2005). However, DDT and its derivatives are found in surface sediments, especially in the rich organic sediments in the deeper, central parts (Schroeder et al., 2002). Some metals and metalloids appear to have concentrated in the sediments, most notably selenium (see above), but also cadmium, copper, molybdenum, nickel, and zinc (Vogl and Henry, 2002). An ecological risk assessment of the pilot evaporation ponds adjacent to the Sea reported elevated concentrations of boron, at levels potentially high enough to cause risks to some breeding birds consuming invertebrates from the ponds (Tetra Tech, 2004).

It is not clear how future conditions at the Sea will affect its ability to sequester or otherwise diminish concentrations of these trace elements. It may be that significant changes will not be apparent before the surface elevation of the Sea re-stabilizes, by which point multi-cellular life in its waters will be largely limited to brine shrimp and brine fly larvae. If expected future increases in sediment transport and resuspension raise the concentrations of the contaminants currently removed from the water column, the biological impacts could include lower reproductive success and higher incidence of disease in the birds that consume invertebrates in the Salton Sea, as described below.

Biota

Most of the organisms inhabiting the Salton Sea in future years will be very different from the current community of fish and invertebrates and birds. Within 12 to 15 years, fish will disappear from the Sea. Shortly thereafter, brine flies and brine shrimp will flourish in the absence of their fish and invertebrate predators, growing in abundance on the high levels of algal and microbial productivity. Within about 40 years, rising salinity will control brine fly and shrimp populations, leaving algal and microbial productivity largely unchecked. The Sea's high internal nutrient loadings will likely ensure high productivity well into the future, though the reduction of brine fly and shrimp populations will diminish the last remaining food sources for those birds that remain. The loss of breeding and roosting habitats will also reduce future avian abundance and diversity at the Sea.

The Salton Sea's nutrient-rich waters generate extremely high primary productivity, supporting a diverse community of micro-organisms, but only one resident fish species (several others periodically pass through the Sea from the drains). This productivity supports a tremendous diversity and abundance of birds: 402 native and 5 non-native species have been recorded in and around the Salton Sea, including more than half a million waterbirds in 1999 (Shuford et al., 2002). At that time, the Sea's fishery was among the most productive in the world (Costa-Pierce and Riedel, 2000), attracting large numbers of fish-eating birds. The abundant invertebrate prey base at the Sea provides a key refueling stop for birds migrating along the Pacific Flyway (Patten et al., 2003). The importance of this stopover has grown in importance as other wetlands along the Flyway, such as those in the Colorado River delta, have disappeared.

Figure 11. Birds at the Salton Sea. Courtesy of Bob Miller, Southwest Birders.

The Sea has an unusual food web. The typical phytoplankton-zooplankton-fish-bird pathway is largely absent. Instead, the predominant food web pathways involves dead plankton falling to the lakebed, to be decomposed by bacteria in anoxic areas and consumed by pileworms (*Neanthes succinnea*), among others, in areas with sufficient oxygen. These detrivores are in turn consumed by fish and birds (Setmire et al., 1993). As pileworm and tilapia populations have decreased from previous years, this food web is in the process of changing.

Many factors drive this change: the persistence and expansion of large areas of stratified waters and resultant anoxic conditions in the hypolimnion; high production of hydrogen sulfide in these anoxic waters and sediments; parasites, selenium toxicity and diseases; increasing salinity; and relatively cold winter temperatures (Hurlbert et al., 2005). Most projections of the Sea's future biota, and especially the persistence of fish, have focused on salinity, to the exclusion of these other factors. Historically, these projections have been incorrect, underestimating the persistence and tolerance of the Sea's biota in the face of rising salinity. The combination of these various factors, and the projected rapid changes in the Sea's water quality after 2017, however, will dramatically alter the composition and abundance of life in the Salton Sea.

Salinity does not determine the health of the Salton Sea, but it does affect what organisms can live there (Setmire, pers. comm.). In the following, the direct impacts of the projected rise in salinity on the Sea's community structure are discussed, followed by the less direct impacts of salinity and the other factors noted above.

According to Hagar and Garcia (1988), four key factors related to increasing salinity can threaten a population with extirpation:

1. The level at which other factors interact with salinity to cause excessive mortality,
2. The loss of primary food supply due to exceedance of salinity tolerance for that organism,
3. Reproductive failure, and
4. Direct mortality due to exceedance of salinity tolerance.

To date, the Sea has been a remarkably dynamic, resilient system. Several species there have adapted to changing conditions, well beyond expectations of their ability to do so. Tilapia, a freshwater fish, offers one of the best examples of this adaptability and resilience. Tilapia colonized the Sea from agricultural drains and rapidly adapted to thrive in the Sea's extreme conditions. Salton Sea tilapia grow quickly and can reproduce six to eight times annually, allowing rapid replacement of populations that may have been decimated by venting of hydrogen sulfide or unusually cold winter temperatures and providing a mechanism for adaptation to changing conditions (Riedel et al., 2002). Limits clearly exist on such adaptability, but in the next 11 years, as the Sea's salinity increases gradually, tilapia may continue to persist longer than projected by controlled laboratory experiments (Hagar and Garcia, 1988). Ultimately, however, the rapid rise in the Sea's salinity after the delivery of mitigation water ends in 2017 will exceed the ability of the Sea's tilapia to adapt after that time.

As salinity increases, the overall diversity of species at the Sea will decline, though the population of those individual species could increase, at least initially. Rising salinity imposes high metabolic costs on organisms. Those organisms that can tolerate higher salinities must expend more energy for basic maintenance functions (notably, their internal water and ion balances), leaving less energy available for growth, development, and competition (Herbst, 2001).

Williams (1998) notes generally that moderately (<50 g/L) saline lakes suffering disruptions in their hydrology demonstrate significant biological changes, while disruptions to lakes with higher salinities have not witnessed such significant changes. The Sea approaches this threshold, but the magnitude and alacrity of the projected increase in salinity will generate significant and dramatic changes in the future Salton Sea after 2017. The precipitous drop in the Sea's surface elevation and the associated tripling of the Sea's salinity and increased concentrations of other contaminants, in the 10 to 12 years after 2017, will dramatically alter the composition and abundance of the Sea's species. This rapid drop in elevation will also decrease habitat availability, for both the benthic organisms that require the coarse substrate that exists around some of the islands and bays at the higher elevations, and for the birds no longer able to use the snags and islands as they become exposed to land-based predators (such as coyotes) as the Sea shrinks. Increased internal nutrient loadings, from sediment resuspension, will likely exacerbate eutrophic conditions at the Sea, though increased mixing may lead to elevated concentrations of dissolved oxygen throughout the water column. The future Sea will host a very different composition of species, as described in the following.

Micro-organisms

The Salton Sea's microbial communities are much more diverse than previously reported: new species (some new to science) are discovered there regularly (Wood et al., 2002; Barlow and Kugrens, 2002). Wood et al. (2002) report high numbers of bacterial and viral particles in the Sea, indicating the importance of primary production by micro-organisms. These communities play a critical role in the Sea's material and energy flows, and will persist at the Sea long after the better-known vertebrate and macro-invertebrate communities have succumbed to the Sea's increasingly hostile conditions.

During the initial transition period, from roughly 2018 to about 2030, as the Sea shrinks and salinity rapidly increases, the Sea's smaller size will permit greater mixing and periodic oxidation of its sediments, introducing organic matter and sequestered nitrogen and phosphorus back into the water column. Increasing nutrient availability coupled with greater current-driven movement of phytoplankton could increase

Fig. 12. The San Francisco Bay salt ponds.[37]

the size and frequency of algal blooms (Stephens, 1999a). Algal blooms at the surface will limit light penetration, likely limiting benthic algae. Within 16-18 years, brine shrimp (*Artemia franciscana*) should be quite abundant. Brine shrimp graze phytoplankton, potentially increasing light penetration, except in winter when brine shrimp populations would diminish due to temperature stress. At the Great Salt Lake (with much lower nutrient loadings), brine shrimp seasonally graze the plankton sufficiently to permit light to penetrate to the bottom, prompting algal growth and prodigious brine fly productivity. The rapid transition from a salinity of roughly 60 to >150 g/L will quickly move the Sea's salinity beyond the optimum conditions for these organisms, to the extent that micro-organisms will quickly dominate the future Sea. Por (in Herbst, 2001) notes that when salinity exceeds 140 g/L (in about 20 years), the grazing pressures brine shrimp exert on phytoplankton will be limited. Thereafter, turbidity will restrict benthic algae to the shallow margins of the Sea. Assuming light penetration of as much as five feet (1.5 m) suggests that benthic algae would be limited to roughly 25 square miles (66 km^2) of shallow lakebed. Benthic algae would also be limited by the absence of a suitable substrate, as the receding Sea would strand rocky and barnacle substrates well above the new shoreline.

Some of the micro-organisms present in the Salton Sea, such as cyanobacteria, produce toxins that can impair or kill other organisms, and will likely persist in the Sea for years to come (Wood et al., 2002). Until about 2018, populations of the toxic algae documented in the Sea would be expected to persist, though such algae are unknown in lakes with salinity greater than 60 g/L (Reifel et al., 2001). Toxic algae present at the Sea include *Chatonella marina*, *Heterocapsa niei* (a dinoflagellate), a *Pfiesteria*-like organism, *Prymnesium*, *Gyrodinium uncatenum*, and *Gymnodium* species (Stephens, 1999a; Reifel et al., 2001). Although toxic algae are almost unknown in high saline environments (No Action Workshop, 1999b), they could be prolific in the future Sea's estuarine areas. Sulfate-reducing bacteria would likely persist, at least in the sediments and anoxic porewater, for at least 25-30 years (Brandt et al., 1999; 2001), and possibly 40 years (Oren, 2000), until the Sea's salinity exceeds their tolerance.

In microcosm experiments with a salinity of 65 g/L, primary productivity decreased by 55-70% while phytoplankton abundance and chlorophyll *a* production decreased 60-90% relative to conditions at 30 g/L, but showed little difference at a salinity of 57 g/L (Gonzalez et al., 2005). This decrease could be buffered by the expected change in the Sea's food web, from the current detritus-pileworm-fish-bird pathway to a phytoplankton-brine shrimp-bird sequence, which could reduce the loss of material and energy to anaerobic bacteria in the sediments.

Stephens (1999a) notes that microcosm studies at SDSU demonstrated the importance of predation on both primary production and water chemistry itself. The increase in diatom abundance at 65 g/L decreased silica concentrations, since the diatoms incorporated the silica in their cells. A decrease in phytoplankton due to grazing by zooplankton increased light penetration to the bottom of the tanks in the SDSU experiments, fostering the diatom population increase. The diatoms and other photosynthetic organisms attached to the bottom also decreased concentrations of soluble nutrients (Stephens, 1999a). In a Mono Lake study, mesocosm experiments showed a decrease in the amount and diversity of diatom-dominated benthic algae as salinity increased from 50-150 g/L. Accordingly, photosynthetic oxygen production also decreased with increasing salinity (Herbst and Blinn, 1998).

The abundance of salt-tolerant green algae (e.g., *Dunaliella salina* and *Dangeardinella saltitrix*) and salt-tolerant bacteria in hypersaline ponds and lakes around the world strongly suggests that such organisms would dominate the Sea in 25 to 30 years, once its salinity exceeds the tolerance of other phytoplankton. High internal loadings driven by frequent mixing and sediment re-suspension, coupled with the continued input of nutrients from agricultural

37 Image ISS007-E-8738 courtesy of the Image Science & Analysis Laboratory, NASA Johnson Space Center - see http://eol.jsc.nasa.gov

and, increasingly, municipal drainage, would assure high productivity of these distinctively colored salt-tolerant organisms. In 25 to 30 years, the Sea's color would very likely resemble the salt ponds in south San Francisco Bay (Figure 10), with red, pink, orange, and amber dominating the palette, depending on the mixing of the Sea's inflows. If rising salinity dampens evaporation rates as expected, it is likely that *Dunaliella* and a host of salt-tolerant bacteria would still be abundant in the Sea 75 years into the future (Joint et al., 2002), coloring the Sea pink to red.

As the Sea's salinity rapidly transitions from 60 g/L in about 2018 to >180 g/L 10 to 12 years later, grazing pressures on algae and on photosynthetic and chemo-synthetic bacteria will diminish (Herbst, 2001). The main check on populations of these primary producers will be from viruses infecting them. Salt evaporation ponds have a very high abundance of viruses, and high viral abundance was recently documented at Mono Lake (Jiang et al., 2004).

The less saline lenses that will form periodically atop the Sea's surface as its waters grow denser would likely host abundant populations of the algal communities currently present in the rivers and drains feeding the Sea. The communities in these lenses would be entirely distinct from that in the hypersaline Sea, and would rapidly perish when a sufficiently strong wind event mixed waters together. In the interim, these lenses would also contain elevated concentrations of selenium and other contaminants present in the inflows.

Invertebrates

The Sea's high primary productivity sustains high invertebrate abundance. The zooplankton and other predators that graze the phytoplankton regulate the populations of these algae and other organisms, increasing the amount of light that penetrates the surface layers of the Sea and permitting some photosynthetic activity on the lakebed, at least in shallow areas. Although the primary producers and the current invertebrate communities thrive at the Sea's present salinity, seasonal anoxia, primarily in late summer after wind events mix accumulated hydrogen sulfide into the water column, dramatically reduces their populations (Tiffany et al., 2005a).

The total macro-invertebrate diversity at the Salton Sea consists of fewer than 20 documented species. Of these, several dominate: the rotifer *Brachionus rotundiformis* grazes the Sea's phytoplankton, while the copepod *Apocyclops dengizicus* preys on rotifers, algae and protozoans; the amphipod *Gammarus mucronatus* primarily lives on algae- or barnacle-covered rocks, and is less prevalent in the softer sediments that comprise most of the Sea's lakebed (Kuperman et al., 2002). Pileworms (*Neanthes succinnea*) are a key link in the Sea's current food web, consuming detrital organic matter in the lakebed and providing food for fish and birds (Kuhl and Oglesby, 1979). Barnacles (*Balanus amphitrite*) filter plankton and other organic materials from the water column when mature; larval stages are prey for fish and birds.

The pileworm provides food for many fish and bird species at the Sea and has been studied for more than forty years. These studies established a baseline distribution and abundance of pileworms, as well as basic life histories and salinity tolerances (Carpelan and Linsley, 1961; Linsley and Carpelan, 1961; Hanson, 1972; Kuhl and Oglesby, 1979). Offshore populations of pileworms decreased by more than an order of magnitude from about 1700 per square foot (18,000/m^2) in the mid-1950s to 2004 (Dexter et al., 2005), due in part to seasonal anoxic events, while inshore populations decreased due to tilapia and bird predation (Detwiler et al., 2002). Offshore pileworm abundance was higher in the southern basin, where shallow conditions encouraged mixing and oxygenation of lake water.

Barnacles, like pileworms, tolerate the salinity and current temperature extremes in the Salton Sea. However, adult barnacles require a hard substrate for attachment. Substrate availability, rather than water quality, likely determines the distribution and abundance of barnacles in the Sea. Since barnacle reproductive output is high and frequent and since mature barnacles have no predators, competition for space limits their population (Detwiler et al., 2002).

Several factors will influence future invertebrate community composition at the Sea. While water quality characteristics such as anoxia and salinity can limit invertebrate populations directly, often their indirect impacts – by limiting the predators on, or prey of, specific invertebrates – can be equally important (Hagar and Garcia, 1988). Brine shrimp (*Artemia franciscana*) population dynamics illustrate this point. In the absence of predators, brine shrimp can thrive at ocean water salinities. However, the Salton Sea teems with predators that quickly consume the slow-moving, energy-rich brine shrimp, so they are functionally absent from the Sea.

Complicating estimates of future community structure will be the limited availability of refuges at or near the estuaries formed by river and drain inflows. Potentially, such refuges could permit reproduction beyond the time projected by the water quality conditions of the main body of the Sea, though at levels considerably diminished from current reproduction and recruitment rates. Predators would also congregate in these estuaries, further diminishing recruitment.

The Sea's stratification and persistent anoxic hypolimnion currently limit the habitat available for macro-invertebrates during much of the year (Dexter et al., 2005). These conditions will likely persist through 2020, suggesting that pileworm populations will continue to decline. By 2021, salinity will have increased to roughly 75 g/L, the upper limit of pileworm survival (Kuhl and Oglesby, 1979). Some pileworm reproductive success will likely occur in estuarine areas, but they will largely disappear within a dozen years. Dexter et al. (2005) note that pileworm densities in algae-covered rocks are more than an order of magnitude higher than in the finer sediments the comprise most of the benthos, so habitat availability may also limit pileworms as the Sea's surface elevation falls.

Figure 13. California Gull eating brine flies at Mono Lake. Courtesy of Scott Hein. www.heinphoto.com

The extent and abundance of barnacles will be dramatically diminished by 2018 due to the near-total loss of appropriate, hard substrate habitat (No Action Workshop 1999a). By 2019, the Sea will have receded to about -235', stranding Mullet Island, Obsidian Butte, and other rocky outcroppings, as well the dikes and piers where barnacles attach themselves. Small populations of barnacles will likely colonize isolated hard surfaces on the lakebed (such as shipwrecks and similar anthropogenic detritus) until about 2021, when salinity is projected to exceed their tolerance of 70-80 g/L (Simpson and Hurlbert, 1998), but they will be functionally absent by about 2018 due to the absence of suitable habitat.

Copepods will similarly suffer from the loss of their preferred rocky habitat. They will likely persist at reduced populations on the softer sediments where their present distribution is limited (Kuperman et al., 2002) until roughly 2022-23, when salinity is projected to exceed their tolerance of about 90-100 g/L, provided that estuarine areas with salinities of less than 68 g/L are sufficiently large to support reproduction and recruitment (Dexter, 1993). Until copepod populations are largely eliminated, colonization of the Sea by brine shrimp will be limited (Hurlbert, 2002).

Water boatmen (*Trichocorixa reticulata* and *T. verticalis saltoni*) will increase in abundance in the Sea itself as fish disappear; boatmen graze phytoplankton and also prey upon brine shrimp and brine fly larvae (Herbst, 2001). Water boatmen can tolerate salinities of 110 g/L or greater (Euliss et al., 1991). "Numerous" water boatmen were observed at the pilot evaporation pond adjacent to the Sea at a salinity of about 100 g/L, and were abundant but less numerous (specific counts were not provided) in the pond with a salinity of 126 g/L (TetraTech, 2004), suggesting that they will persist at the Sea for the next 20 years. Water boatmen greatly diminish brine shrimp populations at the Great Salt Lake, when salinity there decreases to a level the boatmen can tolerate; this aggressive predation indirectly diminishes grazing pressure on phytoplankton, leading to increased algal populations, decreased light penetration and diminished seasonal heating of the water column (Williams, 1998).

Brine fly (*Ephydra*) larvae and brine shrimp will very likely be the dominant macro-invertebrates in the Sea in roughly twenty years, as its salinity increases beyond levels tolerated by copepods and water boatmen. Brine shrimp are at least functionally absent from the Salton Sea, while brine flies are generally limited to protected embayments, away from fish (Kuperman et al., 2002), precluding in situ studies. In other locations, brine shrimp populations and reproductive capacities decreased with lowered DO and pH levels (Hur et al., 1987; Landau and Sanchez, 1991; Rajamani and Manickaraja, 1994; Sadkaoui et al., 2000; Torrentera and Dodson, 2004) and with increased levels of ammonia (Hanaoka, 1977; Ostrensky et al., 1992). Overall, brine fly populations increased with salinity (Herbst, 2001; Ring et al., 1991), with availability of porous substrates (Herbst, 1990; Herbst and Bradley, 1993) and with an increase in pH (Alcocer et al., 1997). Little is known about the relationship between brine flies and ammonia, hydrogen sulfide, and dissolved oxygen concentrations.

Brine fly larvae currently inhabit the Sea's lakebed in limited numbers (Kuperman et al., 2002), due at least partly to predation, and also due to persistent anoxic conditions. Weghorst (2004) noted very large brine fly populations at the pilot project evaporation ponds adjacent to the Sea, with salinities of 63 g/L and higher. As the salinity tolerance of aquatic brine fly predators is exceeded in the next 15-20 years, brine fly populations will very likely explode. Brine fly larvae feed on benthic algae and microbes, which will be abundant given continued internal and external nutrient loadings. By the time the Sea's elevation falls to about -240', its salinity will likely have risen to roughly 80 g/L, compromising most aquatic predators. At this elevation, the Sea would be roughly half the size of the Great Salt Lake (and will boast higher primary productivity). During summer, more than 110 billion brine flies can be found along Great Salt Lake's shoreline at any time; an estimated five trillion brine flies hatch at the Great Salt Lake annually. Productivity at the Salton Sea could be limited by lower DO concentrations due to warmer summer temperatures and persistent eutrophic conditions; the extent to which DO will limit benthic productivity is not known (Hurlbert, 2002). Brine fly larvae reportedly can tolerate salinities as high as 330 g/L (Post, 1977), which if accurate suggests that they could persist, at some level, through 2077.

Brine shrimp have not been reported in the Sea itself, though they have been reported nearby (TetraTech, 2004). Although brine shrimp reportedly did not colonize either of the pilot evaporation pond projects, over the next 20-30 years brine shrimp cysts carried by birds migrating from Mono Lake, the Great Salt Lake, or other locations will very likely arrive at the Sea, providing a source population. After 18-20 years, when the abundance of their aquatic predators has been limited, brine shrimp would be expected to dominate the zooplankton (Stephens, 1999a; Hurlbert, 2002). In laboratory experiments, brine shrimp survived in Salton Sea water with salinities as high as 346 g/L,[38] though they were restricted to the top centimeter of water when the salinity measured 295 g/L or greater. Brine shrimp populations persisted more than 1.5 years at a salinity of 250 g/L (TetraTech, 2004), suggesting that they will exist at the Sea in large numbers from roughly 2026 for 30-40 years, and likely through the end of the study period at reduced populations. Conte et al. (in Stephens, 1999b) reported that salinities above 175 g/L impaired brine shrimp larvae, though subsequent studies have suggested that brine shrimp develop rapidly at this salinity. At the Great Salt Lake in 1994 (with a salinity of ~175 g/L), brine shrimp populations decreased in summer, due to their depletion of their phytoplankton food source (Wurtsbaugh and Gliwicz, 2001), rather than due to salinity. Once the Sea's salinity exceeds 200 g/L in roughly 30 years, brine shrimp reproduction or larval development could be depressed, decreasing subsequent grazing pressure on phytoplankton (Herbst, 2001). However, it is plausible that brine shrimp would continue to exert strong grazing pressures at the Salton Sea beyond this point. Brine shrimp will likely improve water clarity by aggressively grazing phytoplankton, increasing light penetration into the Sea and raising benthic productivity.

38 TetraTech (2004) provides the original values as 'parts per thousand'; they have been converted here for consistency [g/L = (value in ppt*1000)/(1000-value in ppt) (after Stephens, 1999a)]

Laboratory experiments and examples from other hypersaline lakes provide information about potential future conditions at the Sea, but should not be taken as definitive. Such experiments lack the species diversity and scale of the Sea, as well as the Sea's broader hydrodynamics (Gonzalez et al., 2005). Wind action at the Sea, for example, will increase surface mixing and the depth of oxygenated water. Higher concentrations of selenium and other trace elements in the water column would be absorbed by phytoplankton and subsequently concentrate two to eight times in brine shrimp (Petrucci et al., 1995), potentially above levels of concerns for the birds that consume them. Less clear is whether these elevated concentrations would have any direct impacts on brine shrimp.

The extent and persistence of the expected less saline lenses atop the Sea will limit brine shrimp abundance: brine shrimp that managed to cross the salinity gradient would be rapidly consumed by fish, water boatmen, and other organisms within the lens. If these lenses do extend broadly across the surface of the Sea, they would disturb phytoplankton productivity and reduce the abundance of brine shrimp. The impacts of such lenses on benthic organisms is more speculative: expected algal blooms in these waters would limit light penetration, reducing benthic productivity and limiting abundance of brine fly larvae. However, if primary production in the freshwater lenses were sufficiently limited by grazing or other factors, the underlying benthos would still be productive.

Fish

In 1999, the abundance of a hybrid tilapia (*Oreochromis mossambicus x O. urolepis hornorum*) (Riedel et al., 2002) at the Salton Sea may have exceeded 100 million fish (Cohn, 2000). Since that time, the tilapia population plummeted to about 1% of its former abundance, though in the past few years their population has slowly increased.[39] However, none of the other three formerly predominant fish in the Sea – orangemouth corvina (*Cynoscion xanthulus*), croaker (*Bairdiella icistia*), and sargo (*Anisotremus davidsoni*) – have

39 CA Dept. of Fish & Game quarterly fish monitoring reports.

appeared in the California Department of Fish & Game's quarterly fish sampling in three years, suggesting that they are at least functionally absent from the Salton Sea (Crayon et al., 2005).

Periodic large-scale fish kills, with mortality sometimes in excess of seven million fish, have been linked to wind-driven mixing of anoxic water rich in hydrogen sulfide into the main water column (Tiffany et al., 2005b). Fish kills at the Salton Sea from 2000-2003 included varying numbers of corvina and croaker (the latter constituted 94.7% of one mortality event in 2003), but no corvina or croaker were found in a 2004 fish kill, or has been documented since then.

Previous studies predicted that corvina could disappear at the Sea's current salinity, but projected that croaker and sargo would persist until salinity reached 52.5 g/L (Thiery, 1998). Their apparent extirpation likely reflects the Sea's increased anoxia and rise in sulfide concentrations, especially in open-water areas (Riedel et al., 2002), and may also reflect the high parasite loads in fish (Kuperman and Matey, 2000; Kuperman et al., 2002) and high selenium concentrations (Setmire et al., 1993). These species' reproductive strategy of broadcasting eggs in open-water areas may have hastened their demise, by subjecting eggs and larvae to anoxic or toxic conditions (Crayon et al., 2005).

Tilapia

Tilapia will disappear from the Salton Sea within 12 years. Tilapia, originally a freshwater fish, escaped into the Salton Sea in 1964-65. Since then, their tolerance of high salinities and greater adaptability has enabled them to dominate and outlast the marine fish community (Suresh and Lin, 1992; Riedel et al., 2002). Low temperatures, diminished DO concentrations, high parasite loads, and ammonia and hydrogen sulfide apparently affect tilapia more than the Sea's current salinity (Crayon et al., 2005). Tilapia mortality increases at temperatures below 55°F (13°C), reducing winter populations (Setmire et al., 1993; Hurlbert et al., 2005). Laboratory acclimation studies note that tilapia survive transfers to water with 95 g/L TDS at 77°F (25°C), while suffering 100% mortality in a transfer to water with 60 g/L at 59°F (15°C) (Sardella et al., 2004). In 1999 and 2000, tilapia were observed congregating in near-shore and estuarine areas in the summer, when dissolved oxygen levels in the middle of the Sea were lower (Riedel et al., 2002). Tilapia populations in the Salton Sea have also adapted to grow more quickly and to reproduce more frequently than tilapia in other locations, contributing to their resilience in the Sea's extreme conditions.

In other locations, tilapia have successfully reproduced at salinities of 49 g/L, and survived at 120 g/L (Riedel et al., 2002). Brauner and Sardella (2005) report that salinities of 55-65 g/L can impair tilapia. Thiery (1998) also projects that tilapia will disappear once the Sea's salinity reaches 64 g/L (by about 2018). Tilapia have demonstrated remarkable resilience and adaptability in the face of the Sea's rising salinity, persisting long past previous projections of their demise. Ultimately, however, as salinity continues to rise, tilapia will expend so much energy regulating their internal water and salt balance that their other life functions will suffer, increasing their susceptibility to disease and parasite infestations, as well as reducing their resistance to the Sea's other stressors. Estuaries in the Sea will offer refuge and breeding habitat for tilapia, though the lower winter temperatures in these shallower, fresher waters may provide false haven.

Desert Pupfish

The desert pupfish (*Cyprinodon macularius*), listed as endangered in 1986, tolerates high salinities and temperatures and very low DO concentrations, but it has not fared as well in the drains around the Salton Sea in the face of predation and competition from other fish (Martin and Saiki, 2005). In addition to many of the drainage ditches around the Sea, pupfish inhabit Salt Creek and San Felipe Creek, and occasionally are also found in shoreline pools and depressions that bar access to larger predatory fish. Pupfish do not tolerate fast moving water, such as found in the rivers. Pupfish, which grow to about 2.5 inches (6 cm), consume detritus, algae, and small invertebrates when available. Barlow (in Thiery, 1998) reports desert pupfish surviving in Salton Sea shoreline pools with salinities of 99 g/L. However, reproductive viability was limited at 75 g/L, especially when temperatures exceeded 33°C. Pupfish eggs did not develop at 93 g/L (Thiery, 1998).

Although Sutton (2002) reports limited use of the Salton Sea for pupfish migration, recent sampling efforts have found them in the Sea. Pupfish were also found miles from shore among tilapia and mollies in recent fish kills in the Sea (Crayon et al., 2005). Once the salinity of the Sea exceeds ~90 g/L (by 2021-23), the individual drain populations would be effectively isolated. At that time, more frequent mixing should increase DO concentrations at the Sea, though it is not clear what other stressors might limit pupfish movement in the Sea before then. The IID water transfer mitigation plan (IID, 2003) requires habitat connectivity for the desert pupfish, to promote the exchange of genetic material between pupfish populations that would otherwise be isolated in individual drains, and within the natural streams. Once the Sea's salinity exceeds about 90 g/L, IID will construct connections between individual drains, permitting pupfish movement between drains. The location and form of these connections has yet to be determined; presumably, they would be constructed well above the -240' contour, to promote pupfish movement from one drain to the next and to avoid the nearly fifteen foot drop in elevation from the present drain discharge elevations. High selenium concentrations in the drains and in these connections could threaten pupfish reproduction and viability.

Sailfin Molly

Crayon and Keeney (2005) report high sailfin molly (*Poecilia latipinna*) abundance in drains and in shallow areas of the Sea itself: roughly 2/3 of the 23,000 mollies trapped as part of their sampling were caught in saltwater sites. Unlike tilapia and the marine fish in the Sea, mollies and pupfish apparently can move freely between drain and Salton Sea habitats, despite the strong salinity gradient (Crayon and Keeney, 2005). Like pupfish, mollies can tolerate high salinities, reportedly to 87 g/L (Nordlie et al., 1992). Mollies grow roughly twice as large as pupfish, to about 5 inches (12.5 cm), with a similar diet (Waltz and McCord, no date).

The disappearance of predatory fish could explain the recent increase in pupfish and molly use of the Sea itself. If current trends continue, pupfish and molly populations in the Sea could increase substantially in the Sea in the next decade, especially given the availability of food resources. Within about 15 to 17 years, salinity at the Sea will exceed their tolerance, though they will probably continue to use estuaries.

Birds

The Salton Sea provides critically important habitat to a tremendous diversity and abundance of birds: 402 native and five non-native species have been recorded in and around the Salton Sea, including more than half a million waterbirds in 1999 (Shuford et al., 2002; Patten et al., 2003). Some 140 waterbird species have been recorded there; many of these birds use both the Sea and nearby agricultural fields, as well as adjacent freshwater and managed wetlands, including lands periodically inundated by duck clubs. The rich mosaic of habitat types and their proximity to one another offer exceptional value for birds, and helps to explain their diversity and abundance. Other factors increasing bird use of the region are the loss of other wetland habitats along their migratory routes, the abundant supply of food, and the relatively low levels of human disturbance (Friend, 2002).

Figure 14. Habitat mosaic at the Salton Sea.

The Sea may provide the most important wintering habitat anywhere for eared grebes: on March 5, 1988, an estimated 3.5 million eared grebes were at Salton Sea (Jehl and McKernan, 2002). The presence of a large body of water rich with food resources amidst the harsh Colorado desert proves very attractive to birds migrating along the Pacific Flyway, as well as to birds inhabiting the upper Gulf of California. Shuford et al. (2002, p. 255) state:

> Various studies indicate the Salton Sea is of regional or national importance to various species groups – pelicans and cormorants, wading birds, waterfowl, shorebirds, gulls and terns – and to particular species – the Eared Grebe, American White Pelican, Double-crested Cormorant, Cattle Egret, White-faced Ibis, Yuma Clapper Rail, Snowy Plover, Mountain Plover, Gull-billed Tern, Caspian Tern, Black Tern, and Black Skimmer.

The Salton Sea is but a smaller incarnation of the ancient Lake Cahuilla, a former terminus of the Colorado River that appeared and evaporated repeatedly as the river periodically meandered north to fill the Salton Sink, and then reverted south, to run again to the upper Gulf of California. Birds would quickly colonize each new incarnation of Lake Cahuilla, moving on to other ephemeral and permanent wetlands when the lake evaporated. The threat now is that 90-95% of California's wetlands have disappeared, primarily due to land conversion and water diversions and depletions. The loss of the these former wetlands greatly increases the importance of the Sea and its surrounding wetlands.

All but 2 of the 36 bird species from Lake Cahuilla, identified from pre-Salton Sea Native American archeological middens,[40] are now present at the Salton Sea, in roughly their former relative abundance (Patten and Smith-Patten, 2004). The formation of the Salton Sea in 1905 quickly attracted many of its current inhabitants. By 1908, both white pelicans (*Pelecanus erythrorhynchus*) and double-crested cormorants (*Phalacrocorax auritus*) were breeding there, and various other waterbird and landbird species colonized the region within 20 years (Patten et al., 2003).

Currently, the basin provides myriad habitat types, including marshes, upland areas, riparian corridors, agricultural fields, and the Sea itself, with its embayments, extensive shoreline, mudflats, deltas, estuaries, islands, snags, and open water (Patten et al., 2003).

Marshbirds

Future impacts to freshwater marshes, home to the endangered Yuma clapper rail (*Rallus longirostris yumanensis*) and the Virgina rail (*R. limicola*), among other marshbirds (Shuford et al., 2000), are not well known: clapper rails could be affected by changes around some of the marshes right at the edge of the Sea, such as at Salt Creek (N. Warnock, pers. comm.). Managed wetlands on the refuge might, with sufficient funding, be expanded upon currently inundated refuge land. The refuge and several of the other managed wetlands currently use raw Colorado River water, rather than agricultural drainage water, and thus will be insulated from future degradations of drainage water quality. Wetlands along the New and Alamo rivers, however, will see increased concentrations and accumulations of selenium and other contaminants.

Landbirds

Landbird use in the region around the Sea will change over the next seventy years, most notably due to urbanization in the Imperial and Coachella valleys. Urbanization tends to reduce avian diversity, favoring introduced species (Chace and Walsh, 2006). Nonetheless, there are more than 450,000 irrigated acres in the valley (more than 300,000 of which are currently in field crops), suggesting that even if the urban footprint more than triples to 150,000 acres by 2075, there will continue to be a broad expanse of agricultural land available to birds. Increased irrigation efficiency in the Imperial Valley will reduce the extent of standing water, a preferred habitat of species such as cattle egrets (*Bubulcus ibis*) and white-faced ibis (*Plegadis chihi*), and frequently used by at least a dozen other species of waterbirds (Shuford et al., 2000; Warnock et al., 2004). Although leaching requirements for Imperial Valley soils suggest that standing water will continue to exist in the valley for years to come (probably at less than current levels), the cumulative effects of the water transfer, in conjunction with changes in farm irrigation practices and cropping patterns, urbanization, and dust control measures, could well diminish avian use of the agricultural mosaic (K. Molina, pers. comm.).

Fish-eating Birds

The greatest and most immediate impacts of changes at the Salton Sea will be to fish-eating birds. White pelicans historically bred at the Salton Sea, though breeding has not been observed in recent years (Shuford et al., 2000). Extensive surveys in 1999 recorded 24,974 white pelicans at the Sea in the winter of that year, while the highest population of brown pelicans (*Pelecanus occidentalis*) – 1,995 birds – was recorded in mid-summer (Shuford et al., 2000). However, these surveys coincided with what may have been the Sea's highest population of fish; tilapia populations have since declined by more than 95%, while the other marine species have disappeared entirely. Pelican surveys in the past several years have recorded fewer individuals, with a peak monthly count in 2005 of only 422 white pelicans; the peak monthly count that year for brown pelicans, however, was 5,344.[41]

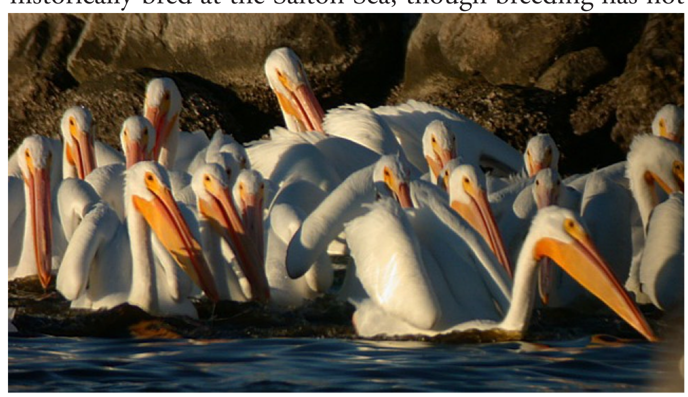

Figure 15. White pelicans at the Salton Sea. Courtesy of Bob Miller, Southwest Birders.

40 Middens are mounds marking the site of prior human habitation, often containing shells, animal bones, and other refuse.

41 Data from the Sonny Bono Salton Sea National Wildlife Refuge.

Tilapia will likely persist at the Sea for the next 10 to 12 years, though their populations will decline as salinity increases. Pelicans may increasingly subsist on sailfin mollies, and possibly desert pupfish, as the numbers of these prey species increase and tilapia populations diminish, affording a food source for about the next 15 to 17 years. However, the total biomass of mollies and pupfish will likely be only a small fraction of that of tilapia, limiting the food resource for these birds. Anecdotal evidence suggests that pelicans have increased their foraging at fish farms near the Sea in recent years. In 10 to 17 years, however, the Sea will fail to provide a sufficient prey base for more than a few pelicans, eliminating an important wintering and stopover point (Patten et al., 2003).

As the Sea recedes, Mullet Island will become connected to the mainland, exposing this pelican and cormorant roosting area to land-based predators. The New and Alamo river deltas should continue to provide roosting habitat for these species, but by about 2018, all current island habitats will be connected to the shoreline.

Like white pelicans, populations of double-crested cormorants peak at the Salton Sea in winter; the 1999 survey recorded 18,504 individuals (Shuford et al., 2000). Their abundance will similarly be linked to fish abundance. Both pelicans and cormorants will probably continue to forage in the Sea's shallow estuaries after salinity in the main body of the Sea excludes fish, though limited prey abundance and the area's limited depth may discourage them. In any case, within 10-17 years, the Sea will not provide a significant prey base for large fish-eating birds.

Wading Birds

Ten native species of long-legged wading birds, totaling some 6,000 individuals, were observed during 1999 surveys at and around the Salton Sea (Shuford et al., 2000). Many of these species forage in agricultural fields, returning to the Sea to roost; such roosts included some 40,000 cattle egrets and more than 37,000 white-faced ibis (Shuford et al., 2000). These wading birds consume a broad variety of prey, including fish, aquatic and terrestrial invertebrates, small reptiles and amphibians, and small birds in some cases. Their broad diet and use of agricultural areas suggest that expected changes in prey availability at the Sea itself will not greatly affect the long-legged wading birds.

While the projected river and drain extensions and potential new wetland and riparian habitat that these generate should increase tamarisk habitat and prey abundance for the wading birds, their current roosting habitat will be degraded by changes at the Sea. Many of these species breed at the New and Alamo river deltas, as well as at managed wetlands near the Sea, in various types of vegetation, especially snags

Figure 16. Snags with cormorants. Courtesy of D. Barnum

(standing dead trees) (Molina and Sturm, 2004). Snag habitat exists in shallow areas, predominantly at the north and south ends of the Sea. As the Sea recedes in the next several years, eliminating the snags' isolation by water, and as the snags themselves break and collapse due to the degradations of wind, brine, and time, this habitat will disappear (D. Barnum, pers. comm.).

Waterfowl

Thirty-six species of waterfowl (ducks and geese) have been recorded at and around the Sea (Patten et al., 2003). Many of these waterfowl species consume pileworms and other macro-invertebrates. Barnum and Johnson (2004) report midwinter counts of waterfowl at the Salton Sea as high as 133,597 birds, noting that this figure misses transitory migrants and therefore greatly underestimates the total number of waterfowl that use the Sea. The Sea provides an important winter stopover for waterfowl migrating along the Central Flyway, in addition to the Pacific Flyway (Barnum and Johnson, 2004). While the number of diving and dabbling ducks decreased from 1986-2000, numbers of geese did not change much in that period (Barnum and Johnson, 2004).

Warnock et al. (2004) report that the two predominant species of geese observed in the area were found solely in managed wetlands at the southern end of the Sea, at the wildlife refuge, the Wister Unit, and nearby duck clubs. If funding permits, the refuge could be expanded as the Sea exposes its currently submerged lands, increasing the abundance of geese if these new lands were managed for their benefit. The percentage of dabbling ducks at the Sea varies from about 10-60%, with the remainder found at freshwater wetlands near the south end of the Sea (Warnock et al., 2004). Diving ducks, especially ruddy ducks, favor inshore areas of the Sea, typically within a kilometer of the shoreline (Shuford et al., 2000).

As the Sea recedes in future years, the distance between the shoreline and adjacent freshwater wetlands will increase to several miles, diminishing ready movement between the two. As salinity increases, prey diversity and abundance for these ducks will decrease, potentially reducing duck abundance within 15 to 17 years. It is not clear how these birds will react to the Sea's period of rapid transition. For about a decade, as salinity spikes from about 60 g/L to more than 150 g/L, the Sea's aquatic fauna will undergo dramatic changes in composition and abundance. As the Sea transitions from pileworms and copepods to brine flies and brine shrimp (with a brief intermediate period dominated by water boatmen), these rapid changes will likely lead to a marked decrease in invertebrate abundance. This decrease in prey abundance could encourage migrating waterfowl to seek other stopovers. After this transition period, observations at Mono Lake[42] suggest that some dabbling and diving ducks may change their diet to include the brine shrimp-brine fly populations expected to dominate the future Sea. At Mono Lake, ducks use the less-saline lenses that form at inflows, affording their preferred habitat while providing access to the hypersaline fauna.

Eared grebes currently migrate between the Great Salt Lake, Mono Lake, the Salton Sea, and the Gulf of California (and several other staging areas); their numbers at any of these locations can exceed one million individuals, as they feed to prepare for the next leg of their migration. At the Sea, grebes currently prey upon pileworms, but are expected to transition readily to the brine shrimp that comprise their diet at Mono Lake and Great Salt Lake. If brine shrimp microcosm studies prove accurate predictors of their persistence at the Sea (see *Invertebrates*, above), eared grebes and ducks would be expected to have a plentiful prey base (after the transition period) for a period of 30 to 40 years. By about 2060, most of the Sea's invertebrate production will have disappeared, eliminating its value as a staging area for these birds.

Shorebirds

Shuford et al. (2004) report maximum shorebird counts at the Sea of nearly 130,000 individuals, and recorded 34 species during surveys from 1989-1995, and in 1999. Numbers of black-necked stilts (*Himantopus mexicanus*), American avocets (*Recurvirostra americana*), western sandpipers (*Calidris mauri*), and dowitchers (*Limnodromus* spp.) at times each exceeded 10,000 individuals. Some of the stilts and avocets reside and breed at the Sea, their numbers swelling in Spring and Fall with passing migrants. Although not as numerous, 30-38% of the world's total population of mountain plover (*Charadius montanus*) were observed in agricultural fields south of the Sea (Shuford et al., 2004). Snowy plovers (*C. alexandinus*), on the other hand, concentrated along the beaches and exposed areas at the Sea itself (Shuford et al., 2000).

Figure 17. American avocets. Courtesy of Bob Miller, Southwest Birders.

Avocets and phalaropes (*Phalaropus* spp.) should adapt well to the Sea's future invertebrate fauna, as demonstrated by their abundance at other hypersaline habitats such as the Great Salt Lake and Laguna Salada (Hinojosa-Huerta et al., 2004). Other shorebirds will likely continue to congregate at the deltaic areas in the Sea, and use the nearby freshwater wetlands and agricultural fields in the Imperial Valley.

Gulls and Terns

More than 20,000 ring-billed gulls (*Larus delawarensis*) were observed at the Salton Sea in November, 1999, by far the most abundant of the thirteen species of gulls recorded that year (Shuford et al., 2000). Ring-billed gulls also predominated in agricultural fields. Six species of gulls and terns breed at the Sea, including as many as 480 pairs of Caspian terns (*Sterna caspia*) and 360 pairs of black skimmers (*Rynchops niger*) (Molina, 2004).

If mollies and pupfish colonize the Sea in great numbers in the future, black skimmers should have an adequate food supply at the Sea for the next 15 to 17 years. Although some fish will remain in the limited estuarine areas after that time, black skimmer populations will likely abandon the Sea within 17 years. Though food resources in agricultural fields, estuaries, and freshwater wetlands should continue to be abundant for gulls and terns, it is likely that the availability of their preferred breeding habitat will decrease markedly as the Sea recedes. Such breeding habitat consists primarily of small (<¾ acre (<⅓ ha)) areas surrounded by

42 See http://www.monobasinresearch.org/timelines/waterfowl.htm

water, isolated from terrestrial predators (Molina, 2004). Sediment deposition in the deltas will probably continue to form such areas even as the Sea recedes, though their size and location might not be attractive to breeding birds. The loss of these regionally-important breeding populations could have broad repercussions, notably for gull-billed terns and black skimmers (Molina, 2004).

Habitat changes

Breeding habitat in particular, and roosting and loafing habitat more generally, will decrease at the Sea in future years. The most obvious change will be the general loss of island and snag habitats as the Sea recedes. Without human intervention, no new snag habitats will become available, though some deltaic island habitats could be formed. The loss of snag habitat will particularly discourage Great, Snowy and Cattle egrets, and to a lesser extent will limit night-herons, cormorants, and Great Blue Herons (Shuford et al., 2000). The long river extensions could continue to provide roosting and loafing habitat for pelicans and cormorants and other colonial waterbirds.

The abundance and diversity of migratory birds at the Sea reflect changes in other locations along their routes. Such changes are difficult to predict. What is clear is that future changes at the Sea will affect bird populations throughout their range.

Wildlife Disease & Toxicity

Disease

The incidence of disease tends to increase during periods of environmental change, increasing the stress such changes impose upon organisms (Friend, 2002). The Salton Sea has effectively been in a period of change since its formation a century ago, due to rising salinity and the introduction of marine invertebrates and fish, and particularly due to the colonization of the Sea by tilapia. Increasing periods of stratification and rising concentrations of ammonia and hydrogen sulfide represent more recent changes, affecting tilapia populations and directly and indirectly affecting population dynamics up and down the food web. The abundance and diversity of migratory birds stopping at the Sea also increases the incidence of disease, as these birds carry disease organisms along the flyway (Friend, 2002).

The first reported incidence of avian botulism at the Sea occurred almost 90 years ago, and remains common (Friend, 2002). In the past thirty years, avian cholera, salmonellosis, and Newcastle disease have also become prevalent at the Sea, with the number and severity of disease outbreaks increasing each decade since the 1970s (Friend, 2002). West Nile virus was first detected at the southern end of the Salton Sea in 2003 and could become prevalent in the region's extensive mosquito habitat. In the 1990s, more than 200,000 birds died at the Sea due to various disease outbreaks, including 155,000 eared grebes in 1992 and nearly 10,000 pelicans in 1996, due to avian botulism. The transmission of botulism to pelicans via toxins in live fish had not previously been documented (Nol et al., 2004).

The expected disappearance of tilapia within 10 to 12 years should eliminate the incidence of botulism in fish-eating birds, as mollies and pupfish are not known to carry the disease-causing organism. However, shorebirds and waterfowl will remain subject to large-scale botulism outbreaks in the estuaries, especially in stagnant embayments near the deltas and estuaries at the south end of the Sea (Rocke and Samuel, 1999). If bird density increases in these areas due to limited food availability in other, hypersaline areas, disease transmission could also increase. Higher waterfowl density in estuaries would also increase the incidence of avian cholera (Hurlbert, 2002). Generally, as salinity at the Sea rises, waterbirds limited to estuarine areas will face a higher risk of disease.

Selenium Toxicity

Selenium increases in concentration up the food web. Such accumulation and bio-magnification has already been observed in and around the Salton Sea, posing a risk to birds, especially fish-eating birds (Setmire et al., 1993; Setmire and Schroeder, 1998). Selenium concentrations in the Sea will increase in future years, due to both external and internal factors. As the Sea shrinks and sediments remobilize, the accumulated, selenium-rich organic material will become available to benthic organisms such as pileworms and, later, brine fly larvae, and will also enter the water column generally. Additionally, as the volume of the Sea decreases, the proportional loadings from the inflows will rise, promoting greater uptake by phyto- and zooplankton.

These higher concentrations will increase uptake and accumulation within the aquatic food web, likely reaching toxic levels in birds. The ecological risk assessment of the pilot evaporation ponds projected an increased risk of deformities and reproductive failure due to selenium toxicity, and, to a lesser degree, due to high concentrations of boron (TetraTech, 2004).

As noted above in *Selenium*, the peak selenium concentrations (occasionally in excess of 300 µg/L) are more important indicators of potential selenium accumulation and toxicity than is the mean (Skorupa, pers. comm.). Such peak values in the external loadings, as well as the projected increase in internal loadings, pose a significant risk of selenium-related toxicity at the Salton Sea in future years.

Figure 18. Black-necked stilt embryos from Kesterson Reservoir: S-9 Eyes missing, brain protruding through orbits, lower beak curled, upper parts of legs shortened and twisted, and only one toe on each foot; S-313 normal. Courtesy of H. Ohlendorf.

Higher selenium concentrations will compromise birds' immune systems, decreasing their resistance to the diseases described above (Fairbrother and Fowles, 1990; Bobker, 1993; Bruehler and de Peyster, 1999). Arsenic and boron, both present at the pilot evaporation ponds in elevated concentrations (TetraTech 2004), may exacerbate selenium-induced immuno-suppression (Fairbrother et al., 1994). The combination of greater crowding, warmer summer temperatures, and immuno-suppressed birds could greatly increase the incidence of already-prevalent diseases, raising mortality.

By decreasing their reproductive success, selenium poses the greatest direct risk to breeding birds. Sensitivity to selenium toxicity varies in birds, with some evidence suggesting that salt tolerance decreases selenium sensitivity (Hamilton, 2004). Freshwater ducks appear to be among the most sensitive and may show impairment when water concentrations exceed 4 µg/L, while stilts are more sensitive than avocets (Skorupa, 1998). The following breeding birds would be at greatest risk:

Table 6. Birds breeding at and near the Salton Sea

Name	Total Nesting Pairs (Year)
Cattle Egret	6600[43] (1999)
Double-crested Cormorant	5425 (1999)
Great Blue Heron	888 (1999)
Black-necked Stilt	abundant
Ruddy Duck	>500
Killdeer	500 (1992-93)
Black Skimmer	423 (1999)
Western Grebe	common[44]
American Coot	common
Snowy Plover	200-225 (annual)
Caspian Tern	211 (1999)
White-faced Ibis	210
Snowy Egret	167 (1999)
Great Egret	165 (1999)
Gull-billed Tern	101 (1999)
Black-crowned Night-Heron	100 (1999)
Cinnamon Teal	<100
Least bittern	fairly common
Green heron	fairly common
Redhead	fairly common
Pied-billed Grebe	fairly common
Common Moorhen	fairly common
California Gull	44 (1999)
Forster's Tern	20 (1990)
Clark's Grebe	uncommon
Yuma Clapper Rail	uncommon
Virginia Rail	uncommon
American Avocet	2, 5 (1977, '78)
Laughing Gull	1 (5 in 2001)
Fulvous Whistling Duck[45]	1 (1998, '99)

Sources: Shuford et al., 2000; Patten et al., 2003; Molina, 2004; Molina and Sturm; 2004

Trace Contaminants

Boron bioaccumulates in Salton Sea biota (Setmire et al., 1993). In the pilot evaporation ponds it concentrated to levels of concern (TetraTech, 2004). Boron can impair development of chicks, reducing weight gain. In the future, other trace contaminants, including DDT and its derivatives, could also concentrate to levels of concern. The combination of rising concentrations of selenium and these other trace contaminants may significantly reduce future avian reproductive success.

43 Maximum reported as 30,055 breeding pairs, median of 2544 (1986-2005) (K. Molina, presentation at DWR Habitat workgroup, 4/19/06).

44 "Common" – occurs in large numbers; "fairly common" – occurs in modest numbers; "uncommon" – occurs in small numbers (Patten et al., 2003).

45 Formerly a fairly common breeder, now nearly extirpated at the Salton Sea (Patten et al., 2003).

Air Quality

In both Imperial County and the Coachella Valley, air quality fails to meet federal and state standards, most notably for the small dust particles known as PM_{10} (particulate matter with a diameter less than 10 microns (~0.0004 inch)). Both areas are currently classified as "serious nonattainment areas" for PM_{10}.[46] Table 7 shows estimated PM_{10} emissions in the Salton Sea air basin in 2004, by source.

Table 7. Estimated Daily Average PM_{10} Emissions in the Salton Sea Air Basin, 2004

Emission Source	*(tons/day)*
Fugitive Windblown Dust	180.3
Unpaved Road Dust	35.4
Farming Operations	18.8
Paved Road Operations	9.9
Construction and Demolition	8.3
Other Sources	8.1
Total All Sources	**260.8**

Source: California Air Resources Board, in CH2M-Hill, 2005

PM_{10} can lodge deep in the lungs, impairing human health. The California Air Resources Board website[47] states:

> PM_{10} can increase the number and severity of asthma attacks, cause or aggravate bronchitis and other lung diseases, and reduce the body's ability to fight infections…. Although particulate matter can cause health problems for everyone, certain people are especially vulnerable to PM_{10}'s adverse health effects. These "sensitive populations" include children, the elderly, exercising adults, and those suffering from asthma or bronchitis.

PM_{10} can decrease the growth and development of lung function in school-aged children (Gauderman et al., 2000; CEH, 2004), and also increases the risk of cardiac disease, heart attacks, and mortality in adults (Peters et al., 2001). Elevated PM_{10} concentrations were associated with increased asthma-related emergency department visits by children (Norris et al., 1999). Imperial County's childhood asthma rates, as measured by hospital discharge records, are the highest in California, and roughly three times the state average, as shown in Figure 19.

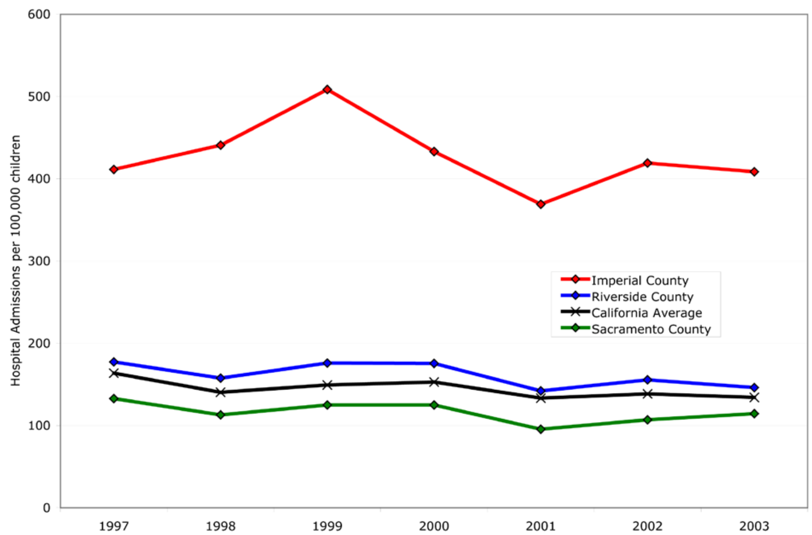

Figure 19. Childhood asthma hospital admission rates.

In November 2005, the Imperial County Air Pollution Control District adopted new rules and regulations, requiring actions to prevent, reduce, or mitigate PM_{10} emissions (among others).[48] These include actions such as wetting roads, phasing work in shifts, covering loads, etc. However, the overall impact of these new regulations may be to reduce current PM_{10} emissions in the county by as little as six percent (Lee, 2006).

Emissions will likely increase in future years. Inflow projections used here indicate that the Sea will recede from its January 1, 2003 elevation of -228.6' to approximately -233.6' by 2018, exposing 26.5 square miles (69 km^2) of currently submerged lakebed. By roughly 2036, when the Sea's surface elevation re-stabilizes at about -255', a total of approximately 134 square miles (350 km^2) of lakebed will be exposed. Exposure of about 52% of this acreage could be attributed directly to the implementation of the QSA (CH2M-Hill, 2005); the remainder would be caused by non-QSA factors (see *Hydrology*). This projected exposure raises several key issues:

- the percentage or extent of the exposed lakebed that can or will emit dust;
- monitoring and mitigation of emissive lakebed;
- cost and effectiveness of such mitigation;
- liability and responsibility for exposed lands; and
- potential impacts to human health, wildlife, and agricultural productivity.

The extent of the exposed lakebed that will generate more PM_{10} is not known. Several methods exist for estimating this extent. One is simply to assume the worst, that *all* exposed land will generate dust. Extrapolating from

46 California designates a nonattainment area when there was at least one violation of a State standard for that pollutant in the area. The U.S. EPA designates any area that does not meet (or that contributes to ambient air quality in a nearby area that does not meet) the national primary or secondary ambient air quality standard for the pollutant. For a map of "serious nonattainment areas" in California, see http://www.arb.ca.gov/desig/adm/fed_pm10_class.pdf

47 See http://www.arb.ca.gov/html/brochure/pm10.htm

48 See http://imperialcounty.net/ag/APCD RULES Nov 8 2005.pdf

estimates generated by using an Air Resources Board equation and further assuming no control or management (CH_2M-Hill, 2005) yields worst-case emissions of an additional 43 tons/day of fugitive windblown dust by 2018, and 215 tons/day more than current emissions by about 2036. This worst-case projection would more than double the total current estimated amount of fugitive windblown dust in the Salton Sea basin. A best-case scenario assumes that parts of the receding Salton Sea will form a cemented, non-emissive cover of desiccated salts on top of exposed seabed sediments, reducing blowing-dust problems (Enzweiler, 2006). Research is underway to determine the emmissivity of currently exposed lakebed.

Figure 20. Dust blowing off of the New River delta, December 23, 2004. Photo courtesy of M. Morgan.

In 2002, the Salton Sea Science Office organized a workshop of thirteen air quality experts to address the question of potential fugitive dust problems at the Salton Sea. The consensus opinion of those experts was that "episodes of windblown dust should be expected if there is a significant reduction in Salton Sea water levels" (Sculley et al., 2002, p. 22). Their report also states (p. 21):

> The variability of onshore conditions around the Salton Sea makes it almost certain that some areas of exposed lakebed sediments will have the potential for generating meaningful quantities of fugitive dust under some conditions. The Whitewater River delta area has a mix of sand and fine sediments which is conducive to wind erosion. Surface conditions in that area indicate that some localized wind erosion events have occurred.

On December 23, 2004, a local farmer photographed white clouds of dust rising off of exposed sediments on the westside of the New River delta, with winds reported at 15 mph (Figure 20). A wind station at Salton City documented more than 400 hours of wind speeds of 15 mph or greater in 1998 (Sculley et al., 2002).

The Salton Sea's vast scale suggests that even if a small percentage of the acreage exposed due to decreased inflows does in fact generate dust, the problems could be severe. Preliminary estimates[49] suggest that forty percent of the exposed lakebed could generate dust some of the time, meaning an increase in fugitive windblown dust of as much as 86 tons/day by 2036, roughly one-third of current total emissions in the Salton Sea basin. While this estimate is speculative, it does offer a general sense of the potential magnitude of increased dust emissions off of exposed Salton Sea lakebed.

The IID-SDCWA water transfer final environmental impact report describes a mitigation program to address potential dust emissions, but claims that such dust emissions were a "potentially significant, unavoidable impact" of the transfer (IID, 2003). Under various agreements, IID, the Coachella Valley Water District, and SDCWA assume responsibility for the first $133 million in environmental mitigation costs associated with the QSA. Such costs include, but are not limited to, mitigation for air quality impacts. The State of California accepted responsibility for mitigation costs associated with the transfer that exceed this amount.[50]

California's State Water Resources Control Board required the implementation of the following four-step monitoring and mitigation plan:[51]

> **Mitigation Measure AQ-7.**
>
> **1) Restrict Access.** Public access, especially off-highway vehicle access, would be limited, to the extent legally and practicably feasible, to minimize disturbance of natural crusts and soils surfaces in future exposed shoreline areas.
>
> **2) Research and Monitoring.** A research and monitoring program would be implemented incrementally as the Sea recedes. The research phase would focus on development of information to help define the potential for problems to occur in the future as the Sea elevation is reduced slowly over time.
>
> **3) Create or Purchase Offsetting Emission Reduction Credits.** This step would require

49 From an initial, speculative range of estimates offered by air quality experts at the Salton Sea Air Quality working group meeting in Ontario, CA, March 14, 2006.

50 See QSA Joint Powers Authority Creation and Funding Agreement, at http://www.crss.water.ca.gov/docs/crqsa/Parts/QSA_ST.pdf

51 SWRCB WRO 2002-0013, WRO 2002-0016.

negotiations with the local air pollution control districts to develop a long-term program for creating or purchasing offsetting PM_{10} emission reduction credits. Credits would be used to offset emissions caused by the Proposed Project, as determined by monitoring (see measure 2, above).

4) **Direct emission reductions at the Sea.** If sufficient offsetting emission reduction credits are not available or feasible, Step 4 of this mitigation plan would be implemented. It would include either, or a combination of:

(a). Implementing feasible dust mitigation measures. This includes the potential implementation of new (and as yet unknown or unproven) dust control technologies that may be developed at any time during the term of the IID Water Conservation and Transfer Project Proposed Project; and/or

(b). If feasible, supplying water to the Sea to re-wet emissive areas exposed by the IID Water Conservation and Transfer Project, based on the research and monitoring program (Step 2 of this plan). This approach could use and extend the duration of the Salton Sea Habitat Conservation Strategy. If, at any time during the Project term, feasible dust mitigation measures are identified, these could be implemented in lieu of other dust mitigation measures or the provision of mitigation water to the Sea. Thus, it is anticipated that the method or combination of methods could change from time to time over the Project term.

(CH2M-Hill, 2005)

If exposed lakebed generates more PM_{10} than can be offset through step 3, direct emission reductions would be required. Re-wetting exposed areas might be effective, but would divert water that would otherwise flow to the Sea, further shrinking the Sea, exacerbating its rise in salinity, and increasing the amount of exposed land. Assuming that forty percent of the exposed lakebed generates dust and that 52% of that amount could be attributed to the QSA transfers themselves (CH2M-Hill, 2005) would mean that about 28 square miles (73 km^2) of emissive surface could be attributed to the QSA transfers. For the sake of comparison, the emissive surface at Owens Lake is about 35 square miles (90 km^2) (Agrarian, 2003b). The cost of the Owens Valley dust reduction project currently exceeds $400 million (J. Anderson, 2005; McGreevy, 2005). The methods and costs of reducing possible dust emissions from exposed Salton Sea lakebed have yet to be determined. If water is applied directly to QSA-generated emissive soils on an acre-foot per acre basis,[52] approximately 20 KAF less water would flow into the Salton Sea, a reduction of about 3% from projected future average annual inflows.

52 The ratio proposed at the Salton Sea Advisory Committee meeting in Sacramento on March 16, 2006.

Liability

It is important to note that the State of California and the water transfer parties collectively are responsible for monitoring and mitigation only for those areas exposed due to the water transfer itself. The transfer FEIR assumed that the surface elevation of the Salton Sea would fall to -235' without the transfer; responsibility for the roughly 31 square miles of land exposed above this elevation rests with the land owner, and does not fall under the water transfer mitigation requirements. Management and mitigation responsibility for emissions from these lands would be determined by the pertinent local and regional regulatory agencies. The transfer-related exposure is estimated to be about 70 square miles of a total of about 134 square miles exposed by 2036; the 33 square miles exposed below -235' that do not result from the transfer would also be the responsibility of the property owner. Figure 21 depicts property ownership of the Salton Sea's lakebed. Note that IID and the federal government own most of the lakebed above -255' in the southern basin, but that the checkerboard-style land ownership in the north reflects a broad mix of interests, including the Torres-Martinez Desert Cahuilla Indians, CVWD, IID, the State Lands Commission, the federal government, and private landowners.

In addition to QSA-related reductions of inflows, other simultaneous reductions, such as decreased flows from Mexico, will occur. Since emissive surfaces will not be distributed uniformly within or between elevations, determining responsibility for the exposure of specific emissive surfaces will likely be contentious once the Sea's elevation drops below -235'. An additional source of contention will be the lack of clear title to some of these lands, which have been submerged for more than 90 years. Private landowners in particular might object to liability for lands exposed due to others' actions. PM_{10} emissions will continue while responsibility is being determined.

Other Air Quality Impacts

Various materials at the Sea can be carried by the wind as PM_{10}, including clay and silt from the sediments, and precipitated salts, selenium, and trace contaminants stranded on exposed land (see Figure 20, above). In addition to the public health hazard posed by PM_{10}, wind-borne dust and salt can impair crop production. Blowing dust and salt can coat plant leaves and clog stomata, impairing photosynthesis and plant respiration (EPA, 2004). Coarser materials, such as blowing sand, can damage plants structurally, increasing their susceptibility to pathogens (Azad et al., 2000). Blowing sand might not create an air pollution problem, but does cause an additional nuisance and can cause property damage, to farms, housing, road ways, railroads, and geothermal facilities.

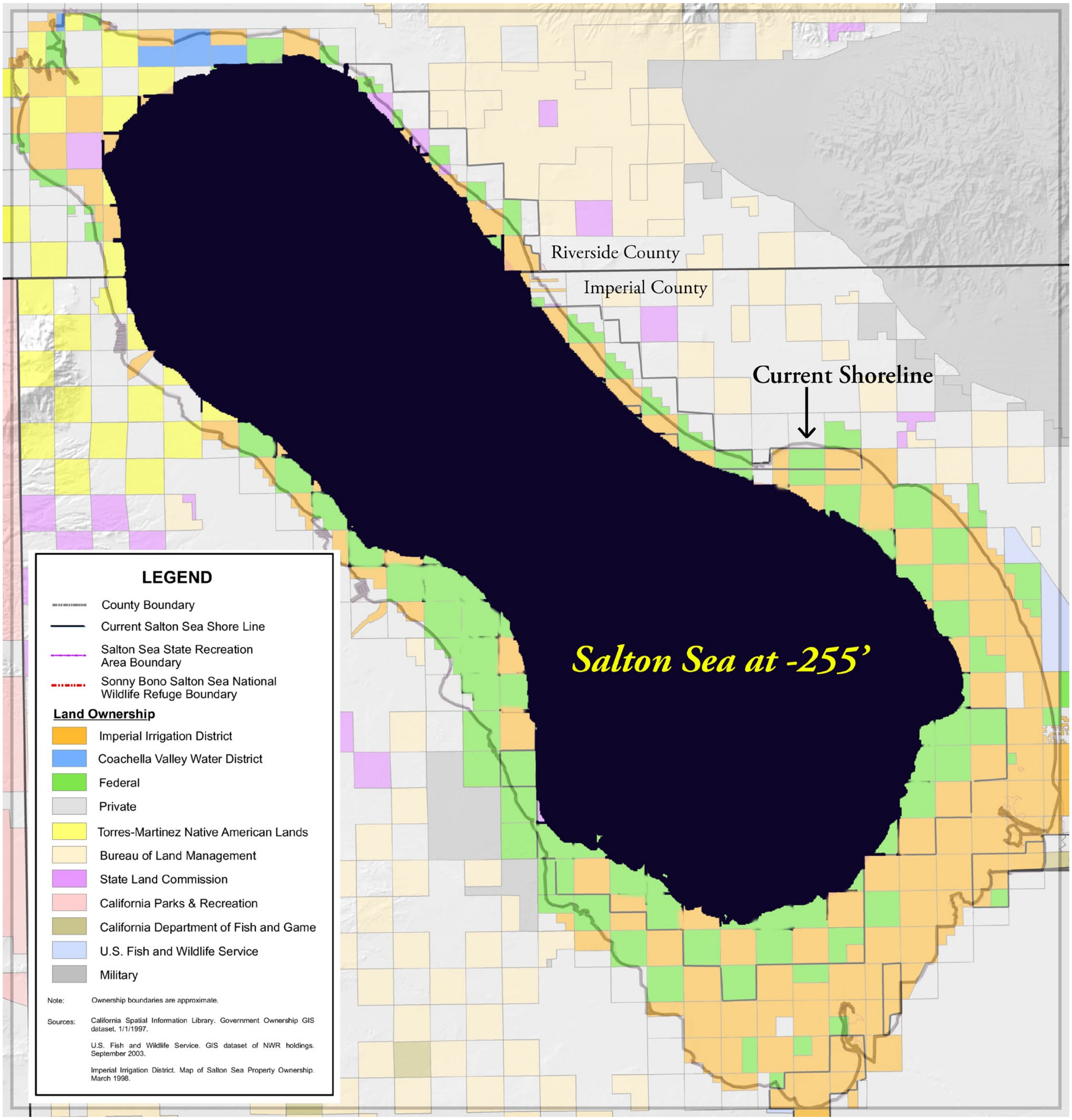

Figure 21. Approximate ownership of lands submerged by the Salton Sea. Source: base map adapted from Salton Sea Authority, http://www.saltonsea.ca.gov/SSea_ownership.pdf.

Farmers adjacent to the Sea have also expressed concern that the Sea's recession will eliminate the beneficial micro-climate effects it has on buffering temperature changes and increasing local humidity. More broadly, both the emissive and cemented salt-encrusted soils exposed by the receding Salton Sea would reflect much more sunlight than does the Sea itself, and more than surrounding soils, affecting local temperatures and increasing glare.

The Sea seasonally generates strong odors, often associated with hydrogen sulfide irruptions. Although the Sea's sediments will continue to produce hydrogen sulfide for another 25 to 30 years, and throughout the study period in estuarine areas, as the future Sea mixes more frequently, the strength of these odors will diminish. The Sea's period of rapid transition, from 2018 to roughly 2030, will cause wholesale changes in the Sea's biological composition and abundance. The first years of this transition will be marked by the extirpation of all of the Sea's remaining fishery (with the limited exception of those fish persisting in estuarine areas) and almost all of the Sea's macro-invertebrate community, as well as a large proportion of the existing micro-organisms. The rapid loss of much of the Sea's existing biomass could quickly overwhelm aerobic decomposers, producing strong odors. The Sea's rapid loss of surface area and volume would likely strand much of this decomposing biomass on the shoreline, further impairing aesthetics.

Sidebar - The Aral Sea

The Aral Sea ranks as one of the foremost ecological catastrophes of the 20th Century (Glantz, 1999; Stone, 1999). In less than half a century, its surface area has shrunk by more than 75% and its volume by 90% (Micklin, 2005). Toxic dust and salt blow off of its exposed lakebed, impairing human health, contaminating regional water sources, and depressing crop production. The region has lost more than 200 species of plants and animals due to these and related changes (Glantz and Zonn, 2005).

Figure 22. The Aral Sea, 1960 and 2005. Sources: 1960 image from http://www.life123.org/images/cotton/arialseamap.gif; April 8, 2005 image courtesy of NASA, available at http://visibleearth.nasa.gov/view_rec.php?id=6945.

In 1960, the Aral Sea extended across more than 26,000 square miles (67,500 km²) (about half the size of the State of Florida) in a terminal basin in Central Asia. At the time, it was the fourth largest lake in the world (Stone, 1999). In the first half of the 20th Century, two major rivers - the Amu Darya and the Syr Darya - annually discharged an average of 45 MAF (55 km³) into the Sea. At that time, its elevation remained fairly stable, at about 175 feet (53.4 m) above sea level (Micklin, 2005). Before about 1970, it supported 24 species of fish, sustaining an industry that employed about 60,000 people (Glantz and Zonn, 2005).

Starting in the late 1950s, the Soviet Union aggressively promoted irrigation in the Aral Sea watershed, especially for the cultivation of cotton (Glantz et al., 1993). Hundreds of miles of unlined canals were constructed in the region, diverting water from the Sea's tributaries (Stone, 1999). Even at that time, prescient observers noted that large-scale diversions would dramatically shrink the Sea, though their warnings were routinely ignored (Glantz, 1999).

From the late 1950s to 2001, inflows to the Aral Sea plummeted by 95%; the salinity of the new large lake increased by an order of magnitude, while that of the small north lake almost doubled, to about 17 g/L (Micklin, 2005). From 1960 to 2005, the surface elevation of the main body of the lake dropped by 76 feet (23.2 m) (Micklin, 2005). The Aral Sea is now three distinct bodies of water (Figure 22); in pessimistic scenarios, the east lake could disappear entirely (Glantz and Zonn, 2005).

The Sea has receded 93 miles (150 km) from the ports on its erstwhile southern shore. Since 1960, almost 20,000 square miles (51,000 km²) of lakebed have been exposed, leading to massive salt and dust storms that afflict a broad area (Micklin, 2005). The respiratory-related mortality rate among nearby communities ranks as one of the world's highest (Stone, 1999). As much as 250 tons of toxic dust and salt are deposited per acre of land, each year, in areas downwind (Micklin, 2005).

The Aral Sea shrunk gradually and incrementally. Glantz (1999) described these changes as a 'creeping environmental problem,' one that initially failed to generate broad political concern and action. Institutional obstacles, in the form of multiple jurisdictions and competing interests, further postponed action until the cumulative impacts generated a crisis (Glantz et al., 1993).

Yet recent efforts to restore part of the Aral have led to quick improvements. An 8 mile (13 km) dike across the strait linking the small north Aral Sea to main lake, completed in late 2005, has rapidly raised the level of the north lake, offering hope that at least a small portion of the Aral can be revitalized (Pala, 2006).

Estimated Conditions in 2017, 2047, and 2077

The following sections describe possible Salton Sea conditions in 2017, 2047, and 2077, at the end of the period of gradual change, at the end of the first transfer period, and at the end of the study period, respectively. These descriptions synthesize the changes described above, providing a broader picture of future conditions at a specific time. Owing to the uncertainty associated with any long-range forecast, the future states portrayed below should be viewed only as illustrative of one plausible set of conditions. Table 8 summarizes the biological changes.

Table 8. Estimated biological changes.		Possible Future Condition		
Biota	**2006**	**2017**	**2047**	**2077**
Viruses	Present and abundant (Wood et al., 2002)	Abundant	›	›
Sulfate-reducing bacteria	Present in anoxic sediments (Brandt et al., 1999; 2001)	Persist in sediments and anoxic porewater	‹	‹
Cyanobacteria	Present, including toxic species (Wood et al., 2002)	Salt-tolerant species persist	»	»
Phytoplankton	Present, with discrete blooms (Stephens, 1999a)	Blooms increase in size and frequency; salt-tolerant species persist	›	›
Benthic Algae	Present (Stephens, 1999a)	Turbidity limits growth. Abundant in shallow margins of sea	≈	≈
Pileworms	Present, but decreasing from anoxia and predation (Dexter et al., 2005; Detwiler et al., 2002)	Restricted to margins of estuarine areas where salinity is lower.	Ø	Ø
Barnacles	Present, but space-limited (Detwiler et al., 2002)	Loss of hard substrate habitat due to receding Sea.	Ø	Ø
Copepods	Present (Kuperman et al., 2002)	Restricted to margins of estuaries	Ø	Ø
Water boatmen	Present (Herbst, 2001)	Increase in abundance with loss of aquatic predators	Ø	Ø
Brine Shrimp	Absent (TetraTech, 2004)	Not currently found, but cysts transported by migrating birds.	»	›
Brine Fly	Present, but limited (Kuperman et al., 2002)	Increase in abundance with loss of aquatic predators	»	›
Tilapia	Present but <90% of 1999 population (Crayon et al., 2005)	Continued parasitic infestations and low DO stresses populations. Estuaries may provide limited future habitat	Ø	Ø
Desert Pupfish & Sailfin Molly	Present (Martin and Saiki, 2005; Crayon and Keeney, 2005)	Restricted to agricultural drains and shallow areas. Increase in population as predators decrease	Ø	Ø
Clapper Rails/ Wetland-dependent birds	Present (Shuford et al., 2000)	Possible increase in habitat via managed wetlands.	⁇	⁇
Landbirds	Present (Shuford et al., 2000). See Table 6 for total nesting pairs in recent years.	Urbanization and efficiency in agricultural water use will decrease habitat and food availability	‹	‹
Fish-eating birds	Present (Shuford et al., 2000). See Table 6 for total nesting pairs in recent years.	Limited prey abundance will limit population.	Ø	Ø
Wading birds	Present (Shuford et al., 2000). See Table 6 for total nesting pairs in recent years.	Loss of breeding and roosting habitats will decrease populations and increase crowding, increasing disease incidence.	›	‹
Waterfowl	Present (Patten et al., 2003). See Table 6 for total nesting pairs in recent years.	Decreased prey and increased distance between shoreline and wetlands may decrease populations.	›	«
Shorebirds	Present (Shuford et al., 2004). See Table 6 for total nesting pairs in recent years.	Some adapted to hypersaline conditions; others aggregate in managed wetlands and agricultural fields.	⁇	⁇
Gulls and Terns	Present (Shuford et al., 2004). See Table 6 for total nesting pairs in recent years.	Loss of breeding populations to reduced habitat and disease.	›	«

» much higher ≈ limited or no change ‹ lower Ø absent
› higher « much lower ⁇ unknown

Conditions 2017

By the end of 2017, the surface of the Salton Sea will have fallen about 5 feet (1.5 m) relative to its elevation in January, 2006, exposing more than 26 square miles (67 km^2) of previous submerged lakebed. Its volume will have shrunk by about 15%, and salinity will have risen to about 60 g/L. The Sea's hydrodynamics will be about the same as now, with extended periods of stratification and occasional, lethal releases of accumulated hydrogen sulfide and ammonia. The combination of agricultural water conservation practices, additional wastewater treatment plant capacity in Mexico, and implementation of Best Management Practices will reduce total external loadings of nitrogen and phosphorus, so that volumetric loadings to the Sea decrease, or remain roughly stable. At the end of 2017, the Sea will still be highly eutrophic, though primary productivity will be slightly lower than it is now.

Rising salinity and continuing anoxia along most of the lakebed will further reduce pileworm populations. The loss of hard substrates will diminish barnacle populations. In the absence of aquatic predators, water boatmen populations could rise dramatically, limiting the abundance of zooplankton. Tilapia populations will dwindle, due to diminishing prey availability, high infestation by parasites, reduced breeding success and recruitment, and stress from rising salinity and low DO concentrations. If unusually low temperatures or some other random event such as the introduction of a new disease organism occurred in the next decade, tilapia populations could be devastated beyond the point of recovery. Desert pupfish and sailfin mollies will increase in abundance, possibly to large populations, though continuing poor water quality will limit their breeding success.

Most fish-eating birds will have abandoned the Sea due to the much smaller prey base. Populations of colonial nesting birds will also decline, since the loss of islands and snags will decrease the availability of their preferred breeding sites. Shorebird and wading bird populations should be about the same, though grebes and ducks feeding in open water areas will suffer from the diminished availability of pileworms and other prey species. Selenium concentrations in birds may rise slightly, but probably not sufficiently to create significant impacts.

The exposure of 26 square miles of lakebed could generate an additional 17 tons of fine dust per day, impairing human health in the basin. Since this exposed land will all be above the -235' contour and not attributable to the QSA water transfers, under existing agreements the State of California and the transfer parties will not be liable for the dust blowing off of these lands (aside from their individual liability, if any, as owners of those lands). Current Imperial County Air Pollution Control District regulations require that property owners prevent, reduce, or otherwise mitigate dust emissions. The potential cost of managing such emissions has not been estimated, but certainly will be significant.

Conditions 2047

By the end of 2047, the Sea's surface elevation will have re-stabilized at about -255', more than 26 feet (7.9 m) below its present elevation, exposing 134 square miles (348 km^2) of lakebed (see Figure ES-3). The Sea's surface area will have contracted by 36%, but its volume will have shrunk by 70%. Salinity could exceed 230 g/L. Calcium and carbonate ions in the inflows will quickly bind and precipitate as calcite in estuarine areas; most of the remaining calcium ions will bind with existing sulfate in the Sea to precipitate as gypsum. The much smaller Sea will mix regularly, cycling organic matter, selenium, and trace contaminants back into the water column.

This internal cycling will more than offset any reductions in total external loadings of nutrients and selenium, which in any case will not decrease sufficiently to reduce volumetric loadings.

These abundant nutrients will fuel high levels of primary productivity, decreasing visibility. Brine shrimp will thrive on this abundant food base, possibly at higher densities than observed at the Great Salt Lake. High turbidity, due to mixing and high concentrations of organic and other suspended sediments in the water column, will probably restrict light penetration to about its current depth, limiting photosynthetic productivity atop the lakebed to areas less than about 5 feet (1.5 m) deep. However, even this limited margin encompasses more than 25 square miles (66 km^2) of lakebed, sustaining prodigious numbers of brine fly larvae.

Although fish-eating birds will have long since abandoned the Sea, the abundant invertebrate prey base will attract very large numbers of grebes, gulls, shorebirds, and ducks. These birds could suffer high mortality from diseases such as avian cholera and botulism, exacerbated by selenium toxicity caused by the high selenium concentrations in their prey. Breeding birds are especially susceptible to reproductive failure caused by elevated concentrations of selenium. Black-necked stilt populations, which suffered high mortality and reproductive failure at Kesterson NWR and currently breed at the Sea, could be devastated.

The broad estuaries formed by inflows at the south end will sustain a broader diversity of invertebrates than the main body of the Sea. Wind-driven currents will determine the extent and salinity gradients of these areas. If current wind patterns persist – which is far from certain given climate change projections – such estuaries will expand for weeks at a time. These conditions would enable colonization by species inhabiting the drains and rivers, though it is unlikely that stable populations will develop there, given their transitory nature. While they persist, they will provide an ample food base for a variety of birds.

The exposure of 134 square miles of lakebed could increase dust emissions in the basin by a third, causing respiratory problems in children and other sensitive populations, and possibly increasing the incidence of other health-related problems, such as heart attacks. Blowing dust will also reduce agricultural productivity in the Imperial and Coachella valleys, though the extent of such impacts has not been estimated. California and the water transfer parties will be liable for monitoring and managing dust emissions off of about half of the exposed land; remaining land will be the responsibility of the individual property owners. The costs of monitoring and managing exposed lakebed are not known, but could certainly exceed $500 million.

Conditions 2077

By the end of 2077, the Sea's surface will still be at about -255', but its salinity will exceed 300 g/L. Isolated and shallow pools at the Sea's edges will begin to precipitate halite (NaCl) and bloedite, and extensive crusts of calcite and gypsum will cover the shoreline. The Sea will still be biologically productive, though the high salinity will limit brine shrimp and brine fly larvae populations to the margins of the estuaries. Green algae and cyanobacteria will dominate the main body of the Sea. Figure 23 shows an orange-red layer of cyanobacteria and an underlying green layer of filamentous cyanobacteria, as well as the general abundance of cyanobacteria in the water and within the gypsum deposits in an evaporation pond with a salinity of 286 g/L (Oren, 2000). The reduced numbers of invertebrates will decrease bird use, though their populations will still be high. Disease and selenium toxicity will be common.

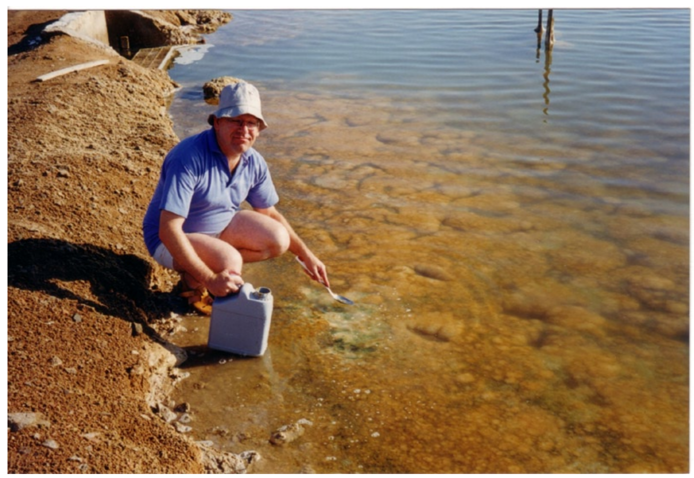

Figure 23. Cyanobacteria in a hypersaline pond. Courtesy of A. Oren.

Air quality will be similar to conditions in 2047. By this time, the higher exposed elevations will have endured more than 50 years of weathering. Periodic rainfall and possible groundwater movement could alter the structure of the salts stranded at these higher elevations. In some places, the desert may have begun to reclaim some of the higher elevations, though the expected heavy deposition of calcite and gypsum and other salts along the shoreline below -250' will preclude vegetation.

Conclusion

Without a restoration project, the future Salton Sea will change dramatically. Although the Sea will continue to be filled with life, even 70 years into the future, it will be more akin to a primordial soup than the fish-filled lake that attracted hundreds of thousands of tourists just a few decades ago. The impacts of the loss of this key stopover to migrating birds could be severe, especially given the increasing number of other impacts felt along their routes. Combined with the increased mortality due to disease and selenium toxicity, these changes could jeopardize the survival of entire species.

Worsening air quality could hinder economic development in the rapidly-growing lower Coachella and Imperial valleys, and especially along the Sea's current shoreline. If air quality in the two valleys degrades to the extent estimated by this report, the impacts to human health will be severe, especially among the children and retirees that live in these areas. Impacts to the local $1.5 billion agricultural economy are more difficult to quantify, but include damaged and ruined crops and the need for additional water to leach airborne salts from the soil.

Glantz (1999) captures the slow, incremental changes that devastated the Aral Sea as "creeping environmental problems." Without intervention, the Salton Sea will suffer a similar fate. Unlike an oil spill or a levee breaking, the gradual, at times imperceptible accumulation of slights and damages and injuries to the Sea will not be immediately apparent, though ultimately they too will be catastrophic. Eventually, the problems at the Salton Sea will constitute a crisis.

The creeping environmental problems at the Salton Sea will carry exorbitant costs, in terms of human health, ecological health, and economic development. As California and Congress decide whether and how to move forward with restoration of the Salton Sea, the high cost of funding a Salton Sea restoration project must be weighed against the catastrophic long-term costs of doing nothing.

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Appendix A

Abbreviations

CDFG - California Department of Fish & Game

cfs - cubic feet per second

CIMIS - California Irrigation Management Information System

CVWD - Coachella Valley Water District

DO -dissolved oxygen

DWR - California Department of Water Resources

EPA - U.S. Environmental Protection Agency

FWS - U.S. Fish and Wildlife Service

g/L - grams per liter

IID - Imperial Irrigation District

KAF - thousands of acre-feet

MAF - millions of acre-feet

mg/L - milligrams per liter

µg/L - micrograms per liter

PM_{10} - particulate matter less than 10 microns in diameter

ppt - parts per thousand (eg, mg/g)

QSA - California's Quantification Settlement Agreement

Reclamation - U.S. Bureau of Reclamation

RWQCB - Regional Water Quality Control Board

SDCWA - San Diego County Water Authority

TDS - total dissolved solids

Glossary

Acre-foot - 325,851 gallons of water, sufficient to cover an acre of land a foot deep.

Anoxic - without oxygen

Benthos - the bottom of a sea or lake, or the organisms living there

Hypolimnion - the bottom layer of a stratified lake

Precipitate - in chemistry, to cause a solid to settle out of a solution

Appendix B

Quantification Settlement Agreement Delivery Schedule By Conservation Method

QSA Year	Calendar Year	IID and SDCWA	IID and CVWD a,	IID and MWD	Total Delivery	Total Efficiency	Fallowing for Delivery	Mitigation Fallowing	Total Fallowing
1	2003	10	0	0	10	0	10	5	15
2	2004	20	0	0	20	0	20	10	30
3	2005	30	0	0	30	0	30	15	45
4	2006b	40	0	0	40	0	40	20	60
5	2007	50	0	0	50	0	50	25	75
6	2008	50	4	0	54	4	50	25	75
7	2009b	60	8	0	68	8	60	30	90
8	2010	70	12	0	82	12	70	35	105
9	2011	80	16	0	96	16	80	40	120
10	2012b	90	21	0	111	21	90	45	135
11	2013	100	26	0	126	46	80	70	150
12	2014	100	31	0	131	71	60	90	150
13	2015	100	36	0	136	96	40	110	150
14	2016	100	41	0	141	121	20	130	150
15	2017	100	45	0	145	145	0	150	150
16	2018	130	63	0	193	193	0	0	0
17	2019	160	68	0	228	228	0	0	0
18	2020	192.5	73	2.5	268	268	0	0	0
19	2021	205	78	5	288	288	0	0	0
20	2022	202.5	83	2.5	288	288	0	0	0
21	2023	200	88	0	288	288	0	0	0
22	2024	200	93	0	293	293	0	0	0
23	2025	200	98	0	298	298	0	0	0
24	2026	200	103	0	303	303	0	0	0
25	2027	200	103	0	303	303	0	0	0
26	2028	200	103	0	303	303	0	0	0
27 to 45	2029 to 2047	200	103	0	303	303	0	0	0
46 to 75c	2048 to 2077	200	50	0	250	250	0	0	0

All values in thousands of acre-feet (KAF).

a If CVWD declines to acquire these amounts, MWD has an option to acquire them, but acquisition by MWD of conserved water in lieu of CVWD during the first 15 years is subject to satisfaction by MWD of certain conditions, including subsequent environmental assessment.

b In addition to the conserved amounts shown on this table, additional amounts of up to 25,000 acre-feet in 2006, 50,000 acre-feet in 2009 and 70,000 acre-feet in 2012 could be conserved to meet the Interim Surplus Guidelines (ISG) benchmarks. IID has the discretion to select the method of conservation used to make the ISG backfill water. If fallowing is selected to conserve water to meet the ISG benchmarks, the total acres of fallowing would be within the amount originally evaluated in the EIR/EIS.

c This assumes that the parties have approved the extension of the 45-year initial term of the IID Water Conservation and Transfer Project.

Source: IID (2002).

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May 2006