

**The Salton Sea: Geology, History, Biology, Potential Problems, Politics, and  
Possible Futures of an Unnatural Desert Salt Lake**

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## TABLE OF CONTENTS

Abstract	2
Introduction	3
Geological Setting and Geological History of the Salton Triangle	6
Origin of the Below-Sea Level Salton Trough and its Pleistocene and Holocene Lakes	17
Formation of the Salton Sea and its Recent History	34
Sources of Water to the Salton Sea	52
Chemical and Physical Limnology	57
The "tideless intertidal" Zone	63
Mini-estuaries	64
Shoreline Pools	66
Biology of the Salton Sea	67
Invertebrates and Aquatic Plants	68
Amphibians, Reptiles and Mammals	96
The Sport Fish and Sport Fishery	97
Other Fish	112
Birds	125
Food Chains and Webs	132
Is the Salton Sea Polluted?	144
Public Health	157
Cleaning Up the New River	162
Energy Development in the Salton Sea	164
Water Politics and the Salton Sea	168



Possible Futures for the Salton Sea	177
“Restoration” of the Salton Sea	182
Conclusions	207
Acknowledgments	207
Literature Cited	210

*Abstract.* — The Salton Sea is the second-largest lake in the western US, lying at the bottom of the largest below-sea level depression in the Western Hemisphere. The Salton Trough is geologically active: the western side is being rafted away from mainland North America through crustal spreading along the East Pacific Rise. The most recent of a series of lakes in the Salton Trough, the present Salton Sea began with the Colorado River breaking through ineptly built irrigation works and flooding the Salton Sink from 1905 to 1907. Even had that event not occurred, the Salton Sea would be exactly the same size and composition today. Virtually all inflowing water is nutrient-rich agricultural wastewater ultimately derived from the Colorado River. The Sea's current salinity is about 130% of normal ocean seawater, and its ionic composition is similar to seawater. The Sea's biology is remarkable. The Sea is hypereutrophic and all larger biota are introduced from outside the Salton Trough, forming a strange quasi-marine ecosystem, remarkable for being detritus-based rather than plankton-based, as there are no significant larger planktivores in the Sea. The Salton Sea has the most productive sport fishery in the US and is a vital stopover for migratory birds of the Pacific Flyway. Major die-offs of fish and birds have increased concern about the biological future of the Sea, though such die-offs have actually occurred for decades. As a terminal lake in a closed basin, the future for the Salton Sea probably involves increased salinity, loss of the sport fishery, and other severe biological problems. Diverse proposals have been made to "restore" the Salton Sea, though to what previous state is not at all clear. Most proposals deal only with salinity, ignoring all other potential problems, such as pathogens, parasites, pollutants (not now a problem), and eutrophication. As a result, the Salton Sea's strange ecosystem is not likely to survive for more than a few decades,

## Introduction

The Salton Sea is the largest lake in California and second largest in the American West after the Great Salt Lake in Utah. The Sea is in the Colorado Desert of southeastern California in the bottom of the Salton Trough, the largest below-sea level depression in the Western Hemisphere. See Fig. 1 for a political map of the Salton Sea area. The Salton Trough has been at various times a series of large freshwater lakes (the latest of which may have dried up as recently as 300 to 600 yr ago), a desert playa called the Salton Sink, and now a human-created and artificially-maintained saline desert lake. Marine incursions into this region took place only before the present below-sea level depression developed.

The Salton Sea's quasi-marine ecosystem and trophic structure are unlike those found in any other body of water in the world, being based on benthic detritus formed by decaying plankton, and with the ecologically significant organisms all introduced from somewhere else, often from far away and usually accidentally. The hypereutrophic Sea harbors the most productive sport fishery in California if not the entire US. The Sea, surrounding riparian habitats, and agricultural fields are an oasis of water, food, and cover attracting vast numbers of birds, especially wintering migratory waterfowl and shorebirds, but also summer rarities wandering north from México.

The present Salton Sea was created from 1905 to 1907 by illegal and inept agricultural water diversion from the Colorado River, but would be just the same size and chemical content today had its peculiar origin not happened nearly a century ago. From its lowest elevation in 1925 the Sea has risen more or less steadily to the present. Unless major and expensive intervention is successful, the probable future of the Salton Sea is for the salinity, now as high as 47‰ (134% of ocean seawater of 35‰), to rise to a concentration that will prevent reproduction by the major sport fishes. As a consequence the most productive sport fishery in the state, with 1.5 million recreation days annually in the 1980s and an average catch of 1.5 to 1.9 fish·angler<sup>-1</sup>·hr<sup>-1</sup> (Black 1974; Black et al.

1985; Costa-Pierce and Riedel 2000), will collapse.

The number of campers at campgrounds in the Salton Sea State Recreation Area along the east shore dropped by  $\frac{2}{3}$  since the mid-1980s. The number of fishers similarly declined, apparently due both to negative publicity about unhealthy concentrations of trace elements, pesticides, and other pollutants supposedly in the sport fish and to rumors that the sport fishery is collapsing because fish cannot reproduce in the increasingly saline waters. Neither problem is in fact true. Pollution has never been a problem in the Salton Sea, and while there have been pessimistic predictions for the past 30 or 40 yr that the sport fishery will soon collapse from increasing salinity, it has not happened yet. Bird hunter use of state and federal wildlife refuges near the Sea has declined more than the national average decline of 8% between 1980 and 1995 (Aiken 1999), though sport bird abundance has not changed. Shoreline resort communities are not thriving, both because of reduced tourism and because rising Sea level has inundated houses, house trailers, motels, shops, marinas, jetties, roads, utility poles, and trees -- which now pose navigational hazards as well as attracting fish and fishers.

A *Science News Focus* article in April 1999, alarmingly headlined "Battle Over a Dying Sea," quoted some biologists and wildlife managers to the effect that the Salton Sea was not worth keeping biologically viable because its problems were severe and incurable, but this widely read article did not even hint at the many decades of annual die-offs of fish and birds predating "alarming" die-offs in the 1990s, nor did it recognize that the Sea is not polluted (Kaiser 1999). A second news article by Kaiser (2000) was equally erroneously headlined, "Bringing the Salton Sea back to life." Hypereutrophic, the Sea is not now, and never has been, "dead;" rather, it is burgeoning with life.

Novelist Joseph Wambaugh trashed the Salton Sea in his riveting 1992 mystery, *Fugitive Nights*. Wambaugh's protagonist, a disillusioned Palm Springs cop, is tailing what he thinks is a cheating husband to a desert tryst: "He was wondering why a rich guy like Clive Devon would hang around this dying place. Even the lowliest desert denizens

had just about given up on the Salton Sea. That morning the wind was blowing a foul algae-sewage smell his way. The smell of red tide was blowing in his direction, and from a distance the polluted water looked like it had a crust you could walk on.” deBuys (1999) painted a gloomy picture of major fish and bird die-offs in the 1990s from disease, pollution, and eutrophication. The Archaeological Conservancy’s President Mark Michel (2000) called the Salton Sea “one of America’s biggest ecological disasters.” Much of the commentary on the World Wide Web about the Salton Sea is similarly pessimistic.

Are these worries justified? Probably not. Is the Salton Sea now an ecological disaster? Not yet. For example, read Jim Matthew’s Hot Spots section of his Fishing Report for 26 May 1999 in the Ontario CA *Inland Valley Daily Bulletin* : “SALTON SEA: The corvina bite exploded this past weekend over much of the sea with limits taking less than an hour, unless you were releasing the smaller fish. Five-fish limits typically weighed around [22.7 kg] total with a few over [4.5 kg] and a few under [4.5 kg]. Biggest fish reported in the [8.2 kg] class. The bite has spread over much of the sea. The tilapia bite is also awesome with catches of 150 to 200 tilapia a day common, especially in the northern half of the sea.”

This review summarizes the geological setting and origin of the below-sea level Salton Trough; formation of both Pleistocene and Holocene freshwater lakes (Lake Cahuilla); origin and history of the present Salton Sea; ecology of its biota including sport fish and birds; problems -- both real and potential -- faced by the Salton Sea and its biota; some possible futures; and federally-funded plans to “restore” or “save” the Salton Sea. Because the Salton Sea is totally dependent upon irrigation wastewater ultimately derived from the Colorado River and because many euryhaline biota move freely between the Sea and agricultural waters, the biology of these latter habitats will also be reviewed. For the same reason, the politics of agricultural water use, particularly in the Imperial Valley, must be discussed.

The many undocumented facts and ideas about aquatic ecology, anatomy, biology

and ecology of the biota, and geology in this review derive from my teaching research-focused courses in these topics at colleges, universities, and marine biology laboratories over four decades.

### **Geological Setting and Geological History of the Salton Trough**

The Salton Sea lies in the bottom of a 7722 km<sup>2</sup> below-sea level depression, the Salton Trough, in the Colorado Desert of southeastern California. It is the largest below-sea level depression in the Western Hemisphere and second deepest, only 2 m less deep than California's Death Valley, but that part of Death Valley below sea level is much smaller in area (2124 km<sup>2</sup>). The total drainage area of the Salton Trough into the Salton Sea is 32,300 km<sup>2</sup>, but since the Salton Sea is fed almost entirely by agricultural wastewater from the Colorado River, its watershed is effectively that of the entire Colorado River (~934,000 m<sup>2</sup>, or about 8.3% of the total land area of the continental US: Fradkin 1981) upstream from its last tributary, the Gila River that drains southern Arizona, part of New Mexico, and northern Sonora in México, and which enters the Colorado at Yuma AZ.

The Salton Trough is bordered on three sides (west, north, east) by mountain ranges, highest at the northern end and declining in elevation southerly on both east and west sides. The southern end of the Trough is composed of the low, broad fan delta of the Colorado River, separating the Trough from the Gulf of California (see **Fig.** ).

The intensively cultivated Coachella Valley, northwest of the Salton Sea, begins at San Geronio Pass (sometimes called Banning Pass, 883 m) between the two highest mountains in southern California, Mount San Geronio (3450 m) and Mount San Jacinto (3288 m). To the south of the Sea is the even more intensively cultivated Imperial Valley, continuous with the Valle de Mexicali south of the Mexican border southerly to the crest of the sedimentary delta dam. These three broad, nearly flat, "valleys" were not carved by river erosion, but constitute parts of the tectonically-created Salton Trough. The

Trough is clearly a northwards extension of the axis of the Gulf of California (Sea of Cortez, Golfo de Cortés, Vermilion Sea). The Trough is narrowest (~20 km) at its northern end in the northern Coachella Valley, widens gradually to ~60 km at the international border, and increasingly widens southerly as the Gulf of California.

Norris and Webb (1990) used the term Salton Trough (which they synonymized with Salton Sink) for the entire basin from San Geronio Pass to the Gulf of California, and restricted the term Salton Basin only to the region draining directly into the Salton Sea. No one else has adopted this confusing nomenclature, and the two terms (Basin and Trough) will here be treated as synonymous; the name Cahuilla Basin has sometimes been applied to the Coachella Valley. The term Salton Sink will be used only for the salt playa that occupied the bottom of the Trough when no lake is present.

The Salton Trough is separated from the Gulf of California by a broad low-conical alluvial dam composed of Colorado River sediments, 224 km in north-south extent, with its gentle crest ~16 km wide (north to south) and ~60 km (east to west) across just south of the Mexican border; its elevational apex is at Yuma AZ, 32 m (Fig. 2). The lowest point on the delta dam, on its western edge at Laguna Volcánica (Volcano Lake) in México a few km south of the California border, is only ~10 m above ocean sea level in the Gulf. At its fullest, Laguna Volcánica is up to 5 m deep, 16 km by 9.6 km, and marshy (Cory 1913, 1915). The sediments of the delta came from the Colorado River's excavation of the Grand Canyon, a geologically-recent event that began during the Pliocene, 2 to 4 million yr ago (Lucchitta 1990); deltaic sediments in the southern Imperial Valley and Valle de Mexicali are up to 6.5 km thick (Winspear and Pye 1995; Hunter 1998a).

Geologist William Phipps Blake named the Colorado Desert in 1853, before Colorado itself became a state (Blake 1854, 1914a, 1915), a name he applied to the entire watershed of the Salton Trough and lower Colorado River in California, Arizona, Baja California, and Sonora (Lindsay 2001). The name is now generally restricted to the low desert west of the Colorado River in California. Biologically, the Colorado Desert of



California is a northwesterly extension of the Sonoran Desert of northern México, southern Arizona, and southwestern New Mexico.

Recent volcanism, mud pots and mud volcanoes, CO<sub>2</sub> wells, hot springs, and numerous recent earthquakes all testify to the great geological activity of the Salton Trough. It is bounded and cut internally by many active faults, most notably the San Andreas Fault on the east side, the San Jacinto and Elsinore Faults on the west side, and a number of smaller faults in the Imperial Valley and Valle de Mexicali; all are right-lateral strike-slip faults (Fig. 3). The average right-lateral displacement on the San Andreas Fault system is 20-35 mm-yr<sup>-1</sup>, but there is no current movement along that Fault in the Salton Trough; rather, strain relief is shifted both east (to the East Mojave Shear Zone) and the west (to the San Jacinto and Elsinore Faults, along with many subsidiary faults). Over 60 strong earthquakes have been reported in the Salton Trough since 1900; ~75% have been of M (Richter magnitude) 5.0 or greater, with 1/3 of these over M 6.0; many of these quakes have involved the San Jacinto Fault (US Department of the Interior and The Resources Agency of California 1974a,b). Several large quakes have caused significant damage to buildings, roads, and irrigation structures. The largest in the 20th century, a M 7.1 18 May 1940 quake on the Imperial Fault, killed seven people, had a maximum right-lateral offset of 5.8 m, offset both the Mexican Alamo and US All-American Canals and adjacent international border by 4.6 m, and caused vertical displacements of over 1 m (US Department of the Interior and The Resources Agency of California 1974a,b). A M 7.1 quake in 1892 on the Laguna Salada Fault (a southerly extension of the Elsinore Fault) west of Cerro Prieto in México caused a maximum vertical displacement of 3.5 m (Winspear and Pye 1995). Had current geothermal facilities been as fully developed prior to the last strong quakes (M 6.2 and 6.6 on 23 and 24 November 1987, on the Superstition Hills Fault southwest of the Sea) as they are now, they surely would have been seriously damaged, likely causing brine spills into agricultural drains and then into the Salton Sea. The west side of the Salton Trough and Baja California are on the Pacific



tectonic plate, the east side of the trough and mainland México are on the North American plate. The many faults and earthquakes testify to the intensity and speed of the plates' movements relative to each other.

In addition to lateral offsets from fault ruptures, other geological hazards that must be addressed to protect the ecosystems of the Salton Sea, and adjacent rivers, canals, and drains include ground shaking, unstable slopes, liquefaction, differential settlement and subsidence, and lateral spreading. Because of the active faults in the Salton Trough, many of the proposed projects to "restore" the Salton Sea are within the state's Alquist-Priolo Special Studies Zone, in which special restrictions on development and construction apply (Salton Sea Authority 2000).

Alluvial deposition from the Colorado River, meandering stream deposits, lacustrine deposits from Pleistocene and Holocene freshwater lakes (both central lake muds and coastal beach sands), alluvial and braided stream deposits shed from adjacent mountains, eolian sand deposits, and present-day agricultural practices have all obliterated most direct surface manifestations of these faults on the floor of the Imperial Valley and elsewhere in the Salton Trough (van de Kamp 1973; Remeika and Sturz 1995). Elders et al. (1972) and Crowell and Sylvester (1979a) discussed in detail the geological origin of the Salton Trough, which is only summarized here.

The east side of the Coachella Valley and Salton Sea is dominated by geological features associated with the San Andreas Fault system (Corona 1993a,b). A chain of rugged desert mountain ranges forms the eastern boundary of the Trough, only some of which are sketched in Fig. 1. From northwest to southeast these are: the San Bernardino, Little San Bernardino, Cottonwood, Orocopia, Chocolate, and Cargo Muchacho Mountains, and Ogilby Hills. The San Bernardino Mountains are the highest range in southern California, with summits from 3000 to nearly 3500 m. Summits in the more southerly ranges rarely exceed 1500 m and are mostly lower than 1000 m. Between eastside mountains and the Coachella Valley and Salton Sea is a linear array of low hills

within the Salton Trough: Indio, Mecca, and Durmid Hills, and the Algodones Dunes (Sand Hills, Imperial Sand Dunes) which extend across the border into México. These eastside mountains, low hills, and dune systems are aligned parallel with the San Andreas Fault. There are no equivalent low hills on the west side.

East of the Salton Sea itself the San Andreas Fault is only a single strand rather than the splay of sub-parallel faults further northwest in the Coachella Valley and San Geronio Pass (Fig. 3; Dibblee 1977). This single southernmost strand of the San Andreas Fault, extending southeast from the convoluted and strongly eroded Indio and Mecca Hills, has been seismically inactive in recent times. Sieh and Williams (1990) presented evidence for several major quakes on the Indio fault segment in the last 1000 yr, the most recent of which occurred ~300 yr ago. The southernmost point where surface manifestations of the San Andreas Fault can be seen is at Bat Caves Buttes at the southern end of the Durmid Hills. Just north of Bat Caves Buttes, Salt Creek (sometimes called Salton Creek) enters the Salton Sea, draining a large watershed extending well east of the Orocopia and Chocolate Mountains. In wetter times Salt Creek formed a large alluvial fan that now composes much of the east shoreline of the Salton Sea. Salt Creek is offset 850 m by the San Andreas fault just ~0.3 km upstream from the State Highway 111, the railroad bridge, and the creek's mouth into the Salton Sea, and is incised as much as 40 m into its alluvial fan due to recent uplift along the axis of the fault (Babcock 1974; Baldwin et al. 1997).

The Durmid Hills north and south of Salt Creek are composed of soft lacustrine deposits dating only to the Pleistocene, much deformed into a system of east-trending folds arranged in a right-stepping *en echelon* pattern oblique to the northwest-southeast axis of the San Andreas Fault (Dibblee 1977; Burgmann 1991; Corona 1993a,b; Baldwin et al. 1997). The Durmid Hills are a rising anticline whose axis is parallel to the San Andreas Fault and whose rapid present-day uplift is demonstrated by its youthful drainage pattern. Direct measurements showed the Durmid Hills rising at the rate of 1

mm·yr<sup>-1</sup> between 1985 and 1987. This rate has persisted over the past ~1 million yr, based on stratigraphic studies of the 40 m incision of Salt Creek (Sylvester 1988; Sylvester et al. 1993) and the known age of a layer of Bishop Tuff (or Ash). The white Bishop Tuff (rhyolite ash) is an aerial deposit from a massive volcanic eruption of the Long Valley caldera on the east side of the Sierra Nevada south of Lake Tahoe ~760,000 yr ago (Burgmann 1991); it is exposed in complex folds both in the Mecca Hills to the northeast of the Salton Sea (M. Rymer, pers. comm.; Oglesby pers. obs.) and in the Coyote Badlands of Anza-Borrego Desert State Park to the southwest of the Salton Sea (M. Rymer 1991, pers. comm.; Corona 1993a,b). Curiously, the Durmid Hills uplift stopped completely after the M 7.3 June 1992 Landers earthquake well to the north in the Mojave Desert (M. Rymer pers. comm.). Following that quake there was “sympathetic” right lateral movement (triggered slip) of the San Andreas Fault in the Coachella Valley, creating 1 to 20 mm dextral surface breaks discontinuously over 54 km from the Indio Hills to Bat Caves Butte, with minor, ~1 mm, vertical slip in the Mecca Hills. These slips occurred within 1 min of the Landers mainshock. Dextral triggered slip had been observed in this same area from three recent large earthquakes in the Imperial Valley and northern Coachella Valley (M. Rymer 2000, pers. comm.).

It is now believed that the San Andreas Fault itself has its southern terminus just south of Bat Caves Buttes, with a 40 km gap separating it from the northern end of the Imperial Fault to the southwest. The several faults in the Imperial Valley between the southern end of the San Andreas Fault on the east side and the westside San Jacinto and Elsinore Faults step *en echelon* across the southern Salton Sea, Imperial Valley, and Valle de Mexicali from northeast to southwest. In this 40 km gap is the northernmost crustal spreading center (pull-apart zone) of the East Pacific Rise, here called the Brawley Seismic Zone (Fig. 3). This fault gap generates earthquake swarms and displays strong geothermal and volcanic activity. A flurry of small earthquakes in October and November 1999 at the southern end of the San Andreas Fault was apparently triggered by the M 7.1

October 1999 Hector Mine earthquake epicentered east of the Landers quake epicenter in the Mojave Desert (Hunter 2000; Scientists of the US Geological Survey 2000). Later, a swarm of over 30 small (the largest M 4.3) took place on one day near the southern terminus of the San Andreas Fault at Bat Caves Butte. Quake activity continues near Obsidian Butte, ongoing since 1989 (Scientists of the US Geological Survey 2000).

Together, these geological activities demonstrate a major change in crustal deformation processes: a transition between the San Andreas right-lateral strike-slip system to the ridge-transform system of the East Pacific Rise in the Gulf of California -- one of the few places on earth where zero age crust is being created at an active plate margin within a continent (R. D. Brown 1990; Herzig and Jacobs 1994; Johnson et al. 1994; Glockhoff 1998). The next southerly crustal spreading center of the East Pacific Rise underlies the Cerro Prieto volcanic area on the west side of the Valle de Mexicali (Fig. 4); the next one south of Cerro Prieto is under the very northern Gulf of California (Elders 1979c; Irwin 1990; Corona 1993a,b; Remeika and Sturz 1995; Residencia General de Cerro Prieto 1998). Evidence indicates that the East Pacific Rise and Gulf of California rift system are actively extending northerly into the Salton Trough (Larson and Reilinger 1991).

At the southeast end of the Salton Sea, within the Brawley Seismic Zone, are five Holocene volcanic buttes in a northeast-southwest alignment, rising 35 to 40 m above the valley floor (Figs. 1 and 5). Their current names (from northeast to southwest) are Mullet Island (-57.9 m), Red Hill (-41.8 m) joined with Alamo Butte (-38.7 m), Rock Hill (-41.5 m), and Obsidian Butte (-36.9 m), but other and often confusing names have been used for them in the past (Fig. 1); the name Obsidian Butte has been used for at least two different buttes as well as for the entire group of five. Cahuilla Chief Francisco Patencio and ethnographers such as Bean used the names Paint Island, Pelican Island, Three Buttes, and Mullet Island, but how these four older names translate to the five present buttes is not known (Patencio 1971; Bean et al. 1991). The buttes were formed between

55,000 and 2000 yr ago, either as underwater extrusions of magma (Red Hill) or as single aerial explosions (Obsidian Butte, Rock Hill) (Kelley and Soske 1936; Muffler and White 1969; Robinson et al. 1973; Korsch 1974; Elders 1979c; Hunter 1998a). Norris (1995a) concluded, "The Obsidian Buttes are probably only a few thousand years old, at most." When Lake Cahuilla was at its still-stand elevation of ~10 m above ocean sea level (see below), these buttes would have been completely submerged. At the high point of the new Salton Sea in 1907 all five buttes were islands; since then, the four southern buttes were re-connected to the mainland by desiccation of the Salton Sea (Fig. 5). The four southern buttes would today all be islands, but are connected to the mainland by raised road dikes (Oertle 1964; Oglesby pers. obs). Land access to Mullet Island was cut off by rising Salton Sea waters in the 1940s and the buildings on it abandoned.

Tufa ( $\text{CaCO}_3$ ) deposits occur on all five buttes, indicating that they were covered by at least one iteration of Lake Cahuilla (see below). The buttes are composed of acidic rhyolite and several have obsidian flows; active fumaroles occur on at least three buttes (Oglesby pers. obs.). These buttes were a major source of obsidian for Indian arrowheads throughout southern California (Patencio 1971; Koerper et al. 1986; Salton Sea Authority 2000); they are also the source of the pumice ("the rock that floats") that washes ashore all around the Salton Sea. Between 1934 and 1972, Red Hill moved southeast ~15 cm ( $0.4 \text{ mm}\cdot\text{yr}^{-1}$ ) relative to Obsidian Butte (Hunter 1998a), a right-lateral slip in the Brawley Seismic Zone that did not involve active seismicity. Elders (1979c) concluded that the processes operating to form the five buttes were consistent with those operating at oceanic crustal centers.

A resort called Hell's Kitchen, named for nearby mud volcanoes, was started on Mullet Island in 1908 and lasted into the 1930s. de Stanley (1976) paraphrased a 1852 report by a Major Hutchinson: "a great eruption of hot water and mud, with jets of steam, issuing from conical hillocks. Masses of dark-colored mud were thrown to a height of [12.5 m]." Patencio (1971) described them: "There were acres of boiling mud springs

all around. They were very hot. They boiled and hissed. No one could get close to them, for the ground was very sticky and the air was poisoned with gas. The hot gray mud piled on itself until it rose [5.1 to 6.7 m] in the air. Then it fell, to build up once again. The steam rises from the center of the mud stacks and at the top, mud could be seen jumping and whirling. Many lives have been lost going too near them. The crust of the ground breaks under one's feet. One is apt to disappear into the hot mud forever. The Indians called the place *Par-Powl*, which means water bewitched, and they stayed away.” No terrestrial mud volcanoes in the Salton Trough are remotely this active today; the Mullet Island field is now under water. Geothermal exploration began near Mullet Island in 1927 (Wynn 1975) but was soon abandoned because of the highly saline and erosive groundwaters brought to the surface.

The Cerro Prieto area just south of the Mexican border on the west side of the sedimentary deltaic fan is volcanic, with Laguna Volcánica, on the low point (~10 m) of the broad crest of the delta dam, being named for this feature (Figs. 2 and 4). Volcán Cerro Prieto (a basalt cinder cone, 260 m) has not erupted in historic times, but based on the lack of erosion of the cone after its one eruptive event, must be youthful (Elders 1979c; Lindsay and Hample 1998). The Cerro Prieto area has active mud pots and mud volcanoes, hot springs, and geothermal fields, commercially exploited beginning in 1958 (Residencia General de Cerro Prieto 1998).

A large salt playa occupies the closed and somewhat below-sea level Pattie Basin to the southwest of Cerro Prieto on the west side of Sierra de las Cocopás (Cocopah Mountains), called Laguna Salada (Mexican name) or Laguna Maquata (Indian name) (Figs. 2, 4, and 6; Sykes 1914, 1915, 1937; Carpelan 1961a; Elders 1979c). Laguna Salada, when filled with water to its maximum elevation, is ~64 km by 32 km and is supposedly occasionally filled by extremely high tides (~10 to 13 m; Sykes 1915) in the northern Gulf of California (Residencia General de Cerro Prieto 1998). Laguna Salada also receives agricultural wastewater from México (Fig. 6). Elders (1979c) and Quintanilla



Montoya and Suarez Vidal (1996) concluded that the mechanism of magma generation at Cerro Prieto was not related to crustal spreading. Glowacka and Nava (1996) proposed that withdrawal of geothermal fluids from the Cerro Prieto field triggers sometimes significant earthquakes in the region, including a M 6.6 quake on the Imperial Fault in October 1979.

In the volcanic buttes area at the southern Salton Sea, ~50 CO<sub>2</sub> wells (the Imperial Carbon Dioxide Gas Field), reaching depths of 152 to 213 m, were in production from 1934 to 1954; two processing plants converted recovered CO<sub>2</sub> gas to dry ice (Rook and Williams 1942; Lande 1979; Vedder et al. 1993; Baldwin et al. 1997; Sturz et al. 1997, 1998; Hunter 1998a). A few capped CO<sub>2</sub> wells, mud pots and mud volcanoes, and deserted, flooded buildings can still be seen along Davis Road: a bleak and surreal vista. A small group of active mud pots and volcanoes is located ~2 km south.

Groundwaters brought to the surface by pressurized CO<sub>2</sub> in these mud pots and mud volcanoes vary considerably in temperature, salinity, water level, amount and color of mud, and growth of bluegreen algae (cyanobacteria), other bacteria, and halophytic vascular plants (Oglesby pers. obs.). Water boatmen (*Trichocorixa reticulata*) inhabit some pools (Oglesby pers. obs.). Salinity varies from nearly freshwater to as much as 108‰. Temperatures are usually relatively cool, 12 to 32°C, reflecting ambient air temperatures. Temperatures as high as 40 to 60°C are characteristic of those mud volcanoes with the most vigorous venting (Sturz et al. 1998; Oglesby pers. obs.). Activity, temperature and salinity vary both seasonally and over longer periods of time (Sturz et al. 1998; Oglesby pers. obs.). There are two fluid sources, surface groundwater and deeper geothermal water; different mud volcanoes and pots vary in the relative proportions of the two water sources (Sturz et al. 1998).

The southern end of the Salton Trough (Imperial Valley and Valle de Mexicali) lacks a mountain rim, being formed by the low, broad delta fan of the Colorado River (Fig. 2). The gradient sloping north here is very shallow, as low as ~0.1 m per km; as a result,

even a small change in Salton Sea elevation covers or uncovers a great extent of land area. Small mountain ranges are rather far to the southwest, such as the Sierra de las Cocopás (Figs. 2 and 6), whose northernmost peak is the conspicuous Signal Butte (689 m; also called Signal Mountain or Mt. Signal) in México just south of the US border, and the Coyote Mountains and Superstition Hills in California (Figs. 1 and 4).

The geology of the west side of the Salton Trough is markedly different from that of the east side (Remeika and Linsley 1992; Remeika and Sturz 1995; Norris 1995a). In brief, Anza-Borrego Desert State Park and the southwestern end of the Salton Trough are dominated by the Western Salton Trough Detachment. Detachment faults (listric, or concave, faults) are steep normal faults at the surface. As they deepen and here extend to the east, the fault planes curve and become increasingly parallel to the surface and fracture into distinct bedrock faults which subside domino-style into the Salton Trough. This process forms a parallel series of ridges separated by half-graben basins: the hanging wall of the western side of each half-graben is the footwall of the next one east. Remeika (1995b) stated that this “tectono-sedimentary behavior of progressive basinward stepping-down of bounding faults” from west to east is strong evidence of crustal extension. Axen and Fletcher (1998) and Lough (1998) described in detail the Anza-Borrego and Laguna Salada detachment fault systems.

The Santa Rosa Mountains to the north of Anza-Borrego Desert State Park dominate most of the west side of the Salton Sea (Fig. 1); the highest summit, Rabbit Peak, is 2160 m. The Santa Rosas are partly formed by detachment faults and partly by right-lateral strike-slip movement along the San Jacinto and Elsinore Faults, both west of the Santa Rosas (Fig. 3; Remeika 1995b). The San Jacinto fault shows the greatest accumulation of surface strain in this area, strain which increases to the southeast as it enters the Imperial Valley. The San Jacinto fault seems to be taking up the strain of the San Andreas Fault which dominates to the east (Johnson et al. 1994; Miller 2000). The steep eastern scarps of the Santa Rosa and San Jacinto Mountains, both with long rocky spurs



extending eastwards into the Coachella Valley, such as Travertine Rock (Travertine Point) at the northwest end of the Salton Sea and several even larger spurs to the north, do not seem to be fault controlled. Evidence suggests that either these ranges were arched up by compression or else tilted northeastward from the San Jacinto Fault as the Coachella Valley subsided and filled with sediments (Dibblee 1977).

### **Origin of the Below-Sea Level Salton Trough and its Pleistocene and Holocene Lakes**

Conspicuous beachline features on the lower slopes of the Santa Rosa Mountains west of the community of Desert Shores testify to the former presence of a very large body of water, one that occupied the Salton Trough north of the Colorado River delta, called Lake Cahuilla. The popular story is that Lake Cahuilla was initially formed by deposition of the Colorado River sedimentary delta across a seawater-filled below-sea level depression (the Salton Trough), blocking off ocean access to the northern Gulf of California and isolating a  $\sim 8500 \text{ km}^2$  ocean seawater lake which then gradually dried up, leaving the conspicuous shorelines at  $\sim 10$  to  $12 \text{ m}$  above ocean sea level. This story is perpetrated in the popular and semi-popular press and popular (but not geological) guidebooks to the Salton Trough, by several major water districts, in programs at the Visitor Center at the Salton Sea State Recreation Area, and in semi-popular, scientific, and government publications (e.g., Usinger 1958; Imperial Irrigation District Public Information Office 1991b; Laflin 1995, 1998; deBuys 1999; Salton Sea Authority; US Bureau of Reclamation). From looking at maps or space photos, this scenario seems plausible. As a typical example, Pomento (1998), writing for the Metropolitan Water District, wrote: "Historically, the Salton Sea, or more accurately the Salton Sink, was part of the Gulf of California that extended north to a few miles above the town of Indio, about [230 km] from its present northernmost reach. For centuries, the Colorado River has carried a heavy silt load that gradually created an immense, broad, fan delta that cut

off the northern end of the gulf, leaving the Salton Sea [*sic*], the bottom of which lies [91.2 m] below sea level, to evaporate.” This story is not true, even though it was espoused by some early geologists (e.g., Blake 1854, 1914a; Sykes 1914). Even recently, de Stanley (1976), Pepper (1999) and deBuys (1999) as well as federal agencies (Salton Sea Authority, US Bureau of Reclamation, etc.) adopted Blake’s incorrect 1854 version. As described below, the growing Colorado Delta did not post-date but coincided with subsidence forming the Salton Trough. There is no geological or paleontological evidence for the northern part of the Gulf of California being cut off by the growing delta, leaving a ocean-saltwater lake to desiccate.

An early geologist (Free 1914) advocated a different explanation for the origin the below-sea level Salton Trough, one that is now generally accepted by geologists. As the alluvial Colorado River delta sediments, derived from excavation of the Grand Canyon beginning during the early Pliocene, accumulated to their present great depth, the proto-Salton Trough to the north of the broad delta gradually subsided below sea level as a direct consequence of crustal spreading (Free 1914; McKibben 1993; Howard 1996; Hunter 1998a). forming a probably-dry below-sea level depression. Maximum Colorado River sediment depths are as much as 8040 m (8.04 km) just south of Mexicali, and >3000 m (3 km) throughout most of the Salton Trough (Winspear and Pye 1995; Hunter 1998a; Salton Sea Authority 2000). Only later did freshwater lakes (Lake Cahuilla) fill this below-sea level depression.

The last marine incursions into the pre-Salton Trough from the proto-Gulf of California occurred in the late Miocene or early Pliocene, at least 4 million yr ago. There are marine fossils in the late Miocene/early Pliocene, stratigraphically complex Imperial Group composed of the Latrania Formations, Coyote Mountain Clays, and the Yuha Formation (Remeika 1988), e.g. oysters (*Pycnodonte heermannii*, up to 0.3 m long, and the smaller *Dendrostrea vespertina*), as well as other bivalves in the well-known Yuha oyster beds, all located some 300 m above present ocean sea level -- recognized as early as

1775 by Padre Pedro Font of Anza's second expedition of 1775 to 1776. Font hypothesized that the ocean had once extended this far north, as did Blake in 1853 (Blake 1854, 1914a; Watkins 1990a; Remeika 1998; Lindsay 2001). These uplifted marine beds have been much studied in Anza-Borrego Desert State Park as well as in other parts of the Salton Trough (Remeika and Sturz 1995; Powell 1995; Remeika 1995b; Whistler et al. 1995; Frost et al. 1997; Sylvester and Smith 1997; Remeika 1998). Many popular and semi-popular writers state that the Yuha oyster beds document a recent seawater incursion into a below-sea level Salton Trough from the Gulf of California, but these Miocene marine beds are in fact much higher than present ocean sea level, and have no relevance to any recent marine incursions, which geologists do not accept. Marine invertebrate fossils found in recent deposits, including the late Pleistocene, are reworked from older deltaic deposits (Remeika 1998). A below-sea level Salton Trough did not exist during Miocene times (Glockhoff 1998; Remeika (1998).

Beginning at the same time (~5.5 million yr ago), the Baja California peninsula became increasingly separated from mainland México through tectonic movements of the Pacific Plate relative to the North American Plate, opening the proto-Gulf of California from south to north, a process that is ongoing. Remeika and Linsley (1992) wrote, "Commencing about five million years ago, the Gulf of California unzipped like a horseshoe opening to the south, with the tip at Cabo San Lucas rotating [237 km] away from the Mexican mainland." The Colorado River reached its present ~1550 m depth in the Grand Canyon only ~1.2 million yr ago (Remeika and Fleming 1995). Remeika (1995a) wrote that the Salton Trough is "downdropped by faulting that is [also] rafting Baja California away from mainland México." The Salton Trough (including the Coachella Valley, Salton Sea, Imperial Valley, and Valle de Mexicali), Colorado Delta, and Gulf of California form a large graben, a subsided area between the Pacific and North American tectonic plates (Remeika and Fleming 1995; Howard 1996; Glockhoff 1998; Remeika 1998).

The crest of the delta, at its lowest point at Laguna Volcánica in México, showed a net tectonic rise (uplift) of ~1.5 m from 1926 to 1978, forcing the Colorado River further away from the Salton Trough and towards the Gulf (Gilmore and Castle 1983). Precise geodetic surveys since 1972 show that Imperial Valley crust continues to be significantly deformed: there is a downward regional tilt from just south of the Mexican border to the Salton Sea, both deepening and widening the Salton Trough at rates of 3.5 to 4.0 cm·yr<sup>-1</sup> (Lofgren 1979b). At the time of Lofgren's study, geothermal fluid extraction had not developed sufficiently to cause soil subsidence in the Imperial Valley. As a result of continued tectonic spreading and subsidence, gradients of streams, canals, and drains in the Imperial Valley are steepening, and the capacity of the Salton Sea is increasing. Not all the drowning of agricultural lands and shoreline structures at the edge of the Sea is caused by rising Sea level -- some is due to continuing subsidence of the land surface (Lofgren 1979b; Glockhoff 1998; Hunter 1998a; Miller 2000).

The closed basin of the Salton Trough has been repeatedly filled by bodies of fresh water for at least 50,000 yr, many of them to same still-stand elevation -- roughly the elevation of the low point of the Colorado delta dam, ~10 to 12 m. These large lakes (~92 m deeper and 10 times the area of the present Salton Sea) are usually called Lake Cahuilla (Figs. 1 and 4). They were freshwater at the times of their formation and while they were full and out-flowing to the Gulf; they would eventually become saline as they desiccated (Cagle 1998).

Conspicuous and diverse shoreline features, such as sand and gravel beaches, wave-cut cliffs as high as 7 m, shingle terraces of small smoothed rocks, sand spits, and bay-mouth bars, are found all around the Salton Trough at approximately the same height (~10 to 12 m), testifying to the presence of large and long-lasting lakes, 8500 km<sup>2</sup> in area, 1600 km long, 36 km wide, and 91.4 m deep, extending from near Palm Springs to south of the Mexican border (Figs. 1 and 4). The tips of the Durmid Hills, including Bat Caves Buttes, would have formed a series of small islands in Lake Cahuilla (Sykes 1914;

Maloney 1986; Norris 1995; Winspear and Pye 1995; Oglesby pers. obs.). Winspear and Pye (1995) attributed the sand supply of the Algodones Dunes to blow sand from the shorelines of Pleistocene Lake Cahuilla and later lakes, ultimately derived from the Colorado River sediments.

The most spectacular place to see this impressive fossil shoreline is on the east-facing base of the Santa Rosa Mountains just west of Desert Shores, to the west of the present north Salton Sea shore. Above a conspicuous horizontal shoreline on the rock slopes, where tufa deposits below end and naked cliffs above begin, the reddish desert varnish has been eroded off the gray and tan granite cliffs by wave action; this erosional feature is particularly evident on what would have been rocky promontories extending out into the lakes. Below the horizontal shoreline, cliffs and rocks are covered with tufa deposits like cake icing; this tufa is locally called “travertine,” or, even more inaccurately, “coral,” but is formed by quite a different process.

Tufa is a freshwater deposit of  $\text{CaCO}_3$  requiring photosynthetic bluegreen bacteria in a warm, hardwater lake; the bluegreen alga *Calothrix* is often implicated in tufa deposition. Bluegreens do not actually *secrete*  $\text{CaCO}_3$  (thus, they are not coralline algae), but their photosynthetic activities lower  $p\text{CO}_2$  locally, enhancing precipitation of  $\text{CaCO}_3$ . Tufa deposits above Desert Shores and at Travertine Rock are as much as 1 m thick, and within overhangs show evidence of growth upwards towards light; these tufa deposits were described in some detail by Jones (1914).

Radiocarbon dating indicates that the major layers of tufa in the Salton Trough were deposited beginning ~17,590 yr ago with the main deposition period ending ~7205 yr ago, that is, primarily during the Pleistocene, but tufa deposition continued during the Holocene whenever a lake was present. Repeated deposition of tufa layers was so regular that the designs of petroglyphs (incised Indian rock designs) were transmitted to the most recent tufa surface; these petroglyphs have been dated up to ~9000 yr ago (MacDougal and Sykes 1915; Reynolds and Turner 1971); photographs of petroglyphs in tufa are in

Laflin (1998) and deBuys (1999). In both photos the locations are not identified and the petroglyphs look like they were incised directly into the tufa and not carried through from the underlying rock during later tufa deposition. Unfortunately, the fine display of tufa and petroglyphs on Travertine Rock has been largely destroyed by vandals with spray paint (Lindsay 2001; Oglesby pers. obs.). Indian artifacts recovered from below the still-stand line of the most recent Holocene lake(s) often have thin tufa deposits (Oglesby pers. obs.). Jones (1914) described  $\text{CaCO}_3$  deposition (tufa, since *Calothrix* filaments were present) on drowned shrubs and the volcanic buttes by the desiccating but still low-salinity Salton Sea during the first years after its initial formation in 1905 to 1907. In the present Salton Sea 95 yr later, gypsum ( $\text{CaSO}_4$ ) precipitates out before  $\text{CaCO}_3$ , because of different solubilities in this now saline lake (D. Zenger pers. comm.; Oglesby pers. obs.).

Desiccating lakes, including the present Salton Sea at times (Oglesby pers. obs.), form erosional cliffs and broad, level beach terraces during the winter still-stand, terrace width depending on the steepness of the slope. During summer's rapid evaporation, these beach terraces are marooned above water level. If there is no significant inflow, such as when the Colorado River abandons the Salton Trough and flows directly to the Gulf of California, these recessional cliffs and terraces are spaced ~1.8 to 2 m vertically apart, reflecting the high evaporation rate in this intensely hot, arid climate. The Durmid Hills and all five volcanic buttes have (or had, before quarrying) conspicuous recessional terraces; thin layers of tufa ( $\text{CaCO}_3$ ) coat much of the most recent obsidian and rhyolite. Recessional features on the four buttes reachable by road have been severely damaged by recent quarrying (Oglesby pers. obs.). Recessional terraces on less steep slopes are easily recognized from the air (Corona 1993a,b; McKibben 1993; Oglesby pers. obs.). These terraces were presumably created during desiccation of the most recent large lake to occupy the Salton Trough, whose desiccation dates to 300 to 600 yr ago.

Studying ~2 m yearly recessional terraces formed during the initial desiccation of



the Salton Sea right after its formation in 1907, MacDougal (1914b) observed that desert shrubs germinate preferentially at the moister, more shaded, bases of these little cliffs, creating lines of shrubs growing on contours. Vegetation contour alignments can still be seen on recessional shoreline topography around the present-day Salton Sea (Oglesby pers. obs.), including the Durmid Hills and Bat Caves Buttes. One of the best places to have seen desert shrubs growing on successive contour intervals was from the top of Travertine Rock, looking out on the sand bar that connected it to the main mass of the Santa Rosa Mountains -- Travertine Rock would have been a tombolo when Lake Cahuilla was full. Planting of vineyards in 1985 and long-time infestation by off-road vehicles have obliterated all native vegetation and the recessional beach terraces on which they grew on this large sand bar (Oglesby pers. obs.). During the past 30 yr and more, with the Salton Sea elevation more or less stabilized, the same pattern of cliff and terrace forms yearly, with successive terraces only a few cm apart vertically, drowned and eroded during the next high water period, late spring.

Myriad fossil freshwater mollusc shells litter the uncultivated desert surface below the Lake Cahuilla shoreline all over the Salton Trough, blown by the wind and consolidated several m deep in washes (Table I). Their abundant presence is perhaps commemorated in the name Coachella, which may be a corruption of the Spanish *conchilla*, meaning "little shell" (Pepper 1972, 1999; Nordland 1978; Laflin 1998). A second hypothesis for the name Coachella is that it is a variant spelling of Cahuilla or Coahuilla (e.g. Nordland 1978; Laflin 1998; deBuys 1999). A third possibility for the name is that it is artificial, made-up from COA(huilla) and con(CHILLA) (Nordland 1978; Laflin 1998); Laflin considered this third explanation the most likely. Commonest fossils (Table I) are the tiny, long-spined prosobranch *Tryonia protea*, the larger and more globular pulmonate *Physa virgata*, and the swan mussel *Anodonta californiensis*. Only fragments of *Anodonta* shells are found where people have access, as they are very fragile. Intact *Anodonta* shells, some even articulated, may be found in places where people

seldom go, such as the Navy's Salton Sea Test Base on the southwest shore of the Sea (Fig. 1; Oglesby pers. obs.). Whistler et al. (1995) listed these and other freshwater mollusc species (Table I), as well as diatoms, sponges, and ostracods, found in trenches dug through lacustrine sediments northwest of the present Salton Sea, below the conspicuous Lake Cahuilla shoreline. These freshwater mollusc fossils are embedded in tufa deposits, further indicating the freshwater origin for tufa deposition. Those molluscs listed in Table I still living in the southwestern US live in freshwater to slightly saline environments. Blake (1857, 1914) recognized these as freshwater shells, but some more recent authors, though following Blake's geology, erroneously call the fossils marine (e.g. Laflin 1998). Clearly, the several bodies of water in the Salton Trough in which these fossil molluscs lived were freshwater, not marine, including both Pleistocene and Holocene lakes, as pointed out by Blake (1914), Free (1914), and many others.

A restricted marine fossil fauna is found in the Salton Trough below -61 m (Van de Kamp 1973). These marine fossils do not indicate flooding of the Salton Trough by an incursion of the Gulf of California. Rather, high salinities of desiccating small remnant lakes at the bottom of the Trough permitted temporary survival and reproduction of marine mud flat organisms brought in from the Gulf by birds and other overland transport mechanisms (Van de Kamp (1973).

Elders (1979c) described the currently accepted explanation for both the series of Pleistocene and Holocene lakes in the Salton Trough and the fact that the Colorado River normally empties southerly across its broad delta into the Gulf of California: "When the river flowed to the Gulf, it graded its bed to [ocean] sea level. There was, therefore, a greater gradient to the *north* to the closed basin [Salton Trough]. In times of flood, when the river topped its levees, any distributaries which flowed north could capture the flow. Thus the basin filled until over the low point of the crest of the delta [~10 m at Laguna Volcánica]. The river then graded its bed to the elevation of the lake it had created, ~11 m above sea level. At this point the gradient to south to the [Gulf] would be steeper than



that to the north. Consequently in times of flood, when the river topped its levees, any distributaries which flowed *south* could capture the flow. Thus the delta oscillated between two metastable conditions.” The overflow of full-stand lakes in the Trough to the Gulf of California was apparently by way of the Río Hardy, the westernmost major distributary of the delta. Winspear and Pye (1995) estimated that it would have taken 10 to 20 yr for a northwards-flowing Colorado River to fill a Lake Cahuilla to the elevation of the ~10 m shoreline, and ~60 yr to desiccate under present climatological conditions. They pointed out that there is no correlation between the geological record of major Colorado River floods (Ely et al. 1993; O’Connor et al. 1994) and fillings of Lake Cahuilla; rather, the gradient of the fluvial channel and perhaps tectonic movements are the more important.

Remeika and Linsley (1992) observed that the southern side of the delta dam is being actively eroded by the great tidal range of the northern Gulf of California, especially recently as the many dams on the Colorado River prevent most deltaic silt deposition. They predicted that the delta dam, composed of soft sediments, will eventually be breached by the Gulf, which will then invade the Salton Trough, drowning the Valle de Mexicali, Imperial Valley, and Coachella Valley, and turning Palm Springs into a beach city; they are in no immediate danger.

Geologist William Phipps Blake was the first to recognize the geological evidence for a very large prehistoric lake in a below-sea level Salton Trough, in 1853 while scouting for the best route for the Southern Pacific transcontinental railroad (Blake 1854, 1857, 1914a, 1915; Hoyt 1990; Remeika 1998). He was the first Euro-American to recognize that the low and comparatively gentle San Geronio pass was the best route to the coast in all California; despite the rigors of the desert, this route avoided the Sierra Nevada and other mountains. Blake listened to Desert Cahuilla stories which recounted in some detail a vast lake (“*agua grande*”), filled with fine fish (“*pescados finos*”), and which dried up little by little (“*poco-a-poco*” [Blake’s hyphens]), and which Blake calculated must have

been present as recently as 400 to 600 yr before 1853. This Holocene lake of the Desert Cahuilla oral traditions was much more recent and temporary than the long-lasting Pleistocene lakes which constructed the impressive shoreline features, but it reached the same still-stand line marked by the earlier Pleistocene beaches. Blake named this most recent of the ancient lakes Lake Cahuilla in 1909. Separate names have sometimes been given to the more temporary Holocene lakes, to distinguish them from Pleistocene Lake Cahuilla, including Blake Sea and Lake LeConte, but these names are not used consistently, and all three names have been applied both to the long-lasting Pleistocene lakes and to the several more ephemeral Holocene lakes. The present-day Lake Cahuilla is a small reservoir on the west side of the Coachella Valley, the terminus of the Coachella Canal (Fig. 6).

Several Indian groups made extensive use of the Salton Trough. Both the easternmost of the Western (or Pass) Cahuilla and the Desert Cahuilla, of the Uto-Aztecan (Shoshonean) linguistic group, were resident in the Coachella Valley, having arrived from the north and northeast ~1000 to 2500 yr ago. Desert Cahuilla maintained permanent villages on both sides of the southern Coachella Valley south nearly to the Imperial Valley, near springs and fan palm (*Washingtonia filifera*) oases along traces of the San Andreas Fault splay on the east side, and at the mouths of canyons on the west side, where there was reliable water. Western (Pass) Cahuilla maintained villages on the western side of the Coachella Valley north and west from Palm Springs, especially near fan palm groves in mountain canyons. Cahuillas traveled seasonally from the low desert to higher elevations to take advantage of diverse seasonal food supplies, often using regular camping sites. There is considerable controversy of the origin of the name "Cahuilla" (Kroeber 1925; James 1960; Bean 1972; Bean and Saubel 1972; Bean et al. 1991; Lindsay 2001).

The high water table in the southern Coachella Valley, derived from groundwater runoff from the San Bernardino and San Jacinto Mountains, meant that the valley

provided ready access to water. The Desert Cahuilla was the only California group to dig water wells, usually reached by a ramp or series of steps; at least 10 wells have been recorded (Bean et al. 1991; Schaefer 1998). A photograph of an 8.2 m deep stepped well was taken before the area was damaged in the great flood of 1916 (photo reproduced by Nordland 1978, Dozier 1998, Laflin 1998; the dates of this one photo are different in the three different sources). The Desert Cahuilla irrigated crops using water from mountain streams brought out on the desert floor by stone ditches (Bean and Saubel 1972; Laflin 1998); they may have also irrigated with water from springs and artesian wells (Laflin 1998). The Cahuilla cultivated such Mesoamerican crops as squash, melons, beans, maize, and barley, the only California Indians known to have done so (James 1960; Bean 1972; Bean and Saubel 1972; Dozier 1998; Schaefer 1998).

Other tribes, including the Kumeyaay (Quemeya and many other spellings; also called Eastern Tipai and Southern Diegueño), Cocopa (Cocopah, Cucapá), and Quechan (Yuman), all of the Yuman linguistic group, occupied the Salton Trough south of the Salton Sink, the west side of the lower Colorado River, and northern Baja California, having arrived ~1500 to 2000 yr ago. The Kamia were the most desert-adapted of the Kumeyaay (Schaefer 1998). The Kamia occupied part of the riparian corridor along the New River, and made seasonal use of the Imperial Valley, including flood plain agriculture along the New River and perhaps growing maize, squash, melons, and beans like the Desert Cahuilla (Kroeber 1925; Bean and Saubel 1972; Schaefer 1998; Lindsay 2001).

On the west side of the Salton Trough the border between Kumeyaay and Cahuilla was somewhere between San Sebastian Marsh on San Felipe Creek (elevation -10 m), where there was a large Kumeyaay village when no Lake Cahuilla was present, and Desert Shores near Travertine Rock. The two groups interacted extensively, though this would have been difficult when Lake Cahuilla was full, as the still-stand shoreline is on steep mountain slopes, forcing travelers to trails on the cliffs (Schaefer 1998; von Werlhof *in press*).

The Cahuilla and other groups exploited the shoreline of one or more iterations of the Holocene Lake Cahuilla. von Werlhof (*in press*) discussed what Cahuilla life might have been like when Lake Cahuilla was present. He speculated that the northern portion of Lake Cahuilla was “stagnant” and that the Cahuilla were able to take advantage of that situation. But it is highly unlikely that a large, deep lake such as Lake Cahuilla would even have reduced horizontal circulation, even if it did stratify during summers (Hutchinson 1957); Whistler et al. (1995) found a diverse array of molluscs and other fossils in buried lacustrine sediments of the Coachella Valley, suggesting all eight iterations of the Holocene Lake Cahuilla had the usual mixing pattern and biota. Many Desert Cahuilla artifacts are associated with Holocene Lake Cahuilla shorelines and recessional terraces in the northern Salton Trough, such as fishing camps, fire pits, pottery and pottery shards, bedrock morteros, rock shelters, charred bones of freshwater fish of the Colorado River system then inhabiting Lake Cahuilla, and personal adornments, found both along the Lake Cahuilla still-stand elevation of ~10 m above sea level and on recessional terraces down to at least -33 m (Bean and Saubel 1972; Balch and Balch 1974; Karr 1985; Bean et al. 1991; Gobalet 1992, 1994; Schaefer 1998; J. von Werlhof *in press*, pers. comm.; Oglesby pers. obs.).

Two major styles of Indian stone structures in the Salton Trough have been called “fish traps.” One type is easily seen at the west end of Avenue 66 at Jefferson Street -- a display of some 650 pits, first described over 100 years ago (Bowers 1891; Rust 1891; Gates 1909; James 1918; Strong 1929; Kniffen 1932; Treganza 1945; Balch and Balch 1974; US Department of the Interior and The Resources Agency of California 1974a,b; Wilke 1979; Karr 1985; Bean et al. 1991; Schoenherr 1993a; Dozier 1998; deBuys 1999; Pepper 1999; Cornett 2000; Lindsay 2001; Oglesby pers. obs.). These pits are roughly circular depressions, some with built-up walls, <1 to 2 m deep by 1 to 4 m across, arranged linearly and close together along 15 successive recessional shoreline terraces. The terraces are ~2 m apart in elevation on a steep talus slope composed of large (0.3 to

0.7 m) rounded boulders, corresponding to falling lake elevations in 15 successive years of maximum Lake Cahuilla desiccation rates. Similar pits occur on talus slopes elsewhere below the still-stand shoreline of Lake Cahuilla along the base of the Santa Rosa Mountains (Bean et al. 1991; Schaefer 1998; Lindsay 2001; G. Ridgeway pers. comm.). Pits may have originally had two separate openings on the downslope side, each ~0.6 m wide. Because of the yearly ~2 m desiccation of the lake when deprived of Colorado River inflow, each row of depressions could be used only one season while at the water's edge.

Despite the popular name, the actual function of these pits is not known. Most people assume that the name "fish traps" is correct, and so argue about *how* they might have been used for fishing, rather than questioning *whether* they were used for fishing at all or what other possible uses might have been (G. Ridgeway, pers. comm.). Schaefer (1998) quoted extensively from early reports (Bowers 1891; Rust 1891; Gates 1909) which recounted Cahuilla oral traditions that these pits were used in conjunction with tides to catch fish; several writers believed Lake Cahuilla was connected to the ocean in the Gulf, at least at high tide. But Lake Cahuilla was never connected to the ocean at sea level -- its still-stand elevation was ~10 m above sea level. When desiccating, Lake Cahuilla was a terminal lake in a closed basin. No inland body of water in the world, however large, displays lunar tides (see below). These reported Cahuilla oral accounts involving tides were seriously in error, a fact which casts some doubt on the validity of other aspects of contemporary Cahuilla accounts of their pre-contact cultural practices. Various recent writers have proposed diverse other pit fishing methods, some clearly impossible, include weir fishing (impossible on such steep slopes, since there would be no shallow substrate support for the "wings"), trapping fish that entered the depressions to feed or spawn by blocking the downslope openings with boulders or other objects, frightening fish to seek shelter in the pits, luring fish into the pits by night-lighting with torches, baiting, inserting nets within the depressions, or catching floating dead fish in

some unstated way; poisons were apparently not used (James 1918; Strong 1929; Treganza 1945; Bean 1972; Wilke 1976, 1979; Bean et al. 1991; Dozier 1998; Schaefer 1998. Pepper 1999; Cornett 2000; Lindsay 2001). Treganza (1945) suggested that these pits were not used for fishing, but Wilke (1976, 1979, 1980; Wilke and Lawton (1975), Schaefer (1998, pers. comm.), and J. von Werlhof (pers. comm.) called his arguments “flawed” and dismissed his interpretations. Wilke (1976, 1979) wrote that usage of the pits as traps would have stopped when the salinity of desiccating Lake Cahuilla became too high for freshwater fish, but the lake’s elevation would have had to drop much lower than the lowest pit “fish trap” elevation ( $\sim 33$  m) before becoming too saline for freshwater fish.

A much different type of “fish trap” is found on the more gently sloping bajadas below the steep slopes of the southern Santa Rosa Mountains, Fish Creek Mountains, and Superstition Mountain, as well as at the mouth of San Felipe Creek at the present Salton Sea and the Salton Sea Naval Test Base (J. Schaefer 1998, pers. comm.; Dower 2000; J. von Werlhof *in press*, pers. comm.; G. Hurd, pers. comm.). These non-circular fish traps are each confined to one broad recessional terrace of a desiccating Lake Cahuilla, some at the still-stand elevation ( $\sim +10$  m), most from  $-13$  to  $-46$  m, and some as low as  $> -60$  m; several traps may occur on the same terrace. Each trap consists of a U- or V-shaped closed end made from available desert rocks about the size of bowling balls, each end connected to a long “wing” of stones, the two wings parallel or sub-parallel to each other with the downslope wing shorter than the upslope wing; these traps are linear, not circular, features. The highest elevation traps have the greatest structural diversity, the lowest elevation traps the least. These structures were built and used underwater: often tufa connects several adjacent rocks and freshwater fossils (ostracods, snails) are found both in the tufa and in the soil under the rocks (G. Hurd, pers. comm.). von Werlhof (*in press*,) provided dimensions in his Table 1: lengths of the two arms may have varied from  $\sim 0.3$  to  $\sim 4.5$  m, with the longer arm being  $\sim 2.5$  as long as that of the shorter. Such



structures would be appropriate for weir fishing, given the gentle slope and the two wings. Once fish were herded into the closed end of a trap, it would have been easy to block the small opening with stones or baskets and then to harvest the fish. Fish traps on any single terrace could have been used only one season as Lake Cahuilla desiccated. Well over 450 weir fish traps have been documented since ~1940, but many have since been lost to development and highway construction.

A major question concerns the date of the last desiccation of Lake Cahuilla. Early Spanish explorers made no mention of a large lake in the Salton Trough (Sykes 1914; Vedder et al. 1993). The first European to enter the Salton Trough was perhaps Hernándo de Alarcón in 1540, a member of Francisco Vásquez de Coronado's expedition out of Sonora, México, to find the fabled Seven Golden Cities of Cibola. Sailing north along the eastern shore of the Gulf, Alarcón was the first European to "find" the Colorado River; he traveled upstream by boat and interacted with local Quechans. Melchior Díaz's 1540 land expedition also explored the lower Colorado River while looking for both Alarcón and Coronado. In 1605 Juan de Oñate, the first governor of New Mexico, found the Colorado River flowing and explored it from its mouth in the Gulf north to the Gila River, as did Padre Eusebio Kino, for 24 yr Arizona's beloved "padre on horseback," in 1700. The 95 yr between Oñate's and Kino's observations is the longest single time period since 1540 during which a Lake Cahuilla might have been present, a time span too short to accommodate a complete filling to the still-stand elevation and then desiccation (Winspear and Pye 1995).

Had any of these early explorers from 1540 on entered the Salton Trough, they would have encountered Lake Cahuilla had it been in existence; surely they would have investigated such a huge lake. Furthermore, if there was a Lake Cahuilla in the Salton Trough at that time, the Colorado River would not have been flowing to the Gulf except by way of the Río Hardy, well west of the main channels explored by the Spanish (Wilke, 1976; Schaefer 1998). Wilke (1976) and Schaefer (1998) concluded that 20th century

Cahuilla accounts of Lake Cahuilla desiccating, rapidly refilling causing residents to flee for their lives, and then desiccating again in the 1600s or 1700s “represented a mythic catastrophism evoked from oral traditions . . . and not historical events.” Schaefer (1998) qualified this conclusion by arguing that recent recognition that many Indian fish camp artifacts and fish traps from 0 m down to -60 m date, in radio-carbon years, to the 95 yr period from 1605 to 1700, when no Spanish explorers were in the region, “provid[e] compelling evidence of a late refilling, perhaps [only] a partial one.” Archeologists, anthropologists, ethnographers, geologists, and paleontologists still differ on the date of the final desiccation of Lake Cahuilla, some preferring a date as recent as 1750 (e.g. J. von Werlhof *in press*, pers. comm.), while others espouse a date several centuries earlier (e.g., Blake 1857, 1914). They also differ strongly on how many different iterations of Lake Cahuilla occurred in the Holocene.

The first Juan Bautista Agustín de Anza expedition of 1774 is generally credited as being the first real European contact with the Salton Trough and its several native groups, and was certainly the first to cross the Colorado Desert in the Salton Trough. Anza’s first expedition opened the first inland route to the California coast, which the Spanish had begun to colonize only as recently as 1769 at San Diego; 1769 is generally recognized as the start of the Historic Period in California (Chartkoff and Chartkoff 1984). Anza crossed the southern Salton Sink (impossible had Lake Cahuilla been present) and left by way of Coyote Canyon in what is now Anza-Borrego State Park. With him were Padres Francisco Gárce and Juan Díaz, and the Indian guide Sebastián Tarabal, a runaway from Misión San Gabriel Arcángel. Anza camped near the always reliable water at San Sebastian Marsh on San Felipe Creek, which he named for Sebastián Tarabal. Anza learned that two years earlier (October 1792), Lt. Pedro Fages and three Spanish soldiers had entered the Trough from the west while searching for deserters from the Presidio in San Diego; Fages camped as far east as San Sebastian Marsh, and his visit was well remembered by local Kumeyaay (Lindsay 2001).



Several times in the last 200 yr the Colorado River temporarily abandoned its normal southward course to the Gulf to flow into the Salton Trough, usually through the New River channel, which heads at Laguna Volcánica (Fig. 4; Sykes 1914). Overflows are known to have occurred in 1840, 1842, 1849 (when the New River was named, though not created), 1850, 1852, 1853, 1859, 1862, 1867, 1891, and 1899, some creating small lakes in the Salton Sink playa (Blake 1914a; Sykes 1914; Oertle 1964; Nordland 1978).

The published dimensions of the 1891 lake (called Salton Lake) are controversial and some are self-contradictory: James (1907), Oertle (1964) Nordland (1978), and Cohen et al. (1999) described the 1891 lake as 24 km by 56 km, and 247 km<sup>2</sup> in area (thus, only slightly smaller than the present Salton Sea), but only 1.5 m deep (10 times less deep than the present Salton Sea), dimensions that are incompatible. The 1891 lake had to be much smaller and shallower than the present Salton Sea since it lasted only ~2 yr, suggesting that it was not more than ~4 m deep at its deepest. Investigating the 1891 overflow into the Salton Sea, Sykes (1937) followed Beltran Slough from the Alamo River to the lake, thus establishing the Alamo River's connection with the Colorado River for the first time (Carpelan 1961).

Before the formation of the Salton Sea in 1905, the Salton Sink playa was covered with a thick layer of salt (NaCl) which overlay a ~7 m layer of wet, black ooze. This wet layer was sometimes thought to represent seepage of ocean seawater from the Gulf of California through the deltaic dam, but this is not the case (Dowd 1960). Like Badwater in Death Valley well to the north, saline groundwater rose close to the surface in the playa coming from the New River and other local sources (de Stanley 1976). Johnston (1987) quoted a mid-19th century traveler who was appalled to see the Salton Sink in full moonlight, "the ghastly pallor of death . . . a great plain of snowy salt." In 1892 the Salton Sink was described as a salt marsh (Blake 1914a), but it was really a desert playa with a surface of evaporite NaCl deposits, long used by the Desert Cahuilla and Kumeyaay (Blake 1914a; Laflin 1995, 1998), probably with alkaline or salt marshes near

areas of permanent seep water. In 1815 Spanish colonists on the coast finally listened to the Indians and instead of importing salt from México began to mine it from the Salton Sink from Los Angeles every spring, in an arduous trek using Coyote Canyon. In the 1830s, the Spanish switched to exploiting NaCl concentrated from evaporation ponds at Redondo Beach on the seacoast, much closer to Los Angeles (Johnston 1987; Laflin 1995, 1998). Salt (“excellent quality”) was again mined from the Salton Sink beginning in 1884 by the New Liverpool Salt Company, continuing until the salt works were permanently flooded out in 1905; New Liverpool was also flooded by 1891’s smaller lake (Cory 1913, 1915). A railroad siding and a small support community were named Salton for the Company. New Liverpool’s salt works and the community Salton were inundated by as much as 20 m of water by 1907. Nordland (1978) and Laflin (1995) wrote that suits for damages were unsuccessful, but Dowd (1956) wrote that the New Liverpool won “excessive” damages (\$458, 246.23) against the California Development Company, a judgment ultimately upheld by the US Supreme Court.

### **Formation of the Salton Sea and its Recent History**

Many popular, semi-scientific, and even scientific discussions of the Salton Sea perpetuate a number of errors about its formation, early days, and present condition. Wambaugh (1992) in *Fugitive Nights* provided a précis of common errors mixed with a few facts: “The Salton Sea was a mistake of man and perhaps of nature. Just after the turn of the century, some railroad builders made a horrible error with the Colorado River, and a levee burst, allowing millions of cubic feet of water per day to rage into a high salt marsh left over from an ancient inland sea. The Salton Sea submerged everything under water fifty percent saltier than the ocean. It was said that pumice rock could float in this saltiest of water, 235 feet below sea level.” The real origin of the Salton Sea is strange enough without such embellishments.

Right from its remarkable beginnings in 1905 to 1907, the Salton Sea has been

much written about (Byers 1907; Davis 1907a; James 1907; Rockwood 1909, 1918; Howe and Hall 1910; Cory 1913, 1915; Sykes 1914; Weaver 1915?; Kennan 1917; Farr 1918; Tout 1931; Woodbury 1941; Burns 1952; Dowd 1956; Carpelan 1961a; Elders 1979b; Fradkin 1981; de Stanley 1976; Laflin 1995, 1998; and deBuys 1999). Early accounts were often promotional pieces about the Imperial Valley, either explaining away the two-year flood or just ignoring it. Kennan's (1912) little book is typical of this approach, despite good maps.

Other early books were written by active participants. Rockwood's (1909) account is defensive and partisan. He was head of the California Development Company which dug the inadequate Mexican Cut (whose expectable breach by the Colorado River had created the Salton Sea). Rockwood had been severely criticized for "gross negligence and criminal carelessness" ("but how could one foresee that which had never happened before?"); he was more responding to his critics than writing a chronological history. Tout (1931) reprinted Rockwood's (1909) apologia, but wrote little on the breach, flood, or repair. Woodbury's (1941) enjoyable account is detailed and accurate, but couched in a strange setting of fictional surrogate characters and imagined dialog.

The best early account, with excellent maps and diagrams, is by Harry T. Cory (1913, 1915), the Southern Pacific Railroad engineer who managed the final, successful attempts to close the Colorado River's levee breach. Though Cory covered only the later portion of these events, his account is detailed and accurate. In addition, the paper by Cory (1913, reprinted in Cory 1915), provided an evaluative and valuable discussion of his paper by water engineers. One of these, Andrew Chaffey (son of George Chaffey, Jr., who was for a while, prior to construction of the Mexican Cut, the chief engineer for the California Development Company) praised Cory's paper as "the first serious history of the Imperial Valley" and called it "fair and unprejudiced." By contrast, Chaffey was scathing in his criticisms of Rockwood (1909) and Howe and Hall (1910), using such words as, "rambling sketches," "unsystematic," "partisan and misleading statements,"

and “untrustworthy and unsatisfactory.” By contrast, Howe and Hall (1910) described Rockwood as a man “of largest possible vision.”

Modern accounts of the events of 1905 to 1907 often contain errors about dates, facts, and incorrect assignment of responsibility (e.g., see the quote by Wambaugh [1992], above). The best and most complete modern accounts are Burns (1952), de Stanley (1976), Laflin (1995, 1998), and deBuys (1999); even so, they cannot be relied upon for their discussions of the geology and biology of the Salton Sea. Many popular and semi-scientific articles stimulated by proposals by the Salton Sea Authority to “save” or “restore” the Salton Sea are both superficial and error prone.

Proposals to bring Colorado River water by gravity to irrigate the Salton Trough were put forward as soon as Blake recognized in 1853 that the basin was below sea level. Beginning as early as 1857, Dr. Oliver Meredith Wozencraft, forty-niner, physician, federal Indian Agent for southern California, and visionary, spent nearly four decades unsuccessfully trying to convince the US Congress to finance irrigation projects for agriculture in the Trough; in 1857 he persuaded the fledgling California legislature to pass a bill to encourage bringing Colorado River water to irrigate what is now the Imperial Valley. All it would take, Wozencraft said, would be money, since Colorado River water could be delivered by gravity alone. Congress shied away from the proposal, being involved in issues over the pending Civil War. Wozencraft died before his 1887 proposal was considered by Congress. Wozencraft is often called the “Father of the Imperial Valley” (Lindsay 2001). In 1873, Dr. Joseph P. Widney, in *Overland Monthly*, proposed diverting the entire Colorado River into the Salton Trough, recreating Lake Cahuilla. The plan (“Lake Widney”) was opposed by Congress, most of whose members thought that the Salton Trough was better suited for agriculture than for a very large lake (Laflin 1995, 1998; Lindsay 2001).

Blake (1854, 1914a) wrote: “It becomes evident that the alluvial soil of the Desert is capable of sustaining a vigorous vegetation. The only apparent reason for its sterility is

the absence of water. By deepening the channel of the New River, or cutting a canal so low that the water of Colorado would enter at all seasons of the year, a constant supply could be furnished to the interior portion of the Desert. With work it is probable that the greater part of the Desert could be made to yield crops of almost any kind."

Prophetically, Blake also warned in his initial report of 1854, "It is indeed a serious question, whether a canal would not cause the overflow [of the Colorado River] once more of a vast surface, and refill, to a certain extent, the dry valley of the Ancient Lake."

Water engineer and developer Charles R. Rockwood organized the California Irrigation Company in 1891 to carry water from the Colorado River to the Salton Trough, but the company failed in the panic of 1893. Agricultural development in the Imperial Valley began in earnest in 1901 when the California Development Company, reorganized in 1896 by Rockwood and water engineer and developer George Chaffey, Jr., opened the Alamo Canal (also called the Imperial Canal) (Fig. 4). Chaffey grandly renamed the desert south of the Salton Sink the Imperial Valley. Rockwood's Alamo Canal brought water to the Imperial Valley by gravity from the Colorado River, roughly following one of the drainages (the then-dry Alamo River) that the Colorado would take when it naturally shifted its course into the Salton Trough. James (1907) and deBuys (1999) described in detail the rapid development of agriculture in the Imperial Valley once water was first delivered in 1901, including the establishment of eight town sites. Chaffey resigned from the California Development Company in 1902 "before its collapse, [but] his reputation suffered from this brief alliance" (Kahrl 1982). Chaffey was replaced by Anthony Heber, who worked with Rockwood to make as much money as possible through the California Development Company, characterized by "bungling, negligence, and greed" (deBuys 1999), although other writers have been more charitable (e.g., Laflin 1995, 1998).

With cheap water made abundantly available by gravity and intense publicity throughout the US, often with much hyperbole, about the fertile soil and year-long growing season, the population of the Imperial Valley quickly rose to >10,000 by 1904

and ~15,000 by 1909 (cultivating 40,000 ha), but did not rise much higher than 40,000 until after World War II. The population of the Valley is now ~100,000, cultivating somewhat over 100,000 ha. In 2000, at a surface elevation of -74.5 m, the Salton Sea was 58 km long, 14 to 24 km wide, and 930 km<sup>2</sup> in area, with a total shoreline of 153 km, maximum depth ~16 m (in both basins), average depth 5 m, and a total capacity of 9,420,566 acre-feet (Ferrari and Weghorst 1997). (Note: 1 million acre-feet = 1.233 km<sup>3</sup>. Since the acre-foot is the unit used by all US water and agricultural agencies, and since there is no convenient metric equivalent, acre-feet will be used throughout this article.)

The original 1901 headgate (Chaffey Gate at Hanlon's Landing: Woodbury 1941) of the Alamo Canal was on US soil in California at Pilot Knob, just downstream from Yuma, at an elevation of ~32 m above ocean sea level and 120 m above the deepest part of the Salton Sink (Fig. 4; ). To avoid the Algodones Dunes, the Alamo Canal initially ran for ~65 km through México just south of the California border until it nearly reached Laguna Volcánica. At that point (Sharp's Landing, with a concrete headgate smaller than Chaffey's at Hanlon Landing: Woodbury 1941; Dowd 1956), irrigation water was turned north to flow to the Imperial Valley. The price for this international concession was that México's Valle de Mexicali was to get half the water diverted by the Alamo Canal. Rockwood also had to set up a subsidiary company chartered in México, La Sociedad de Irrigación y Terrenos de la Baja California. In 1902 the Southern Pacific Railroad built connecting lines from its main transcontinental track (completed from Los Angeles to Yuma in 1877 via San Geronio Pass and the Salton Trough, the last link in its transcontinental railroad) into the Imperial Valley for shipment of crops (Fig. 4). The first crops, chiefly wheat and barley from ~6200 ha, were harvested in 1903. But the low flow gradient at the Alamo Canal intake at Hanlon's Landing in California, created partly because Chaffey did not make the headgates high enough, coupled with the always silty Colorado River, meant that the intake system regularly silted up. Simple bypasses were constructed nearby for the low-water flow winters of 1902 to 1903, and 1903-1904, using



brush mats held down by wire as expedient headgates (not shown in Fig. 4; see Cory [1913, 1915]). These bypasses were inadequate for the winter of 1904 to 1905 (Dowd 1956). Farmers complained.

In October 1904, after a long period of canal siltation and non-delivery of irrigation water, the California Development Company hurriedly opened a “cheap wooden headgate” (Davis 1907a) downstream from the initial one, 6.4 km south of the Mexican border where there was a greater slope -- the “Mexican Cut” (Fig. 4). James (1907) described this new headgate as “a temporary expedient,” and wrote that Rockwood took “desperate chances” in relocating the canal’s headgate downstream in México. Rockwood (1909) explicitly wrote that the Mexican Cut location was *not* selected because the gradient was better there, but because the water capacity was greater there. Rockwood (1909; quoted with apparent agreement by Cory [1913, 1915]) stated that he thought the Mexican Cut would be only a temporary measure, and the breach in the Colorado River could be closed within 6 mo before the usual summer floods in 1905; he would also not have to seek Mexican permission. Cory (1913, 1915) stated clearly that the Mexican Cut headgate was not concrete or wood, but rather like the several bypasses around Chaffey Gate at Hanlon’s Landing, that is, brush bundles held down by wire. Cory (1913, 1915) bluntly stated that, “making this cut was a blunder so serious as to be practically criminal.” George Chaffey was also opposed to the Mexican Cut, saying that the Imperial Valley’s problem was not real lack of water, but siltation (Tout 1931).

The Mexican Cut was not adequate to handle even an ordinary flood. As it turned out, the decade 1900 to 1910 was one of the wettest on record, and was on the crest of a several centuries-high in rainfall and river flow, as document by a millennium of tree-ring weather records. Rockwood was quoted by Laflin (1995) as being worried about the consequences of not getting permission from the Mexican government to relocate the headgate into Mexican territory. He soon got approval by telegram from México’s Presidente Porfirio Díaz in 1904, but did not get formal approval until more than a year

later (Woodbury 1941). During the winter low-water season of 1904 to 1905 Imperial Valley farmers received adequate water.

The Colorado River rises in the Rocky Mountains of Wyoming and Colorado at 3500 to 4000 m. It is fed by highly seasonal and annually variable snowmelt and rainfall, and drops steeply to sea level in only 2720 km (Fradkin 1981). The virgin Colorado River always flooded each year in late spring through early summer, some years much more severely than others: late spring and summer flood flows from Rocky Mountain snowmelt varied by a factor of over 100 times, from a low of  $622 \text{ m}^3\cdot\text{s}^{-1}$  to a high on 22 January 1916 of  $88,288 \text{ m}^3\cdot\text{s}^{-1}$ . The River frequently flooded in excess of  $28,316 \text{ m}^3\cdot\text{s}^{-1}$  (deBuys 1999). In addition, there were often late winter and early spring floods from heavy rains at lower elevations. By late summer and autumn each year, the undammed Colorado became a much smaller, calmer, silty, lukewarm river which posed no flood danger. In spite of the absence of proper headgates, no one watched the Mexican Cut for any signs of trouble during spring 1905 (Cory 1913, 1915). In winter and spring 1905, there were five major floods on the Colorado River, one of which was the second largest recorded in Euro-American historic times (Kahrl 1978), further augmented by floods on the Gila River in southern Arizona. By early spring 1905, the flooding Colorado River had easily breached the Mexican Cut and began to flow into the Salton Trough by way of Laguna Volcánica and the New and Alamo Rivers (Fig. 4). By the end of August 1905, the entire volume of the Colorado River was flowing westerly and then northerly into the Salton Trough instead of southerly to the Gulf of California, chiefly via the New River, erasing several small lakes and lagoons (Cameron Lake, Blue Lake [at 70 ha the largest of these], Calf Hole, Pelican Lake) along the river near the Mexican border, lakes that had provided water for local Indians, travelers, and livestock and which were good wildlife habitat. Broad sheets of flood waters and washed out bridges.

The newly forming lake in the Salton Sink, immediately named the Salton Sea, rose rapidly (by as much as  $17.5 \text{ cm}\cdot\text{d}^{-1}$ : Sykes 1937), submerged the New Liverpool salt

works as well as roads and other buildings adjacent to the playa. Major Colorado River floods again occurred in winter and early spring 1906, washing out almost-completed repair works several times. James (1907) provided much detail, including informative maps, on early efforts to force the Colorado River back into its original bed. When he had completed his manuscript in October 1906, James thought that the Mexican Cut breach would be closed within the month. Despite serious damage again to the almost-finished repair works by a November 1906 flood, James' (1907) prediction was ultimately correct, if postponed. By early spring 1907 the breach was permanently repaired in the seventh attempt, and the entire Colorado River again flowed south to the Gulf (Cory 1913, 1915). deBuys (1999) called this 2-yr flood into the Salton Sink the "Great Diversion," a term that no one else has used. In August 1907, residents of the Imperial Valley voted overwhelmingly to secede from San Diego County, which had always ignored what was going on so far east and continued to do so during the flood, forming Imperial County (Howe and Hall 1910).

Many current accounts, popular and scientific, call the 1905 to 1907 formation of the Salton Sea an "accident." Typical is Skrove (1986) writing for the Metropolitan Water District; the title of his article is "Salton Sea: Nature's mistake in the desert." He called the Salton Sea "a freak of nature," and described its origin as, "A tempestuous Colorado turned inland and gushed down a system of canals and conscripted riverbeds." But writing as early as 1906, James (1907) called the Mexican Cut and several subsequent engineering decisions a "fatal mistake." Davis (1907a) stated bluntly, "the irrigating company [was] responsible for the break." A 1960s letter written by a Wiley Magruder (quoted by Laflin 1995) said, "The Salton Sea lies there a shining shimmering monument to man's carelessness." de Stanley (1976) wrote, "the Salton Sea was born of man's mistake." Pepper (1999) wrote of "careless construction." The California Water Atlas (Kahrl 1978) called the Sea's formation an "engineering mistake." Fradkin (1981) concluded that this human-caused breach was "no accident," based as it was on inferior

construction of irrigation works; rather, it was “one of the greatest engineering mistakes of the century.” Kaiser (1999) was even stronger, calling the formation of the Salton Sea an “engineering debacle.”

The 1905 to 1907 Colorado River floods created a waterfall (called the Cutback) in the New River that, because of soft, highly erodable lacustrine sediments, retreated rapidly upstream (southerly) from the rising Salton Sea, a problem predicted as early as 1853 by Blake (Blake 1854, 1914a). A similar but less publicized cutback developed in the Alamo River. Harold Bell Wright in his best-seller 1911 romance *The Winning of Barbara Worth* correctly wrote about the New River waterfall: “The imminent danger that threatened the [Imperial] Valley was not the danger from the ever-rising sea. Long before the waters could fill the old sea-bed [*sic*], that mighty cataract, moving ever upstream, would pass the intake; and with the floor of the river lowered some [16 m] it would be impossible to take the water out for irrigation. The lands reclaimed by the pioneers would go back to desert years before they would be buried once more under the surface of the sea.” Wright’s (1911) novel fictionalized the “reclamation” of desert lands to agricultural lands, lightly disguised the Imperial Valley, turned promoter Rockwood into a hero (“The Seer”), and ended with a simplified formation of the Salton Sea as the backdrop to plot resolution; the novel is better literature than history. Wright occasionally used one of the older names for the Salton Trough, the lovely La Palma del Mano de Dios (The Palm of God’s Hand).

The 1905 to 1907 cutback in the New River retreated upstream as much as 1 km-d<sup>-1</sup>, becoming progressively higher as it cut south (up to 40 m); it reached Calexico in early 1906. The Alamo River cutback passed Holtville at the same time (Davis 1907a; Elders 1979b). There was great concern that if the cutback reached the Colorado River bed itself, it would take out Laguna Dam (Fig. 6; called Laguna Weir by Cory 1913, 1915), then being constructed a few km upstream from Yuma by the newly established US Reclamation Service to irrigate the Yuma Valley (Davis 1907a; Cory 1913, 1915).

Rockwood (1909) complained that the US Reclamation Service “retarded and handicapped” the California Development Company in dealing with the flood. The cutback was curtailed in Laguna Volcánica in México, by dynamiting. Four-fifths of Mexicali was washed away, and other communities in the Imperial and Coachella Valleys were flooded (Fig. 4).

Rockwood’s California Development Company, always undercapitalized, immediately went into receivership. The Southern Pacific Railroad first loaned money to the company and then leant its engineers, and began attempts to save its own transcontinental railroad and Imperial Valley spurs, several times moving 96 km of its tracks uphill (the last time to the -61 m contour, where they remain) and eastwards as the Salton Sea rose (Blake 1914a; Sykes 1914; Cory 1913, 1915; Laflin 1995, 1998; deBuys 1999). Southern Pacific quickly became entangled in the financial and engineering affairs of the California Development Company.

The 18 April 1906 M 7.8 earthquake and fire in San Francisco delayed repair of the Colorado River breach, as state and national attention and potential money for disaster relief were focused on San Francisco. Southern Pacific suffered great damage in the quake, and its new dredge *Delta*, being built in Oakland, was also severely damaged and therefore much delayed in arriving at the Colorado River. Nevertheless, the *Delta* proved extremely important in the success of the seventh and last attempt to close the levee breach (Cory 1913, 1915).

By heroic efforts of men associated with the Southern Pacific Railroad headed by Cory, greatly assisted by Indians of the Imperial Valley, lower Colorado River, and northern Baja California recruited by Cory, the Colorado River was finally forced back into its normal southwards channel in February 1907. Work was complicated by the presence of a large sand bar covered with cottonwoods (*Populus fremontii*) and arrow weed (*Pluchea sericea*), dubbed Disaster Island, in the middle of the river directly across from the Mexican Cut (not shown in Fig. 4; see Cory [1913, 1915]). Disaster Island

diverted water and flood debris directly into the Mexican Cut, enlarging it and destroying repair work. Ultimate success came only by dumping immense boulders from specially-built train cars on a trestle built on pilings across the levée break. The Mexican Cut breach in the Colorado River had widened in 2 yr from its initial 17 m to 1.2 km. All available rolling stock west of the Mississippi was mobilized by Southern Pacific and Union Pacific, spending >\$5 million on a repayment promise from President Roosevelt to Southern Pacific President Harriman (who also controlled Union Pacific). de Stanley (1976) and Laflin (1995) presented a fascinating December 1906 to January 1907 telegram exchange between Harriman and Roosevelt, who initially believed that the railroad was directly responsible for the flood. Harriman persuaded the President that only the California Development Company was responsible, which deBuys (1999) regarded as debatable given the close control of the development company by the railroad. President Roosevelt promised federal financial assistance. de Stanley (1976) published the entire text of the President's January 1907 message to Congress, making a strong case for federal involvement and financing. Imperial Valley Rep. Smith opposed the bill because of its proposed transfer of all irrigation works to the new federal Reclamation Service, and the bill failed. Southern Pacific was repaid by the US government only in 1930 and then only \$1,012,665.17 (de Stanley 1976; Elders 1979b).

The present New River near Calipatria shows the conspicuous 1905 to 1907 river bed, now dry and here ~0.8 km wide and 10 m deep, cut in only 2 yr; further upstream (south) it is incised as much as 16 m. The post-1907 New River here has cut a much narrower inner channel, ~10 m deep, in the past 90 yr, which meanders across the wide 1905 to 1907 bed (Oglesby pers. obs.). Cory (1913, 1915) pointed that an important benefit of the 2-yr flood was that the creation of *barrancas* (deep gorges) of the New and Alamo Rivers made them much more effective as agricultural wastewater drains than their shallow pre-flood states when waste water frequently flooded adjacent lands.

Construction and careful maintenance of levées along the Colorado River averted a



re-establishment of the breach during the spring and summer floods of 1907. Within a few years, additional levees were built along the distributaries leading to Laguna Volcánica, averting floods from that direction (Cory 1913, 1915). The headgates of the Alamo Canal were soon restored to the US side of the Mexican border, but the initial run of the canal remained in México. In 1909 the US Reclamation Service (renamed US Bureau of Reclamation in 1924) finished Laguna Dam just north of Yuma and relocated the headgates of the Imperial Canal to above that dam. The original Alamo Canal now diverts water from behind México's Morales Dam into the Valle de Mexicali, the final dam on the River.

The powerful Imperial Irrigation District, the largest irrigation district in the US, was organized in 1911 and has prior appropriation rights over all other water agencies in California for water from the Colorado River; it is, in fact, the largest single user of Colorado River water in any state. The District bought the remaining assets of the California Development Company from Southern Pacific and distribution canals from several mutual water companies (US Department of the Interior and The Resources Agency of California 1969). The Boulder Canyon Act of 1928 authorized not only Hoover Dam in Black Canyon of the Colorado, but also a new All-American Canal heading from above Imperial Dam, completed in 1939. The District finally had a canal whose permanent headgates would assure its allotted share of Colorado River water. Not until Hoover Dam was completed in 1936 were the problems of Colorado River floods, siltation, and levée maintenance overcome (Laflin 1995, 1998; deBuys 1999). From the beginning at the turn of the century, the *Los Angeles Times* was a major booster of these irrigation projects. Perhaps not coincidentally, Harrison Gray Otis, publisher of the *Times*, was the leader of a syndicate of southern Californian businessmen that owned most of the Valle de Mexicali under the name Colorado River Development Company, incorporated in México (Cory 1913, 1915).

Imperial Irrigation District now serves 113,671 ha of irrigated lands, involving

6000 headgates and 4800 km of canals, all ultimately draining to the Salton Sea (Fradkin 1981; Breuer 1992). "The Imperial Valley boasts one of the most complex hydraulic engineering projects in the world" (Cohen et al. 1999). The Coachella Canal, a northern branch of the All-American Canal, and its canal and drain system were completed in 1949 (Fig. 6; US Department of the Interior and The Resources Agency of California 1969; Nordland 1978; Fradkin 1981). The Coachella Valley Water District serves 16,447 ha in the Coachella Valley, where irrigated agriculture began in 1884, using both groundwater and Colorado River water (Nordland 1978). Imperial Valley uses 86% of the Colorado River water initially diverted into the All-American Canal, and Coachella Valley the rest. A brief but detailed chronology of Colorado River dams and diversions, state and federal legislation, major legal and political actions, and unresolved issues is provided by Newman (1998).

With 9 major dams and reservoirs on its mainstem and at least 14 additional dams on its tributaries, the Colorado River no longer carries much silt and no longer floods, except when excess water releases are made from upstream dams, as happened in 1983 with releases from Glen Canyon Dam to prevent it destroying its spillway (Weatherford and Brown 1986b; Reisner 1993). Because of its many reservoirs, the Colorado River has been changed from a lukewarm- to a cold-water river. Its suite of extraordinary native fishes (37 species, 23 of which were endemic), marvelously adapted to surviving raging spring floods and low, warm late summer flows, is effectively extinct in the tamed Colorado River itself. Three species are now extinct, and 17 additional species are listed as federally Threatened or Endangered, most hanging on only in the few undammed upstream tributaries (Colorado River Wildlife Council 1977; Holden 1979; Nicola 1979; Hamman et al. 1994; Rinner and Tyus 1994). Two of these Endangered species are no longer found in the California reach of the Colorado River: the Colorado squawfish (*Ptychocheilus lucius*, in an excess of political correctness now officially called Colorado pikeminnow), a predatory minnow that could exceed 36 kg and 2 m, and bonytail chub

(*Gila elegans*), which was found in the newly formed Salton Sea until its rising salinity eliminated the chubs by the second decade of the 20th century. Only one of these Colorado River endemic species is now found in the Salton Trough, the humpback or razorback sucker (*Xyrauchen texanus*). It is on both federal and California lists of Endangered species, and is occasionally seen in dewatered drains and canals (Table VIII; Imperial Irrigation District 1994).

The popular idea that the Salton Sea was immediately saline in 1907 (Wambaugh 1992) is not true: the salt deposits in the Salton Sink playa came from freshwater lakes and were inadequate to raise significantly the salinity of 2 yr of Colorado River floodwaters, a fact well known nearly a century ago (James 1907; Free 1914; Arnal 1961; Carpelan 1961b). Arnal (1961) stated that silt carried in the overflowing 1905 to 1907 Colorado River buried Salton Sink evaporite deposits so fast that they were not fully dissolved into the newly forming Salton Sea. The Colorado River in 1907 was 0.7‰ and the initial Salton Sea was 3.6‰, a value reflecting both Colorado River salt input (20%) and salt leached from the playa (80%) (Table II; Arnal 1961; Carpelan 1961b).

In spring 1907 the new freshwater Salton Sea at its largest extent had a maximum area of 1583 km<sup>2</sup>, twice that of the present Salton Sea; a maximum depth of 25.3 m, 10 m deeper than at present; and a surface elevation of -59.4 m, 10 m higher than today's Sea (Fig. 4). Scientists of the Desert Laboratory of the Carnegie Institute of Washington studied the biology, hydrography, and land forms of the desiccating Salton Sea for 5 yr (1907 to 1912) and published a handsome report edited by MacDougal (1914a).

Cut off from the Colorado River in 1907, the Salton Sea desiccated by  $\sim 2 \text{ m}\cdot\text{yr}^{-1}$ , reaching its lowest elevation of -83 to -87 m in 1925, and only then becoming a salt lake with a salt content near that of ocean seawater ( $\sim 40\%$ ). Initial opinion was that the Salton Sea would actually dry up, but with increasing inflow from increased irrigation wastewater, the Salton Sea in 1926 began in to increase steadily and rapidly in volume, elevation, and area, and to decrease in salinity. President Coolidge in 1924 issued an

Executive Order withdrawing lands below -80 m and in 1928 he further withdrew all lands below -72 m to provide “an evaporative pan for surplus and waste water from Imperial Valley irrigation development,” with flooding rights controlled by the Imperial Irrigation District (Coachella Valley Water District 2000). These withdrawals were apparently done without the President’s staff realizing that 3124 ha had already been withdrawn in 1876, 1891, and 1909 by the Department of Interior for the Torres-Martinez Desert Cahuilla Reservation, including 2340 ha that were soon inundated by the Salton Sea.

One major result of this error has been perpetual law suits, so far never successful for the Torres-Martinez Desert Cahuilla, even though Imperial Irrigation District and Coachella Valley Water District have settled many millions of dollars for inundation of agricultural lands and shoreline developments elsewhere around the Sea’s shoreline, owned by non-Indians (James 1960; Lopez 1998; Pomento 1998; Cohen et al. 1999; deBuys 1999). In December 2000 Congress passed a bill that compensated the Torres-Martinez Desert Cahuilla \$14 million (\$10.2 million from the US, the rest from a settlement between the tribe and Imperial Irrigation District and Coachella Valley Water District).

Prior to the late 1990s, the highest salinity recorded for the Salton Sea was ~43‰ in 1938 (Hely et al. 1966; US Department of the Interior and The Resources Agency of California 1969). The high salinity ( $\pm$  that of the ocean) of the Salton Sea coupled with high evaporation rates and low rainfall associated with the desert climate led to several attempts at commercial salt production along the eastern shore during the 1930s and 1940s, more difficult than at the ocean because of the higher concentration of  $\text{CaSO}_4$  (gypsum) (Table II). None of these operations was particularly successful, and all succumbed to rising waters by the mid 1940s.

In 1968, California enacted a statute declaring that the primary use of the Salton Sea was for collection of agricultural wastewater, seepage, leaching, and control waters (Stats. 1968, Ch. 392, Sec. Z).

In 1980, the US Supreme Court permanently exempted Imperial Valley farmers from two “onerous” provisions of the 1902 Reclamation Act: (1) subsidized federal water could be applied only to farms of 65 ha or less (130 ha for a married couple), and (2) farmers had to live on or immediately adjacent to their lands. These provisions had been ignored in the Imperial Valley since the beginning of irrigated agriculture in 1901. In the 1990s 60% of the land ownership was absentee, and the largest single holding was 17,200 ha, ~10% of all the acreage in the Imperial Valley (Fradkin 1981; Hundley 1986; deBuys 1999).

Once the sport fishery was established so successfully in the 1950s (see below), there was a concerted attempt to turn the Salton Sea into a major destination resort, based on fishing, golfing, boating, relaxation, and the enjoyable climate (ignoring intense summer heat, windstorms, and sandstorms). The most ambitious of these residential resorts was Salton City on the western shore (Fig. 1), promoted as *the* paramount California resort, called the “Salton Riviera” (Lindsay 2001). It was “one of the Sea’s liveliest resorts,” with its golf course, motels, marinas, restaurants, boat-launching ramps, marine supply stores, trailer parks, a casino, and many lots for private residences; now it does not rate even a mention in the American Automobile Association’s *Guidebook to the Southern California Desert Area* (Lindsay 2001). deBuys (1999) described how the promoter fleeced many hundreds of people; others believe that the developer was misguided and over-enthusiastic but fundamentally honest.

Burns (1963) and de Stanley (1976) rhapsodized about the shoreline resorts, but in fact none of them was ever remotely successful. All are ghosts now, with drowned marinas, yacht clubs, motels, and jetties; empty and vandalized motels and restaurants; closed casinos; and many of the few residences abandoned to sandblasting by the strong winds (see Landis 2000; Lindsay 2001; Oglesby pers. obs.). Empty and even developed lots have reverted to Imperial and Riverside Counties for unpaid property taxes, and real estate agents will not take listings since they know the properties will not sell.

Snowbirds still winter in places such as Desert Shores and Bombay Beach, and the few die-hard residents may be found anywhere.

Almost from its beginning in 1907, the Salton Sea was a focus of diverse recreation, including fishing (see below), birding (see below), waterfowl and dove hunting, camping, nature study, photography, sightseeing, ecotourism, boating, off-road vehicle use, rock and gem hunting, speed boat racing, sailboarding, water skiing, and Jet Skiing. The Sierra Club's Executive Director Pope included Jet Skis as one of "Eight Inventions That Make American Life Worse," writing, "The engines on these noisy polluters pump up to a quarter of their fuel directly into our waters" (*Southern Sierran*, Angeles Chapter, Sierra Club, February 2000). In a ride of 2 hr, a Jet Ski can release as much air pollution as a 1998 passenger car driven 222 km. A number of cities and counties around the country have put severe limits on operations of Jet Skis and other personal water craft, including banning them completely (University of Massachusetts Urban Harbors Institute *Coastlines*, October 2000).

It is widely believed that the Sea's below-sea level elevation and thus higher barometric pressure increases absolute concentration of O<sub>2</sub> in the atmosphere, and that its high salinity creates greater water density and thus increased buoyancy, both making the Salton Sea the fastest body of water in the world for speedboat racing (e.g. Laflin 1998). Boat racing began as early as 1928. At the 1951 Regatta, 21 world records were set. Because airplanes could fly such a long distance below sea level in the Trough, a number of world speed records were set over the years (Laflin 1998).

Water contact recreation has declined in recent years (Salton Sea Authority 2000), though the Sea has always been a Class I water, suitable for body contact. In the 1980s, the Salton Sea and adjacent wildlife areas had up to 1<sup>1/2</sup> million use-d-yr<sup>-1</sup>, more visitors than Yosemite National Park (Pomento 1998). An additional 360,000 use-d-yr<sup>-1</sup> were for fishing and 1.1 million use-d-yr<sup>-1</sup> for other forms of recreation, involving yearly expenditures of well over \$4 million. Visitor use gradually dropped to a low of 87,600 in



1994 to 1995, but has since rapidly increased to 275,000 in 1998 to 1999 (Salton Sea Authority 2000). In an attempt to increase visitation, a \$1 million fishing derby was scheduled for summer 2000 (*Los Angeles Times* 29 May 2000).

People have always complained about unpleasant odors emanating from the Salton Sea, particularly in the summer and usually attributed to sewage, which is most assuredly not the case (see below). Odors are at their worst in drowned agricultural fields nearly surrounded by former road dikes that lead to poor circulation, and to summer mixing of hypoxic hypolimnetic waters with surface waters, bringing  $H_2S$  to the surface. These odors have been present for many decades, and do not seem to be getting worse at present, despite increasingly negative publicity (Oglesby pers. obs.). The Salton Sea Authority (2000) attributed odors to the hypereutrophic condition of the Sea which leads to decaying organic matter and  $H_2S$  production, but eutrophication by itself does not necessarily cause odors. Another proposed source of odors is decaying fish from fish kills, also attributed to recent problems in the Sea, though fish kills have been regular since at least the 1950s (see below). Dead fish may rot while floating on the Sea, generating  $H_2S$ , but they desiccate quickly once they wash ashore, without generating any odors (B. W. Walker 1961; Oglesby pers. obs.).

Rumors and errors have surrounded the Salton Sea since its formation in 1907. Davis (1907a) called published rumors that the newly formed Salton Sea was significantly altering the climate of the entire southwestern US “absurd.” Henry (1907a) provided a longer analysis of the supposed climate problem and concluded that at most only a local and modest increase in relative humidity was likely. At various times books and articles in the popular press publicized “imminent dangers,” such as:

- Loss of Colorado River silt trapped behind Hoover and other dams would lead to tidal breaching of the Colorado delta and Gulf of California seawater flooding the Salton Trough.
- Strong earthquakes would open deep cracks in the delta through which Gulf

seawater would flow, causing the Salton Sea to rise rapidly.

- The “mysterious and weird” Salton Sea was rising so rapidly from unstated water sources that it would soon burst its banks and flood the entire Salton Trough (nonsense on the face of it: there are no banks to breach as there are no lower adjacent areas to flood).

Imperial Irrigation District Executive Officer Dowd (1960) debunked all these purported “dangers,” as did Oertle (1964). Dowd’s pamphlet was self-serving to the District, but he was correct in his analyses of why these “dangers” were mere hyperbole and fears based on lack of scientific and historical knowledge.

### **Sources of Water to the Salton Sea**

In 2000, at a surface elevation of -74.5 m, the Salton Sea was 58 km long, 14 to 24 km wide, and 930 km<sup>2</sup> in area, with a total shoreline of 153 km, maximum depth ~16 m (in both basins), average depth 5 m, and a total capacity of 9,420,566 acre-feet (Ferrari and Weghorst 1997). (Note: 1 million acre-feet = 1.233 km<sup>3</sup>. Since the acre-foot is the unit used by all US water and agricultural agencies, and since there is no convenient metric equivalent, acre-feet will be used throughout this article).

The Salton Sea receives almost all its water as wastewater from agriculture in the Valle de Mexicali and Imperial Valley by way of the New and Alamo Rivers, virtually all deriving ultimately from the Colorado River (Arnal 1961; Hely et al. 1966; California Department of Water Resources 1970; US Department of the Interior and The Resources Agency of California 1974; Layton and Ermak 1976; Colorado River Board of California 1992; Salton Sea Authority 2000). Inflow is ~1.3 million acre-feet·yr<sup>-1</sup>; the impounded volume in 1993 (surface elevation -69.5 m) was ~8 million acre-feet. Thus, ~1.4 % of the volume of the Sea enters on a daily basis and 5 times the total volume·yr<sup>-1</sup> (Cook and Orlob 1997). All these inputs are at least somewhat saline rather than pure freshwater, varying from ~2.5‰ to 9‰, depending on evaporation rates and leaching of salts from

fields. Listed in rank order, the individual water sources are:

1. Discharge of the Alamo River at its outlet to the Sea averages  $\sim 620,000$  acre-feet $\cdot$ yr $^{-1}$  (46.1% of total input to the Sea), of which only 0.3% enters the US from the Mexican side of the border. The Alamo River originates in México, crosses the US border some 11 km east of Calexico and Mexicali, and runs 84 km to its mouth at the southeast Salton Sea. The Alamo River (watershed 4344 km $^2$ ) is fed entirely by agricultural wastewater, but does not receive the heavy industrial and domestic pollution of the New River, and so has not been publicized as problematic (US Bureau of Reclamation 1998; but see California State Water Resources Control Board 1981; Moore 2000).
2. The New River (Río Nuevo) discharges an average of  $\sim 438,000$  acre-feet $\cdot$ yr $^{-1}$ , 32.5% of total Salton Sea input, of which  $\sim 1/3$  comes from México. The New River (watershed 6250 km $^2$ ) rises in México (originally at Laguna Volcánica), crosses the US border at Mexicali and Calexico, and runs 97 km to its mouth at the southernmost Salton Sea. The New River is widely regarded as the most polluted river in the US (Anonymous 1989; LFR 1999; *USA Today* 11 May 2000; Moore 2000), receiving pesticides and fertilizers from agricultural fields on both sides of the international border, organic inputs from cattle feed lots, industrial wastes both from Mexican industry and *maquiladoras* (foreign-owned Mexican export-assembly companies), and untreated sewage from Mexicali (population  $\sim 800,000$  to 1,000,000), which lacks a viable sewage treatment system (*Time Magazine* 20 April 1987; Anonymous 1989; *Los Angeles Times* 4 November 1995 7 August 2000; US Bureau of Reclamation 1998; *USA Today* 12 May 2000). Handsome color photos of New River debris are provided by Moore (2000). The New River deposits  $5 \times 10^8$  kg $\cdot$ yr $^{-1}$  of suspended sediment onto its delta in the Salton Sea. At this rate, added sediment from all sources would amount to  $\sim 4\%$  of the total volume of the present Salton Sea (LFR 1999). Diverse projects have been proposed for cleaning up the New River (see below).
3. Surface drains from agricultural fields directly entering the Salton Sea are estimated to

discharge  $\sim 106,000$  acre-feet-yr $^{-1}$ , 7.9% of total input.

4. The Whitewater River draining the San Bernardino and San Jacinto Mountains west and north of the Coachella Valley contributes  $\sim 79,000$  acre-feet-yr $^{-1}$ , 5.9% of total input. Over 40% of the Coachella Valley uses drip irrigation; tailwater disposal was prohibited in the 1950s. Agricultural runoff to the Sea from the Coachella Valley is therefore much reduced compared to the Imperial Valley (Colorado River Board of California 1992; US Bureau of Reclamation 1998). Before it enters the north end of the Salton Sea, the Whitewater River is renamed (and demeaned) as the Coachella Valley Stormwater Channel. See Nordland (1978) for a detailed history of Coachella Valley floods and attempts to control them.
5. Groundwater inflows are hard to determine, but it is estimated that  $\sim 50,000$  acre-feet-yr $^{-1}$  enter the Sea ( $\sim 3.7\%$  of total inflows), with  $\sim 30,000$  acre-feet-yr $^{-1}$  of this volume coming from the Coachella Valley with its high water table and permeable sediments,  $\sim 10,000$  acre-feet-yr $^{-1}$  entering from the general area of San Felipe Creek, and only  $\sim 2000$  acre-feet-yr $^{-1}$  coming from the Imperial Valley because of its mostly impermeable sediments. The remaining  $\sim 8000$  acre-feet-yr $^{-1}$  come from all other perimeter areas (Colorado River Board of California 1992). Groundwater throughout the Salton Trough is saline, varying from an estimated 8‰ in San Felipe Valley to 16‰ in the Imperial Valley, with an average from all sources of 1.3‰ (these conflicting data come from Salton Sea Authority 2000).
6. The only other significant surface flow to the Sea is intermittent San Felipe Creek draining the Laguna and Santa Rosa Mountains (Fig. 4), whose 5,500 acre-feet-yr $^{-1}$  is negligible compared to other sources (Hely et al. 1966). Biologically important is San Sebastian Marsh (Ciéneguita del Tular, elevation -10 m). This marsh is a 23 km $^2$  area of permanent water and marsh at the confluence of four intermittent drainages: Carrizo, Coyote, Fish, and San Felipe Creeks,  $\sim 10$  km upstream from the present Salton Sea (Fig. 4, at the junction of San Felipe Creek and the unnamed Carrizo Creek). Salt Creek

on the east shore (Fig. 1) contributes much less,  $\sim 1,000$  acre-feet-yr<sup>-1</sup>.

7. Seepage from the unlined Coachella Canal contributes an unknown but probably significant amount of water to the Sea (Fig. 6). Cutting off this important source of freshwater by lining major canals, especially the Coachella, with concrete might additionally stress the Salton Sea and its biota, as well as the excellent wildlife habitats of springs and seeps fed by underground seepage (Layton and Ermak 1976; Pryde 1999).
8. Natural runoff and rainfall are inconsequential ( $\sim 46,500$  acre-feet-yr<sup>-1</sup>, 3.5% of the total). Average rainfall is  $< 7.5$  cm-yr<sup>-1</sup>, but both total rainfall and its seasonal patterning are exceedingly variable; some years there is no rain at all (California Department of Water Resources 1970; Layton and Ermak 1976; Rowlands, 1999a). Winter cyclonic storms out of the Pacific Ocean provide the major rainfall to the Salton Trough, but summer rains (from México via Arizona), usually thunderstorms (erroneously called “monsoons”), can be significant. The southern Imperial Valley gets  $\sim 30\%$  of its annual rainfall in the summer, declining northwards to 20% at Palm Springs in the Coachella Valley (Rowlands 1999a). Rare *chubascos* (late summer hurricanes which move northwards along the west coast of México) have sometimes dropped as much as 22.5 cm of rain in 24 to 48 hr. Such downpours can cause flash floods in mountain and desert streams, and can raise Sea elevations dramatically (Oglesby pers. obs.); Hurricane Kathleen in 1976 raised the Salton Sea nearly 20 cm in just 1 d. *Chubascos* were of regular occurrence in the 20th century through 1939, but only three have hit California since, in 1976 and 1977.

It is important to realize that even had the Salton Sea not initially been formed by inept diversion from the Colorado River in 1905 to 1907, it would be the same size and composition now (Table II). Since 1925, increased volumes of irrigation wastewater resulted in a nearly continuous rise in Sea's elevation, with a temporary period of stasis in the mid-1960s and a rapid rise of  $\sim 15$  cm-yr<sup>-1</sup> beginning in the early 1970s. In the late

1970s, above normal rainfall also contributed to a rising Salton Sea. With increasing efforts by Imperial Irrigation District at water conservation, less agricultural water has been “wasted” to the Sea beginning in the late 1980s, leading again to surface-elevation stabilization. Surface elevation in 1984 was ~69 m and was about the same in the late 1990s. Sea elevation varies by ~0.3 m within the year due to seasonal differences in evaporation and wastewater input, being highest in June and lowest in mid-autumn.

In 1981 27 property owners, mostly from the southwest shoreline of the Salton Sea, won a suit against Imperial Irrigation District over loss of lands and buildings to the rising Salton Sea and water-logging of soils adjacent to the shoreline. One of the findings of the state’s Water Resources Board (California Water Resources Control Board 1984, 1988) was that Imperial Irrigation District secretly wasted 550,000 acre-feet-yr<sup>-1</sup>, water that was permitted to go directly into drains, and thus into the Salton Sea, from main canals without ever being put on an agricultural field (spillwater). This spillwater wastage was in addition to the 550,000 acre feet of tailwater discharged into the Sea through ordinary agricultural uses (California Water Resources Control Board 1975, 1982, 1988; Coe 1981; Pryor 1981; California Reporter 433 Cal. App. 4 Dist. 1984; Matthews 1982; *Los Angeles Times* 17 August 1985; Breuer 1992; Colorado River Board of California 1992; deBuys 1999).

The Boulder Canyon Act of 1928 allocated California 4.4 million acre-feet-yr<sup>-1</sup>, but allowed California to take its proportional share of otherwise unused Colorado River water. Of this, Imperial Irrigation District takes 3 million acre-feet-yr<sup>-1</sup>, with ~1.3 million acre-feet-yr<sup>-1</sup> ending up in the Salton Sea. Currently, California is actually taking ~5.2 million acre-feet-yr<sup>-1</sup>, well over its allotment; there are many initiatives to force California to reduce its take to its allocated 4.4 million acre-feet-yr<sup>-1</sup>. In the Imperial Valley, ready availability of cheap, federally subsidized water, extremely arid environment, intense heat, irrigation practices designed to flush salts from the fields, and reliance on water-intensive crops all contribute to the Valley’s high water use (Cohen et al. 1999). There are ample



opportunities for changed agricultural practices, water conservation, and marketing water outside the Salton Trough. One certain result is that much less water will enter the Salton Sea in the future, perhaps as little as ~800,000 to 850,000 acre-feet·yr<sup>-1</sup>, ~62% of present input (see below). This great reduction in inflow will have major effects on the Salton Sea ecosystem, and must be taken into account in any proposed “restoration” plan.

### Chemical and Physical Limnology

The term *salinity* is properly used *only* for open ocean seawater, and not for freshwaters and inland saline waters, either marine in derivation (thalassic) or athalassic, as non-seawaters do not show the ion ratios characteristic of open ocean seawater. But it is convenient to write about the salinity of inland athalassic waters, especially since many authors casually use this terminology and use AgCl titration or salinometers to measure it. Hutchinson (1975) described salinity of inland waters as “the concentration of all the ionic constituents present.” Salinity is expressed as ‰, which is parts per thousand, ppt, mg·l<sup>-1</sup>; by definition, 100‰ ocean seawater is 35‰. There is no “normal” salinity for inland waters, just whatever the actual salinity might be.

The Salton Sea is vertically and horizontally homogenous (well mixed) except for small inshore areas where tributaries enter (Arnal 1961; Cook and Orlob 1997). Salton Sea water represents Colorado River water modified by passage through irrigated fields (soil leaching, exchange of chemicals with the soil, intense evaporation), with relatively higher concentrations of Ca<sup>2+</sup> and SO<sub>4</sub><sup>2-</sup> and relatively lower concentrations of Mg<sup>2+</sup>, Na<sup>1+</sup>, K<sup>1+</sup>, and Cl<sup>1-</sup> as compared with ocean seawater (Table II). Carpelan (1961b) and Arnal (1961) summarized salinity and ionic compositions of the Salton Sea and the major rivers from 1907 to 1955. Lowest salinities in the Sea were found near the mouths of the three rivers. Arnal (1961) concluded that New River water mixed completely with Salton Sea water within ~10 to 13 km of its mouth, along the east side of the Sea. During the 1960s and early 1970s, with Sea elevation more or less stabilized, its salinity rose at the

rate of  $0.5\text{‰}\cdot\text{yr}^{-1}$ . With the increase in Sea elevation and volume since 1975 ( $\sim 15\text{ cm}\cdot\text{yr}^{-1}$ ) its salinity stabilized and even declined somewhat. In 1985, its salinity reached  $\sim 38\text{‰}$ , rising to 39 to  $40\text{‰}$  by 1989, and to 40 to  $47\text{‰}$  by 1999 (González et al. 1998; Hart et al. 1998; Oglesby pers. obs.).

Most attention has been, and is being, paid to increased salinity as the single most important problem facing Salton Sea biota (see below). Hagar and Garcia (1988) pointed out that a species' existence in relation to increased salinity in the Salton Sea could depend on any or all of the following circumstances:

- Direct mortality due to exceeding high salinity tolerance (see below).
- Reproductive failure at high salinities. Many studies indicate that this problem will occur at salinities below the limit for adult survival of a variety of species of fish and invertebrates (see below).
- Loss of food supply due to exceeding the food's tolerance for high salinity; that is, increasing salinity will change the trophic structure of the Salton Sea. Fewer species would be present, though overall invertebrate abundance might not diminish.
- The salinity at which other physiological and biological factors interact with salinity to cause mortality or reduced reproduction.

As discussed by Imperial Irrigation District (1994), Hagar and Garcia in 1988 found little information on the last two of these situations; limits to reproduction and adult salinity tolerance are discussed for many Salton Sea species (see below). Imperial Irrigation District (1994) reproduced a lengthy table from Hagar and Garcia which estimated the severity of impact of increased salinity on Salton Sea biota.

It is sometimes stated that the Salton Sea is an alkaline lake. Available data indicate otherwise. The Salton Sea varied from  $pH$  8.3 to 8.6 in winter and from  $pH$  8.5 to 8.8 in summer in the 1950s (Arnall 1961; Carpelan 1961b). The lowest measurement in the mid-1950s was  $pH$  7.3 in mid-Sea bottom waters and the highest  $pH$  8.9 near the delta

of the New River (Arnal 1961). In the 1970s through 1990s, *pH* varied from 7.5 to 8.7 in the spring (Phelps and Anspaugh 1976; Salton Sea Authority 2000; Coachella Valley Water District, pers. comm.; Oglesby pers. obs.). The usual *pH* (~8.3) of the Salton Sea is only slightly higher than that of the ocean (Sverdrup et al. 1942) and many ordinary freshwater lakes (Hutchinson 1957), and is considerably less than true alkaline lakes in the arid West, whose *pH* exceeds 9; for example, Mono Lake has a *pH* of 10 (Hutchinson 1957; Hammer 1986; Mono Basin Ecosystem Study Committee 1987).

*pH* measurements in irrigation drains and the three rivers in 1969-1975 varied from 7.3 to 8.5 (data of the California Department of Water Resources cited by Swajian 1976). Whitefield Creek in the Salton Sea State Recreation Area, which receives no irrigation wastewater, varies from *pH* 7.4 to 8.4 (higher values reflect Salton Sea water in the bottom of this stratified stream), and the concrete-lined Cleveland Street Spillway near North Shore (Fig. 5, as "Coachella Spillway"), which contains irrigation drainwater, from *pH* 7.1 to 8.0 (Oglesby pers. obs.). These values are well within normal ranges for freshwater streams (Hutchinson 1957).

Always a saline river because of natural saline springs and marine and evaporite geological formations through which it flows, the salinity of the Colorado River increases sevenfold from its headwaters to Imperial Dam just above Yuma (Fradkin 1981). Salts leached from geological formations are responsible for 47% of the river's total increase in salinity. Additional causes of increased salinity of the river include irrigation returns (37%), export of pristine waters (3%), inputs of municipal and industrial wastes (1%), and evaporation from its many reservoirs (12%) (data of Colorado River Water Quality Improvement Program cited by Evans 1976; Fradkin 1981; Reisner 1993).

The Imperial Valley has little usable groundwater because of impermeable sediments and absence of adjacent mountains to provide runoff, and relies entirely on imported Colorado River water for both agriculture and domestic uses. The Coachella Valley has groundwater but now is in overdraft. The Coachella Valley relies almost

totally on Colorado River water for agriculture, while pumped groundwater is still used for domestic uses and the many golf courses (Kahrl 1978; Nordland 1978; Coachella Valley Water District 2000). Imported water for both valleys is diverted from the Colorado River through the All-American and Coachella Canals, and now varies from ~0.5 ‰ to 0.9 ‰ (Oglesby pers. obs.) to as high as 5.2 ‰ (Phelps and Anspaugh 1976), which is almost too saline for agriculture, thus accentuating salt problems for agriculture. The salinity problem is much worse in the Valle de Mexicali downstream, with salinities as high as 27 ‰ being reported (Fradkin 1981). Valle de Mexicali uses only one-third to one-half the amount of water per hectare as Imperial and Coachella Valleys, and so has a lower crop yield.

Salinization of fields is a major problem in both Coachella and Imperial Valleys, because of naturally saline desert soils, irrigation with saline Colorado River water, high water tables, and intense evaporation (Nordland 1978; Breuer 1992; Reisner 1993; Oglesby pers. obs.). Even though Imperial Valley is one of the most productive agricultural areas in the world with up to five crops-yr<sup>-1</sup>, net cultivated acreage has declined in the past several decades due to salinization (Layton and Ermak 1976; Imperial County Agricultural Commission 1990; Breuer 1992). Breuer (1992) quoted Dunbier, "Thousands of acres have been abandoned because of this excessive moisture in what paradoxically is one of the driest parts of the desert." Underground tile drains (plastic pipes with small perforations through which water enters) have been installed in over 80% of irrigated fields in both valleys, removing saline water *downwards* from crop root zones. This water is then pumped into surface drains by sump pumps; these drains flow to the Salton Sea. Water in drains in both valleys is usually in the 3 to 6 ‰ range (Oglesby pers. obs.), much too saline for irrigation or stenohaline freshwater biota. The biota of these drains perforce must be euryhaline, which published reports confirm (see below).

The Salton Trough is one of the hottest places on Earth, comparable to the Persian

Gulf and Red Sea regions. Maximum air temperatures continuously exceed  $38^{\circ}\text{C}$  more than  $110\text{ d}\cdot\text{yr}^{-1}$ ; the highest recorded summer temperature,  $48.3^{\circ}\text{C}$ , has occurred several times. Summer nighttime low temperatures are also amongst the highest on Earth. Frost may occur on winter mornings. The frost-free period is  $>300\text{ d}\cdot\text{yr}^{-1}$  for 9 of 10 yr and  $>350\text{ d}\cdot\text{yr}^{-1}$  for 3 of 10 yr (Layton and Ermak 1976). Relative humidity is always low, ranging from  $\sim 18\%$  to  $33\%$ , with lowest values in summer (California Department of Water Resources 1970; Layton and Ermak 1976; Rowlands 1995a).

Because of these dramatic differences in seasonal air temperature, the shallow Salton Sea varies greatly in seasonal temperature, particularly along its shorelines, from  $<10^{\circ}\text{C}$  in the winter to as high as  $36^{\circ}\text{C}$  in the late summer, with even greater extremes in shallow shoreline pools (Barlow 1958a; Arnal 1961; Carpelan 1961b; Hely et al. 1966; Black 1980; Oglesby pers. obs.). Diurnal temperature variations at the shoreline and in pools are also great both winter and summer (Black 1980; Oglesby pers. obs.).

With an average depth of  $\sim 5\text{ m}$  and a maximum depth of only  $\sim 15\text{ m}$ , the Salton Sea is a very shallow body of water. Arnal (1961) provided details of wind-driven circulation patterns in the Sea. Recent field studies and simulations show two horizontal gyres: a stronger, counterclockwise gyre in the southern basin and a weaker, clockwise gyre in the northern basin. This horizontal circulation is driven by nearly constant northwesterly (north basin) and westerly (south basin) winds, strongest from later winter to late spring (Cook and Orlob 1997; Cook et al. 1998). This two-gyre horizontal circulation is confirmed by space photos, beginning with photos taken by Gemini V astronauts on 22 August 1965 (one photograph was the cover photo for *Science* for 6 October 1972; see also Laflin 1998), which show a striking pattern of floating material, not identified in 1965. More recent space photos sometimes show the same two-gyre pattern, often clearly of patchy phytoplankton blooms as they are red in false-color infrared images. Another possibility for this floating material is rafts of dead fish. Silt plumes move counterclockwise along shore from the mouths of the New and Alamo Rivers, but

do not reach the open Sea (*contra* Norris and Webb 1990).

Even if the Colorado River no longer contains much silt, the New and Alamo Rivers are always silty from agricultural runoff (LFR 1999; Oglesby pers. obs.) and continue to deposit silt at their deltas at the southern end of the Salton Sea. Arnal (1961) concluded from detailed calculations that agricultural wastewater contributed ~75% of total sedimentary input to the Salton Sea, with remaining sediment derived from the Salton Trough itself, shed from surrounding mountains.

Deep lakes may thermally stratify and not show complete vertical mixing for long periods of time; this probably occurred with Lake Cahuilla. In contrast, the shallow Salton Sea is a polymictic lake in terms of vertical stratification and mixis (Arnal 1961; Hammer 1986; Cook et al. 1998; Swan et al. 2000; Oglesby pers. obs.). The Sea can stratify thermally almost any time of the year, doing so most frequently and for the longest time periods during the summer. Stratification is stronger in the northern basin (Cook et al. 1998). Surface to bottom temperature differences are not great during stratification, often no more than 3 to 5°C (Arnal 1961; Hely et al. 1966; Swan et al. 2000; Oglesby pers. obs.). The thermocline in summer is deeper nearshore than in the middle of the Sea (Swan et al. 2000). During thermal stratification,  $pO_2$  below the pycnocline may drop to lethally low concentrations for fish; 0% oxygen saturation and concomitant increases in  $S^{2-}$  in the hypolimnion below 9 m are not uncommon during the summer, especially during periods of calm weather (Carpelan 1961b; Swan et al. 2000; Oglesby pers. obs.). Hurlbert (Salton Sea Authority 2000) stated that 60 to 100% of the Sea's bottom is exposed to  $pO_2 < 1 \text{ mg} \cdot \text{l}^{-1}$  during the summer, and Horvitz (2000) stated that during some summer mixing events, there may be no  $O_2$  found below 1.5 m. Since the Sea is so shallow, the pycnocline is not stable. At any time of the year high winds may occur (Arnal 1961; Oglesby pers. obs.), often causing high winds and sand storms. Waves may reach as high as 1 to 2 m, hazardous to small boats (Oglesby pers. obs.). Ekman grabs of the Sea bottom (>10 to >12 m) of the Salton Sea often smell of  $H_2S$



(Oglesby pers. obs.). When the Salton Sea turns over completely, it brings hypoxic and  $S^{2-}$ -rich (up to  $5 \text{ mg} \cdot \text{l}^{-1}$ ; Swan et al. 2000; Oglesby pers. obs.) hypolimnetic water to the surface and sometimes causes large fish kills. Fish may “gulp” air at the surface as a prelude to die-offs (Horvitz 2000).

**The “tideless intertidal” zone.**—A widespread misconception is that the Salton Sea has moon-driven tides (programs at the Visitor Center of the Salton Sea State Recreation Area; Pepper 1972, 1999; Karr 1985); this error has even seeped into the formal scientific literature (Raimondi 1992). Lunar tides are found *only* in the ocean and connected embayments. No inland body of water has lunar tides, not even Eurasia’s Caspian Sea, the largest inland body of water in the world (Defant 1958). A day spent monitoring shoreline water level of the Salton Sea, even casually, would easily reveal the absence of lunar tides (Oglesby pers. obs.). The fact that the Salton Sea does not display lunar tides was commented upon at least as long ago as 1934 by Cowles.

The Salton Sea might have low-amplitude seiches -- wind-generated oscillations in lake level which may continue for some time after the wind dies down (Sverdrup et al. 1942; Hutchinson 1957) -- but no one has commented on this possibility other than deBuys (1999), who misunderstood the process. Because of the generally northwesterly winds, the southeastern end of the Salton Sea has a “slightly” higher water level than at the northwest shore (Cook and Orlob 1997); this small rise may not be enough to initiate a seiche when the wind dies down. Seiches may also occur following earthquakes (Salton Sea Authority 2000).

Studies in the tideless Baltic and eastern Mediterranean Seas show “intertidal” zonation of a few species of tough algae and sessile animals, based on probabilities of long-term variations in water level caused by variations in both atmospheric pressure and wave action. From the standpoint of the biota, these changes in level are not regular and predictable as are tides, but zonation still occurs because of long-term differences in aerial and aquatic exposure (Segerstråle 1957).

Because of wind-caused wave action, “intertidal” algae grow on hard substrates at the edge of the Salton Sea, such as rip-rap, jetty rocks, utility poles, trees, and buildings. Brown filamentous diatoms (*Nitzschia sigmoides*, attached to *Calothrix* filaments) and the green alga *Enteromorpha* sp. are the major algae involved, harboring small motile zoobenthos, particularly amphipods (*Gammarus mucronatus*) and water boatmen. There is limited vertical zonation over a vertical 0.3 to 0.6 m or so, with filamentous diatoms zoned above *Enteromorpha*. Because of the usually shallow photic zone (~1 m) and limited extent of hard substrates, these benthic plants are only of local ecological importance. Barnacles (*Balanus amphitrite*) also occur in this “tideless intertidal” zone, feeding every time a wave washes over. Many small invertebrates live amongst the barnacles: Coe et al. (2000) reported 4468 individuals in a single 100 cm<sup>2</sup> area. Hard “intertidal” substrates are often coated with a crust of gypsum (CaSO<sub>4</sub>), near its saturation in the Salton Sea (D. Zenger pers. comm.; Oglesby pers. obs.).

**Mini-estuaries.**—The mouths of many drains and all three rivers form small estuaries with strong horizontal salinity gradients that may extend from a few meters into the drain to hundreds of meters, and with sometimes quite steep vertical salinity gradients as well (Oglesby pers. obs.). Estuarine aspects of these tideless mini-estuaries at the Salton Sea have been little studied. Though there are only limited data, low-salinity surface plumes from the New and Alamo Rivers apparently are dissipated within a relatively short distance of their entries into the Salton Sea (Arnal 1961; Salton Sea Authority 2000). Throughout the remainder of the Sea, the water column is well mixed in terms of salinity both horizontally and vertically (Salton Sea Authority 2000; Oglesby pers. obs.).

The estuary of Whitefield Creek in the Salton Sea State Recreation Area, whose lower channel was originally dug by backhoe ~1968 (0.7 m deep, 1 to 1.5 m wide) had a ~15 cm layer of 4 to 5‰ water overlying a deeper layer of nearly full strength Salton Sea water of ~38 to 40‰ in the late 1970s. The halocline extended over a vertical distance of

only a few cm, and was easily visualized because underlying Salton Sea water was turbid and overlying Whitefield Creek water clear; the halocline was very sharp (Oglesby 1977, pers. obs.). In the 1970s there was a horizontal salinity gradient from nearly fresh water to Salton Sea water extending along the 1.6 km long jetties at Red Hill Marina; since then rising water levels have drowned the jetties, and the same gradient now occurs over a much shorter distance (Oglesby pers. obs.).

Similar mini-estuaries are found at the mouths of drains, which are often nearly completely blocked off from the open Salton Sea by barnacle shell “sand” bars, forming stratified ponds. For example, the pool at the mouth of the Cleveland Street Spillway on 24 February 1996 was strongly stratified: 2 to 3‰, 17.6°C and 9.08 mg·l<sup>-1</sup> O<sub>2</sub> at the surface; at the bottom, 1 m deep, 14‰, 22°C, and 6.97 mg·l<sup>-1</sup> O<sub>2</sub> (Oglesby pers. obs.). Because of changing Sea water levels and wave action moving the “sand” bars, ponds often change size, depth, position, and gradients of salinity, temperature, and pO<sub>2</sub>. Drain-mouth ponds and associated riparian vegetation form a complicated, valuable, and variable habitat for aquatic and semi-aquatic biota (Oglesby pers. obs.). At times, such as Whitefield Creek in the late 1970s, salinity gradients and stratification lead to variations in vertical distributions -- fresher water invertebrates in less saline surface water, and Salton Sea biota in higher saline bottom water (Oglesby 1977). By the mid-1980s, the entire distribution pattern of biota in Whitefield Creek had shifted markedly when the rising Salton Sea forced the upper, low salinity layer out of its artificial channel and into adjacent marshes (Oglesby pers. obs.).

The *horohalinicum* is a term introduced by Kinne (1971) for a salinity “boundary” or “barrier” at ~5 to 8‰ for distributions of estuarine biota (see also Oglesby 1978). The horohalinicum is the transition zone between divalent ion ratios characteristic of freshwater (usually dominated by high HCO<sub>3</sub><sup>1-</sup> and Ca<sup>2+</sup>) and those of seawater (dominated by Cl<sup>1-</sup> and Na<sup>1+</sup>). Most freshwater and marine animals, even if euryhaline, cannot cross the horohalinicum because of physiological limitations. Euryhaline estuarine

organisms often are able to cross the horohalinicum, and may be vastly abundant as individuals but not diverse as to species. At the Salton Sea, desert pupfish (*Cyprinodon macularius*), tilapia (*Oreochromis mossambicus*), sailfin mollies (*Poecilia latipinna*), and some other fish cross the horohalinicum readily, as can pileworms (*Nereis succinea*), thiarid snails (*Thiara granifera* and *T. tuberculata*, and some crustaceans and insects (e.g., water boatmen) (Oglesby 1993, pers. obs.; see below). None of these salinity-related distributions has been well studied at the Salton Sea.

**Shoreline pools.**—A biologically interesting feature of the Salton Sea is its shoreline pools, varying from a fraction of a meter in all dimensions to 15 x 200 m, and sometimes even to 1000 m in the longer dimension (usually parallel to shore) and up to 0.5 to 1.0 m or more deep, separated from the Sea by narrow “sand” bars of broken barnacle shells (Barlow 1958a; Black 1980; Oglesby pers. obs.). These pools can be common along gently sloping shorelines, such as at the mouth of the Cleveland Street Spillway, Mecca Beach, Bombay Beach, Red Hill Marina, around Obsidian Butte, and Desert Shores. Most shoreline pools are initially filled by wave action from the immediately adjacent Salton Sea. Some are also fed by “freshwater” drainage from inland -- drains, seepage from unlined canals and drains, springs along faults, and occasionally small streams. Small pools, fed only by wave action, are usually ephemeral. Large pools are often permanent (Oglesby pers. obs.).

Most shoreline pools start out at the salinity of the Sea and increase in salinity as they desiccate, reaching at least as high as 105‰ (Oglesby pers. obs.). Shoreline pools are much more variable in salinity, temperature, pH, and  $pO_2$  than the Sea itself, though only the deeper ones show vertical temperature stratification (Barlow 1958a; Oglesby pers. obs.). Diurnal temperature ranges of 15 to 20°C are not uncommon, and temperatures as high as 43°C have been recorded (Black 1980; Oglesby pers. obs.). pH varies from 7.1 to 9.4 (Oglesby pers. obs.).

Shoreline pools may have a diversity of often highly colored algae and aerobic and

anaerobic bacteria. Pools can be yellow, orange, light green, dark green, pink, red, or purple, depending on the dominant algae or bacteria, which in turn reflect differences in salinity,  $pO_2$ , temperature regimen and extremes, nutrients, and depth (Oglesby pers. obs.). Larger pools contain populations of desert pupfish, mosquitofish (*Gambusia affinis*), longjaw mudsuckers (*Gillichthys mirabilis*), and sometimes bairdiella (*Bairdiella icistia*) (Barlow 1958a; Black 1980); desert pupfish have been rare in recent years (A. Schoenherr, pers. comm.; Oglesby pers. obs.). Macroscopic invertebrates seen in these pools include water boatmen, pileworms, barnacles, nematodes, harpacticoid copepods, heleid and ephydrid fly larvae, and dragonfly nymphs (Table VI; Barlow 1958a; Oglesby pers. obs.). Salton Sea phytoplankters are also found in these pools (Oglesby pers. obs.).

### **Biology of the Salton Sea**

The biology of the Salton Sea is unlike that of any other body of water, fresh or salt. All the important organisms in the Sea came from somewhere else (Gulf of California, Gulf of Mexico, North Atlantic Ocean, Africa, Southeast Asia, Polynesia, tropical Indo-Pacific), usually accidentally and almost always from ocean or inland salt waters, not from freshwater. Most invertebrate and phytoplankton species are well known as highly invasive and are often cosmopolitan. Many attempts have been made to introduce fish and other animals of commercial or sport importance to the Salton Sea. Nearly all attempts failed, either immediately or after changes in the Sea's salinity, but those introductions that succeeded have done so spectacularly. There is only a very limited number of macroscopic species living in the Salton Sea (low diversity), but they often occur in immense numbers. Food webs are short and more like straight-line food chains than in most other bodies of water. The Salton Sea is highly unusual in lacking any significant predators on zooplankton; all the major food chains to sport fish and birds depend ultimately on benthic detritus and detritivorous polychaete annelids. Despite popular opinion, the hypereutrophic Salton Sea, nourished by fertilizer runoff from

agricultural fields, is very much “alive.” Despite its age, the study edited by B. W. Walker (1961) remains the best description of the biology of the Salton Sea. Stuart Hurlbert of San Diego State University is the leader of a comprehensive biological study of the Salton Sea quasi-marine ecosystem in 1999 to 2000; most of this work is not yet published.

### *1. Invertebrates and Aquatic Plants*

**Bacterioplankton.**—There has been no study of pelagic bacteria or their ecological roles in the Salton Sea, even though they are often abundant in other saline lakes, up to  $10^8$  cells·ml<sup>-1</sup> in saline African lakes, and up to  $10^7$  cells·ml<sup>-1</sup> in Nevada’s Pyramid Lake and California’s Mono Lake. In these athalassic saline lakes, bacterioplankton densities are higher by several orders of magnitude than in ordinary freshwater lakes (Mono Lake Ecosystem Study Committee 1987). Hammer (1986) reviewed a number of studies on saline lake bacterioplankton.

**Phytoplankton and Primary Productivity.**—Primary productivity in the Salton Sea is by extraordinarily abundant phytoplankters, chiefly dinoflagellates and diatoms. Recent reports (Hurlbert 2000; Salton Sea Authority 2000) have greatly increased the number of identified and unidentified species in a diversity of algal and protozoan taxa (see Table V), none of which is likely to be restricted to the Salton Sea.

Dinoflagellates are always planktonic, their great density often turning the Sea’s water the color of murky tea. None causes “red-tides,” which in some coastal waters can cause major fish mortalities. See Table V for a list of reported dinoflagellates.

Diatoms are mostly planktonic but some species also occur on “intertidal” rocks as brownish filaments representing non-integrated colonies of many cells, likely *Nitzschia sigmoides*., growing attached to bluegreen algal filaments (usually *Calothrix*). Other species live on the surface of muds and other soft substrates, including algal mats, as long as they are within the photic zone (Tiffany and Lange 2000). Some diatom tests found in the Salton Sea may represent freshwater diatoms washed into the Sea by rivers (Tiffany



and Lange 2000). About 92 species -- chiefly of marine planktonic origin -- were identified by the late 1990s, some new to science. See Table V for a list of reported diatoms, by no means all that are present. Diatoms dominate the phytoplankton assemblage in summer and fall, with densities of  $\sim 10^6$  cells·l<sup>-1</sup> (Lange and Tiffany 2000; Tiffany and Lange 2000).

Fertilizers in agricultural wastewater have turned the Sea into one of the world's most eutrophic lakes, fresh or saline. Surprisingly, there have been very few measurements of nutrient concentrations in agricultural drainwaters or of the Salton Sea itself (Tables III, IV). The great differences in nutrient concentrations between inflowing water and the Salton Sea in 1968 to 1969 were attributed both to dissolved nutrients being taken up by Salton Sea biota and to sedimentary sequestration in organic detritus (Tables III, IV; US Department of the Interior and The Resources Agency of California 1969; US Department of the Interior 1970). In the late 1960s external loading rates (inputs from agricultural drains) were 930 mM NO<sub>3</sub><sup>1-</sup>·m<sup>-2</sup>·yr<sup>-1</sup> and 220 mM PO<sub>4</sub><sup>3-</sup>·m<sup>-2</sup>·yr<sup>-1</sup> (US Department of the Interior 1970). Carpelan's (1961b) data showed a strong summer maximum in NH<sub>4</sub><sup>1+</sup> both in the epilimnion and at the bottom of the hypolimnion at a site off Desert Shores; NO<sub>3</sub><sup>1-</sup> and PO<sub>4</sub><sup>3-</sup> did not show much seasonal variation. Carpelan (1961b) regarded his NO<sub>3</sub><sup>1-</sup> analyses as probably unreliable. His data, summarized in Table IV, were from four stations; highest values were found at a shallow station near Mullet Island, strongly influenced by irrigation runoff from the nearby Alamo River. González et al. (1998) discussed these earlier data, but did not provide any new data for the present Salton Sea; they thought that nutrient inputs were about the same in the 1990s as in 1970. Additional data are reported by the Salton Sea Authority (2000).

Recent proposals for a massive tilapia harvest to lower "excess" PO<sub>4</sub><sup>3-</sup> concentration in the Sea to ameliorate the Salton Sea's hypereutrophic state seem not to be based on recent PO<sub>4</sub><sup>3-</sup> measurements (Table IV). The Salton Sea Authority (2000) assumed that PO<sub>4</sub><sup>3-</sup> was the limiting nutrient in the Salton Sea, as dissolved

orthophosphate concentrations “have been below the detection limit of  $[0.633 \mu\text{M}]$  on several occasions.” The Authority suggested harvesting  $200 \text{ kg tilapia}\cdot\text{ha}^{-1}\cdot\text{yr}^{-1}$  ( $=20,000$  metric tons from the entire Salton Sea), which would remove only 10% of incoming  $\text{PO}_4^{3-}\cdot\text{yr}^{-1}$  (González et al. 1998; Costa Pierce and Riedel 2000; Riedel and Costa-Pierce 2000; Salton Sea Authority 2000). Even the Authority admitted that commercially harvesting tilapia would not reduce the Sea’s hypereutrophic status to any significant degree. The question is, then, Why do it at all?

There are no laboratory or field studies which have determined which nutrient actually limits Salton Sea productivity. While most freshwater lakes are  $\text{PO}_4^{3-}$ -limited (Vollenweider 1968 as cited by Cagle 1998), others are limited by  $\text{NO}_3^{1-}$  or  $\text{NH}_4^{1+}$ , by cofactors for photosynthesis such as Mn, or by trace metals such as Fe and Mo (Hutchinson 1957; Moss, 1988; Lebo et al. 1994; Evans and Prepas 1997). California’s saline Mono Lake is limited by  $\text{NH}_4^{1+}$  (Melack and Jellison 1998). Most marine diatoms (Salton Sea diatoms are primarily marine in origin: Table V) are limited by Fe (Falcatore et al. 2000). Since the photic zone is so shallow, usually  $<1 \text{ m}$ , Salton Sea productivity may be light-limited, rather than nutrient-limited. While Secchi disc values may be as great as  $3 \text{ m}$  in mid-winter (photic zone  $\sim 9 \text{ m}$ ), during summer algal blooms they are often  $<0.3 \text{ m}$ , with a photic zone of only  $1 \text{ m}$  (Arnal 1961; Tiffany et al. 2000; Oglesby pers. obs.). Even in so shallow a lake most of the water column does not receive enough light for photosynthesis. Appropriate experiments on what limits Salton Sea productivity need to be done before “solutions” to nutrient loading, including fish harvesting, are chosen. In any case, much more important would be to reduce inputs of agriculture-derived nutrients at their sources, but this is not proposed by the Salton Sea Authority (2000).

In 1954 and 1955, Salton Sea primary productivity was  $\sim 0.75 \text{ g C}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$  (range:  $0.11$  to  $1.9 \text{ g C}\cdot\text{m}^{-2}\cdot\text{d}^{-1}$ ), as much as  $10$  metric tons dry weight $\cdot\text{ha}\cdot\text{yr}^{-1}$ ,  $\sim 1.7$  times maximum productivity of oceanic upwelling systems (Arnal 1961). A primary

productivity estimate made in 1968 and 1969 was even higher: an average of  $4.4 \text{ g C} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$  over the year, and as high as  $5 \text{ g C} \cdot \text{m}^{-2} \cdot \text{d}^{-1}$  during the summer (US Department of the Interior and The Resources Agency of California 1969). These data demonstrate that the Sea has long been hypereutrophic (Carpelan 1961c). Tiffany et al. (2000) measured highest chlorophyll concentrations in late winter, declining to a late summer low reflecting frequent summer stratification.

In Mono Lake and laboratory experiments with Mono Lake water and its phytoplankton, gross primary productivity decreased by 10% for every 10‰ increase in salinity over the range of 97 to 140‰. An unnamed diatom did not survive above 185‰, while an unnamed green alga survived to at least 237‰ (Mono Lake Ecosystem Study Committee 1987). The high-salinity-tolerant alga *Dunaliella salina*, (a red-colored green alga) not now found in either Mono Lake or the Salton Sea, is an aquaculture species in the Imperial Valley and could easily colonize the Sea when conditions become appropriate. *Dunaliella* grew well in 200‰ Mono Lake water (Mono Lake Ecosystem Study Committee 1987). Studies need to be done with Salton Sea phytoplankton to assess sensitivity of individual species and overall primary production to increased salinity.

The Salton Sea can vary from brown to brick red to light green, reflecting blooms of different species of dominant phytoplankters. The typically brown color of Salton Sea water, indicative of high densities of dinoflagellates, does not represent a “dead” lake as popularly believed, but a hypereutrophic lake with vastly abundant phytoplankton.

**Zooplankton.**—These abundant phytoplankters are fed upon by a very few species of zooplankton, primarily a copepod (*Apocyclops dengizicus*), a rotifer (*Brachionus rotundiformis*), larval stages of benthic pileworms and barnacles, and fingerlings of sciaenid fish (Tables VII, VIII; Carpelan 1961d; Kuhl and Oglesby 1979; Dexter 1993; Oglesby pers. obs.). These few zooplankton species can be exceedingly abundant throughout the year (B. W. Walker 1961; Oglesby pers. obs.), though Tiffany et

al. (2000) reported a zooplankton low in summer during stratification, and also after summer mixing elevated H<sub>2</sub>S throughout the water column.

The abundant cyclopoid copepod *Apocyclops dengizicus*, initially described as a new species restricted to the Salton Sea, *Cyclops dimorphus*, by Kiefer (1934), is known from inland and usually saline lakes on several continents. Johnson (1953) provided a detailed morphological description of this species (as *C. dimorphus*). *A. dengizicus* lives in Australian lakes in salinities ranging from 4 to 69‰ and can tolerate salinities at least as high as 107 ‰ Salton Sea water for at least 60 d (Dexter 1993). In the Salton Sea, development from eggs to sexual maturity takes 10 to 15 d (Carpelan 1961d). Dexter (1993) reported slower and more variable developmental rates varying from 2 wk to 2 mo, with successful reproduction at salinities from as low as 0.5‰ to as high as 45‰; there was reduced reproductive success at salinities as high as 68‰. Carpelan (1961d) concluded that 10 to 15 generations could be produced each year. Carpelan (1961d) collected no *A. dengizicus* during the winter, but Dexter (1993) found *A. dengizicus* year-round near the shoreline, with only reduced density rather than absence in colder months. In the laboratory, *A. dengizicus* is an active predator, feeding upon rotifers, *Artemia* nauplii, protozoans, and insect larvae, as well as on phytoplankton (Dexter 1993; Hart et al. 1998). Dexter (1993) pointed out that laboratory experiments on this and other invertebrates may not well mimic actual conditions in the Salton Sea – laboratory experiments provide stable physical conditions (*p*O<sub>2</sub>, temperature, salinity) and adequate food and usually lack predators and competitors.

The monogonont rotifer *Brachionus* is the most numerous Salton Sea zooplankter during most of the year except mid-winter, with highest densities in the summer (Kuperman et al. 2000). Recent taxonomic work, primarily in the laboratory but supported by field studies, indicates that the cosmopolitan *B. plicatilis* is a species complex composed of at least two different species (*B. plicatilis* and *B. rotundiformis*) and several additional clonal groups that do not mate with each other (Gómez and Serra 1995;

Segers 1995; Gómez and Snell 1996; Gómez et al. 1997; Serra et al. 1998). *B. rotundiformis* form SS seems to be the (only?) species in the Salton Sea, both now and in the 1950s; it is the taxon in this complex most tolerant of high temperatures and high salinities (Serra et al. 1998; Kuperman et al. 2000; Tiffany et al. 2000). Earlier work around the world published under the name *B. "plicatilis"* may have actually been done on that species, or on *B. rotundiformis*, or on a mixture of both species. Recent work that distinguishes the two species demonstrates that there are physiological and ecological differences between them. *B. rotundiformis* is "slightly more tolerant" of high salinities than *B. plicatilis* (Fielder et al. 2000) and has a higher energy content (Yufera et al. 1997). It is therefore not a given that the biology of true *B. plicatilis* is the same as that of *B. rotundiformis*.

*Brachionus plicatilis* and *B. rotundiformis* are non-selective filter-feeders on planktonic algae, protozoa, bacteria, and yeasts (K. F. Walker 1981; Hammer 1986; Turner and Tester 1992; Arndt 1993; Jurgens and Jeppesen 2000). *B. plicatilis* (and presumably *B. rotundiformis*) is a strongly euryhaline hyperosmotic osmoconformer as demonstrated in populations from other geographical areas, surviving from 1 to 97‰; a report of survival in 200‰ is probably a typographical error (K. F. Walker 1981; Hammer 1986). Oxygen consumption is not much affected by salinity, but is depressed in 1‰ (K. F. Walker 1981). *B. "plicatilis"* is eurythermal, "likely" to withstand extreme temperature ranges from 5 to 29°C (K. F. Walker 1981). Salton Sea rotifers obviously withstand even higher temperatures, to well over 30°C. K. F. Walker (1981) and Hammer (1986) reviewed the many physiological studies on *B. plicatilis* (some perhaps including *B. rotundiformis*, not yet recognized as a distinct taxon), commenting that most of the studies had been done on laboratory populations so that little was known about actual ecology of these rotifers in the field.

Both *Brachionus* species show cyclic changes in size and morphology during the year (cyclomorphosis) at the Salton Sea and elsewhere (Carpelan 1961d; Hammer 1986;

King and Serra 1998). Some populations of *B. "plicatilis"* have both sexual (mictic) and asexual (amictic, parthenogenetic) reproduction, depending on season, temperature, salinity, and other factors (Hammer 1986; Gómez et al. 1997). Salinity affects timing of parthenogenetic and sexual cycles in Israel, with no sexual cycles at salinities in excess of 35‰ (Lubzens et al. 1985, 1997). No males were found in Salton Sea *Brachionus* by Carpelan (1961d). Carpelan (1961d) speculated that rotifer reproduction in the Salton Sea was only parthenogenetic (amictic), not sexual, with winter spent as dormant cysts which hatch in May or June. Summer reproductive cycles could be completed in 1 to 2 wk. Since the Salton Sea is now ~43 to 47‰, reproduction obviously does take place at these higher salinities.

Carpelan (1961d) thought that no Salton Sea animals ate living *Brachionus*; rather, he wrote, the rotifers die, sink to the bottom, and become detritus. But many aquaculture operations conduct mass laboratory culture of *Brachionus* as food for aquacultured fingerlings of important food fishes (Hansen et al. 1997; Lubzens et al. 1998). Fingerling and juvenile Salton Sea fishes and zooplankton such as copepods may well feed extensively on *B. rotundiformis* (Kuperman et al. 2000). The actual ecological role of *B. rotundiformis* in the Salton Sea is little known.

See below for discussions of the abundant and ecologically significant zooplanktonic larvae of pileworms and barnacles. Other, apparently less ecologically significant, zooplankters are listed in Tables V and VII (B. W. Walker 1961; Hurlbert et al. 2000; Small and Gebler 2000; Oglesby pers. obs.).

**Bacteriobenthos.**—It must be emphasized that the most unusual aspect of Salton Sea ecology is that plankters, both plant and animal, are *not* eaten by pelagic planktivores. Rather, both phytoplankters and zooplankters die and sink, along with feces and dead fish, to the bottom where they are broken down through bacterial decay to black, rich, odiferous, slimy, jelly-like, organic detritus. Detritus, including bacteria, decayed plant and animal material, and reworked fish and invertebrate feces, is the basic food source for



pileworms and some other benthic invertebrates, ultimately leading to the huge population of sport fish (B. W. Walker 1961). Bacterial decomposition processes have been briefly studied in Mono Lake (Mono Lake Ecosystem Study Committee 1987), but not in the Salton Sea.

Exposed “intertidal” mud flats in drowned fields nearly surrounded by dikes are sometimes colored in rich pinks, reds, and purples by photosynthetic anaerobic bacteria, arrayed in concentric patterns (Oglesby pers. obs.). Bluegreen algae (Cyanobacteria) are common in the Salton Sea, chiefly as benthic mats on solid substrates such as pilings and rocks, and on soft bottoms in areas with little wave action, such as drowned fields (Table V). Bluegreen mats often float to the surface on their own photosynthetic O<sub>2</sub> (Carpelan 1961c; Oglesby pers. obs.). Wood et al. (2000) reported a great diversity of bluegreens in the Salton Sea, especially filamentous species in algal mats (Table V). Floating bluegreen algal mats are responsible for much of the characteristic summer odor (H<sub>2</sub>S) of the Salton Sea, rather than sewage as widely believed (*contra* Wambaugh 1992). See Hammer (1986) for a review of microbial mats in saline lakes.

**Phytobenthos.**—Carpelan (1961c) mentioned the green algae *Cladophora* sp. and *Enteromorpha* sp. as growing in drains, but did not report them in the Sea itself. *Enteromorpha* is now common in the Sea on hard substrates, both on “tideless intertidal” rocks along with filamentous diatoms and “subtidally” to the depth of the shallow photic zone, rarely more than 1 m. *Enteromorpha* is particularly common in low salinity areas, as at the mouths of drains and the three rivers (Oglesby pers. obs.). See Tables V and VI.

No vascular plants grow in the Salton Sea itself (Table VI). An attempt was made in the 1957 to introduce turtle grass, *Halodule* (formerly *Diplanthera*) *wrightii* (Cymodeaceae), from the Gulf of Mexico in Texas but it did not establish (Barnard and Gray 1968, 1969; Oglesby pers. obs.). Feldmeth (1980) suggested that both *Halodule* and the cosmopolitan ditch grass, *Ruppia maritima* (Ruppiaceae) might still grow on the seawards side of the Whitewater Marsh at the north end of the Salton Sea, but there is no

actual evidence that either genus grows in or near the Salton Sea (Oglesby pers. obs.).

Many springs, streams, drains, and permanent shoreline pools are dominated by the noxious and highly invasive alien weedy shrubs salt cedar (*Tamarix ramosissima*) and giant reed (*Arundo donax*), which create impenetrable thickets and poor wildlife habitat. Giant reed can reach >10 m high and dewater shallow springs and streams. Its shallow root system makes it very susceptible to uprooting by flood waters, leading to rapid dispersal downstream. Salt cedar debris raises the salt content of the soil underneath, making it even more difficult for native plants to germinate and grow; it too is extremely difficult to eradicate (England and Laudenslayer 1995; Broussard et al. 2000). Either weedy shrub can completely replace native riparian and marsh vegetation. Both flowing water in streams and shoreline erosion send floating salt cedar and giant reed masses into the Salton Sea, where they serve as impermanent substrates for barnacles (Oglesby pers. obs.). The native common reed (*Phragmites australis*) and cattails (*Typha* sp.) also form dense marshes in similar locations, but are much more valuable as wildlife habitat; cattail (*Typha* spp.)-bulrush (*Scirpus* spp.) marshes are particularly important for rails (Tables VI, X). All these plants are salt tolerant, salt cedar being the most euryhaline.

**Fungi.**—A number of aquatic fungi have been reported for the Salton Sea by Anastasiou (1961, 1961, 1963), who collected them on drowned *Tamarix aphylla* trunks in the southern Salton Sea. While he named several of these as new species, and even one new genus, Anastasiou regarded them all as widespread (though little studied) in the Pacific Ocean and North America; some were primarily terrestrial but obviously can survive and grow in the Salton Sea, while others were primarily aquatic. Ascomycetes included: *Amphisphaeria verrucuclosa*, *Ceriosporopsis halima*, *Halosphaeria mediosetigera*, *Leptosphaeria orae-maris*, *Lulworthia medusa*, *L. opaca*, *Peritrichospora integra*, and *Pleospora herbarum*. Fungi Imperfecti included: *Acrospeira levis*, *Ahernaria radicina*, *A. tenuis*, *Botryotrichum piluliferum*, *Clavariopsis bulbosa*, *Contortospira varia*, *Fusarium solani*, *Pericomia prolifera*, *Scopulariopsis* sp., *Stachybotris atra*, *S.*

*subsimplex*. Mycelia Sterilia included *Populasporea halima*. These fungi are all metabolizers of dead wood; other potential fungal habitats in the Salton Sea have not been investigated.

**Zoobenthos.**—In the open Salton Sea there are only two major benthic animals, pileworms and barnacles, both extraordinarily abundant. At the Sea's margins, particularly near hard substrates, there are additional invertebrates -- protozoans, nematodes, other polychaetes, amphipods, harpacticoid copepods, glass shrimp, and insects (Tables V, VII). Shoreline pools and estuaries of at least many drains, and probably of the three rivers, additionally have euryhaline snails and more species of insects and crustaceans (Tables I, VI).

The vastly abundant pileworm, *Nereis (Neanthes) succinea*, was probably introduced in 1929 when Department of Fish and Game Warden Glidden purchased buckets of live bait in San Diego and dumped them into the Salton Sea in order to establish a food base for striped bass (*Morone saxatilis*, Serranidae), to be introduced the following year. Striped bass and most of the bait animals were not successful, but *Nereis succinea* succeeded beyond anyone's imagination. The pileworm was described as a new species (*Neanthes saltoni*) only 30 yr after the Salton Sea came into existence as a freshwater lake and only 7 yr after its actual introduction (Hartman 1936). *Nereis succinea*, a North Atlantic species widely dispersed by shipping and introductions of oysters elsewhere in the world, does not now occur in San Diego Bay, but is abundant in parts of the Los Angeles-Long Beach Harbor system and in San Francisco Bay (Oglesby 1965, pers. obs.). Whether the pileworm occurred in San Diego Bay in 1929 but has since gone locally extinct, or the bait Warden Glidden bought came from several locations, including Los Angeles Harbor, will never be known (Anonymous 1929, 1930a,b, 1931a,b; J. Fitch, pers. comm.).

Use of the generic name *Nereis* here follows the practice of Smith (1958) and Pettibone (1963), who argued that generic splitting should not be based on juvenile

morphologic characters not found sexually mature adults (in this case, a special seta lost during metamorphosis). The names *Hediste*, *Neanthes*, and *Nereis* are treated here as subgenera of *Nereis*, not as separate genera.

Eggs, trochophores, and small juveniles of *Nereis succinea* are abundant in the plankton year-round (Oglesby pers. obs). Carpelan (1961d) and Linsley and Carpelan (1961b) found a summer maximum of planktonic stages. Planktonic juveniles of ~6 to 9 setigers settle to the bottom (Linsley and Carpelan (1961b), but do not metamorphose into sexually mature adults for at least 6 to 12 mo. Over its wide native and introduced range, *N. succinea* is generally regarded as an unselective bacterivore and detritivore. While no work has been done on this species, Lucas and Bertru (1997) found enzymes appropriate for bacteriolysis in the related deposit feeder *Nereis (Hediste) diversicolor*.

At the Salton Sea, benthic *Nereis succinea* feeds on rich organic detritus, burrowing in any soft substrate as well as barnacle shell "sand," including shoreline pools in salinities as high as 65.5‰ (Barlow 1958a; Oglesby pers. obs.). Benthic abundance in nearshore waters is highest from January through April (Kuperman et al. 2000). Growth rates are also fastest in the spring (Linsley and Carpelan 1961b). In 1954 to 1958, there was up to 67 metric ton·ha<sup>-1</sup> standing crop of pileworms in spring, dropping to 16 metric ton·ha<sup>-1</sup> in late summer, with a yearly mean of 28 metric ton·ha<sup>-1</sup> (Carpelan 1961d); Kuperman et al. (2000) estimated a standing crop of 13.2 million kg for the entire Salton Sea in fall. Carpelan and Linsley (1961b) calculated that pileworms averaged 6500 individuals·m<sup>2</sup> over the entire Salton Sea. Detwiler et al. (2000) reported densities up to 85,500 worms·m<sup>-2</sup> in rocky shorelines. Burrowing pileworms increase the depth of the oxidized layer of the sediments and assist in breaking down tough fecal pellets, such as those egested by the amphipod *Gammarus mucronatus*.

*Nereis succinea* occurs at its highest densities in the depth range of ~1 to ~8 m (Carpelan and Linsley 1961a; Oglesby, pers. obs.). Pileworms disappear from deeper waters (>~9 m) during the summer, apparently due to hypoxic hypolimnetic waters; they

recolonize these deeper waters every autumn; Detwiler et al. (2000) reported total pileworm loss below 2 m during the summer. There is much variability in the maximum depth at which pileworms can be found in the spring, from 8 m to the very deepest part of the Sea off North Shore at 15 m, only occasionally being correlated with hypoxic bottom waters (Oglesby pers. obs.). Some of this spring variability in maximum depth for pileworms may relate to variations in bottom topography or patchy anaerobic bottom waters.

Pileworms are of the greatest significance in the food chain of the Salton Sea, being the major food of bairdiella, young orangemouth corvina (*Cynoscion xanthulus*), and tilapia, as well as wintering eared grebes (*Podiceps nigricollis*). Particularly during the summer, reduced or eliminated populations of benthic pileworms throughout much of the Sea bottom lead to huge summer die-offs of bairdiella, recognized since a few years after its introduction in the early 1950s (Carpelan 1961d; Carpelan and Linsley 1961b; Hanson 1972; Kuhl and Oglesby 1979; Costa-Pierce 1998a; Oglesby pers. obs.).

*Nereis succinea* benthic immatures (atokes) are euryhaline, with maximum survival to 80 to 90‰ (lower at higher temperatures); 65 to 70‰ is the practical highest salinity for long-term survival (Oglesby 1965, pers. obs.; Hargreaves 1968; Hogue 1970; Hanson 1972; Kuhl and Oglesby 1979; Duncan 1986; Simpson et al. 1998). *N. succinea* can live in salinities (both Salton Sea water and ocean seawater) as low as 5 to 8‰, approximately the horohalinicum (Oglesby 1965, pers. obs.; Hogue 1970; Kuhl and Oglesby 1979; Duncan 1986); the report by Foster (1972) that *N. succinea* can live and reproduce in freshwater is in error. Reproduction is not successful above 50‰, due to a salinity bottleneck during cleavage (Kuhl and Oglesby 1979).

Benthic pileworm immatures (atokes) metamorphose into swimming, pelagic, non-feeding, sexually mature adults (epitokes, heteronereids) which swarm at the surface at night for breeding and can be attracted to lanterns or flashlights (Carpelan and Linsley 1961; Linsley and Carpelan 1961b; Kuhl and Oglesby 1979; Oglesby pers. obs.).

Swimming heteronereids are particularly vulnerable to fish predation (Oglesby pers. obs.). Metamorphosis to sexually mature swimming adults occurs after at least 1 yr in ocean and estuarine waters, but less than 1 yr at the Salton Sea, probably due to the high temperatures and abundant food (Linsley and Carpelan 1961b). Pileworm heteronereids die after breeding. Pileworm larvae can be found in the plankton year-round (Oglesby, pers. obs.), but Kuperman et al. (2000) found larvae most abundant in March, least abundant in summer, and then of increasing abundance beginning in November.

The East Coast estuarine spionid *Streblospio benedicti*, now widely distributed on the West Coast, is common in muddy clays in the Salton Sea at depths of 2 to 12 m; the first Sea record was 1999 (D. Dexter pers. comm.). On the East Coast, different populations of *S. benedicti* display either of two reproductive modes, one lecithotrophic in which yolky fertilized eggs are brooded by females in burrows followed by brief, non-feeding planktonic stages, the second planktotrophic with small eggs that hatch, develop, and feed entirely in the plankton (Levin et al. 1991; Levin and Bridges, 1994; Bridges and Heppell 1996). It has not yet been reported which breeding mode is used by Salton Sea *S. benedicti*. Spionids in general feed on benthic detritus and bacteria, brought to the mouth in ciliated grooves that run the length of two long palps that are extended over the substrate or into the water column. *S. benedicti* can survive short periods of anoxia (Llansó 1991), but may not be able to survive the longer periods of anoxia characteristic of the Salton Sea in the summer. See Table VII for other annelids, including two other spionids.

The euryhaline acorn barnacle *Balanus amphitrite* is abundant on any solid substrate: rocks, wood, buildings, trees, barnacle shells, dense mud, the bottoms of boats left in the water overnight, soft drink cans, and beer bottles, as well as at least one of 24 Navy aircraft that crashed during nighttime training exercises during and after World War II. This particular plane crashed on 30 December 1947 and the two crewmen survived (*Los Angeles Times* 15 June 1999). Local television news tapes, taken in March 1999



(KNBC, Los Angeles), showed an almost intact Grumman Avenger torpedo bomber at ~16 m depth several miles off the Salton Sea State Recreational Area, festooned with barnacles. The finding of this wrecked airplane covered with living barnacles demonstrates that barnacle larvae can settle out even at 16 m in the Salton Sea, if the substrate is appropriate. On soft substrates, barnacles are abundant down to ~3 to ~4 m, living barnacles attached to dead barnacle shells forming softball-sized clusters (Oglesby, pers. obs.). Barnacles are so abundant in the Sea that much of the shoreline is covered with thick deposits of “sand” of broken and intact barnacle shells. Clumps of living barnacles thrown up by wave action can survive long periods in the larger shoreline pools (Barlow 1958a; Linsley and Carpelan 1961a; Oglesby pers. obs.).

*Balanus amphitrite* was introduced in the early 1940s, probably from San Diego Bay on seaplane floats and buoys brought in by rail to the Navy’s Salton Sea Test Base at the southwestern end of the Salton Sea (5334 ha, ~2/3 submerged by the Sea; established 1942, mostly abandoned in the 1970s, decommissioned 1989) (Salton Sea Authority 2000). An alternative barnacle source is the Gulf of Mexico: larvae carried in ballast water of Navy seaplanes flown in from Texas (Cockerell 1945; Hilton 1945; Carpelan 1961d; Linsley and Carpelan 1961a; Newman and Abbott 1980; Raimondi 1992). *B. amphitrite* is probably originally native to the Indo-West Pacific (Newman and Abbott 1980), is often found in estuaries, and has been dispersed by shipping throughout the world.

The Salton Sea barnacle has a muddled taxonomic history. It was originally described as a new subspecies (*Balanus amphitrite saltonensis*) within a decade of its introduction (F. L. Rogers 1949), based only on adult morphology, different from that of the same species introduced earlier into southern and central California coastal estuaries, bays, and lagoons. Henry and McLaughlin (1975) regarded the Salton Sea population as a subspecies distinct from *B. amphitrite amphitrite*, again based only on adult morphological differences. Salton Sea barnacles have thinner, more fragile shells and are higher than

ocean barnacles (F. L. Rogers 1949; Oglesby pers. obs.).

Linsley and Carpelan (1961a) thought that crowding accounted for the distinctive Salton Sea barnacle morphology. *Balanus amphitrite* transferred from Salton Sea water to ocean seawater immediately starts to secrete new shell characteristic of ocean seawater barnacles, demonstrating that the two different shell morphologies are environmentally determined (W. Newman pers. comm.; Oglesby pers. obs). Adult morphological differences (based on measurements of tergal plates) vanish when barnacles from the Sea are cultured in ocean seawater, but that there are persistent larval differences (Raimondi 1992). By comparison, Salton Sea barnacle larval development lasts longer, cyprids reach a larger size, and are unpigmented. Raimondi (1992) concluded that Salton Sea barnacles were subspecifically identical to coastal Californian and East Coast populations of *B. amphitrite*, and that morphological differences in adults were based entirely on environmental differences (perhaps because of the relatively higher  $\text{Ca}^{2+}$  and  $\text{SO}_4^{2-}$  concentrations in the Salton Sea).

Raimondi (1992) concluded that the three persistent larval differences between Salton Sea and ocean *Balanus amphitrite* were genetically and evolutionarily based, and argued for natural selection rather than genetic drift as the operative evolutionary mechanism. Flowerdew (1985) showed no genetic divergence in allozymes between ocean and Salton Sea populations for 31 alleles at 11 loci. Sixtus (1978) found phenotypic differences in temperature adaptation between coastal and Salton Sea barnacles, as well as a reduction in heterogeneity in two allozymes in Salton Sea barnacles. Flowerdew (1985), however, found no reduction in heterozygosity in Salton Sea barnacles, presumably because the inoculum in the early 1940s was not small enough to cause a genetic bottleneck or founder effect. Sixtus (1978) concluded that intense selection was occurring at the Salton Sea, and would lead to increased divergence of coastal and Sea barnacles. Raimondi (1992) made the important general point that no one would recognize any genetic differentiation between Salton Sea and coastal *B. amphitrite* if only adult

phenotypic characters were used for analysis.

*Balanus amphitrite* has been collected at salinities as high as 65‰ in Salton Sea shoreline pools (Oglesby pers. obs.), and as high as 75‰ in the hypersaline Laguna Madre in Texas (Simmons 1957). In Salton Sea microcosms, barnacles survived to 70 to 80‰, with much reduced survival at salinities up to 100‰ (Simpson and Hurlbert 1998). Growth was fastest at 48‰ and slowest at 65‰. There were differences in shell morphology at different salinities, with diameter, height, and wall thickness being greatest at 48‰. Simpson and Hurlbert (1998) found no difference in shell material strength with salinity, but the force required to break intact barnacles was highest at 48‰ because of changes in overall shell morphology at different salinities. Larval barnacles survive up to 86.4‰, but with reduced survival above 58 to 74.9‰; low salinity stress at early developmental stages influences low salinity tolerance of later developmental stages (Crisp and Costlow 1963; Perez 1994; Qiu and Qian 1999). Simpson and Hurlbert (1998) suggested that barnacles would disappear from the Salton Sea when the salinity climbs to 70 to 80‰, with a concomitant loss of habitat for several currently important benthic invertebrates.

Adult, benthic *Balanus amphitrite* is a filter-feeding zooplanktivore, like most barnacles, as are its planktonic nauplius larvae. Developing nauplius larvae cannot be supported by bacterivory alone (Gosselin and Qian 1997). Sargo and tilapia commonly feed on adult barnacles.

Acorn barnacles such as *Balanus amphitrite* are hermaphrodites, but normally indulge in cross-fertilization; they can self-fertilize if necessary (W. Newman pers. comm.). After internal fertilization, eggs are brooded in the mantle cavity, hatching as nauplii. Nauplius larvae are released to the plankton where they filter-feed through six molts. Sixth stage nauplii metamorphose into non-feeding planktonic cyprid larvae which seek out appropriate substrates on which they settle and metamorphose into sessile adults. Perhaps because of greater availability of hard substrates and greater density of

adults, barnacle larvae are more abundant near shore than in the open Sea (Carpelan 1961d; Oglesby pers. obs.). Daily settlement rates can exceed  $30 \text{ cyprids} \cdot \text{cm}^{-2}$ , leading to dense aggregations (Linsley and Carpelan 1961). Coastal populations of *B. amphitrite* reproduce only when water temperature exceeds  $20^{\circ}\text{C}$  (Newman and Abbott 1980); Salton Sea barnacles spawn over the range  $17$  to  $27^{\circ}\text{C}$ , and perhaps to  $33^{\circ}\text{C}$  (Carpelan 1961d). There are two spawning peaks, with highs in spring and fall and lows in summer and winter, but nauplii and cyprid larvae are present in the plankton all year (Carpelan 1961d; Oglesby pers. obs.). Kuperman et al. (2000) found nauplius density greatest from January through April.

The benthic amphipod *Gammarus* (*Marinogammarus*) *mucronatus* was apparently introduced from the Gulf of Mexico in 1957 as a contaminant during the attempted introduction of turtle grass *Halodule* (Barnard and Gray 1968, 1969). A detritivore, microherbivore, and predator (González et al. 1998; Hart et al. 1998; Cruz-Rivera and Hay 2000), *G. mucronatus* is abundant, particularly near rocks (as many as 3183 in one  $100 \text{ cm}^2$  patch: Coe et al. 2000), in barnacle shell debris, and shoreline pools with salinities as high as  $65.5\text{‰}$  (Oglesby pers. obs.); Detwiler et al. (2000) reported densities as high as  $126,000 \cdot \text{m}^{-2}$  on rocks. At high salinities in laboratory microcosms, a decline in *G. mucronatus* density led to an increase in water boatman density, presumably because of release from predation (Hart et al. 1998). Its reproduction in Massachusetts was studied by LaFrance and Ruben (1985). *G. mucronatus* is reported to tolerate salinities from 4 to  $50\text{‰}$ , but not above  $57\text{‰}$ , upper laboratory limits contradicted by field observations at the Salton Sea (Hart et al. 1998; Oglesby pers. obs.). There was no successful reproduction in laboratory microcosms above  $39\text{‰}$ , even though gravid females were found in salinities as high as  $65\text{‰}$  (Simpson et al. 1998). Simpson et al. (1998) suggested that *G. mucronatus* suffered osmotic stress at salinities above  $39\text{‰}$ . *G. mucronatus* is fed upon by sargo and perhaps by tilapia. See Table VII for other amphipods.

The extraordinarily euryhaline anostracan brine shrimp *Artemia* sp. does not now live in the Salton Sea itself (Hart et al. 1998; Oglesby, pers. obs.), probably because of fish predation, even though the Salton Sea Authority (2000) stated it was present. Probably only when all fish and zooplanktivores are lost in the Salton Sea due to high salinity will *Artemia* colonize the Sea, as brine shrimp have in Mono and Great Salt Lakes.

The only other large benthic crustacean found in the Salton Sea itself is the glass shrimp *Palaemonetes paludosus* (Table VII). This euryhaline freshwater shrimp, native to the US East Coast, first became established in ditches below Hot Mineral Spa in the Imperial Valley (St. Amant and Day 1972). While glass shrimp were deliberately introduced into the lower Colorado River system by California Department of Fish and Game in 1958 (Hayden and Rinnyo 1963) and are now widespread in the Colorado River system, St. Amant and Day (1972) believed that the Hot Mineral Spa population was derived from a local tropical fish farm. *P. paludosus* could probably survive the present high salinities of the Salton Sea, but its close association with benthic vegetation such as *Chara* and *Enteromorpha* suggests that it will not become abundant in the Sea itself. *P. paludosus* is regularly found in the *Typha* and *Juncus* marsh at the mouth of Whitefield Creek, as well as upstream, in ditches near Red Hill Marina, and the delta of the Alamo River (Oglesby pers. obs.). Glass shrimp are important food for largemouth bass and other introduced cichlids (Hayden and Rinnyo 1963).

Horvitz (2000) reported a "live crab" found in Varner Harbor, Salton Sea State Recreation Area, in the mid-1990s. No one else has reported crabs in the Salton Sea; it is likely that this crab was dumped after not being used as bait. Other aquatic crustaceans of the Salton Trough are listed in Table VII.

Insects are sometimes abundant in the Salton Sea itself as well as in shoreline pools. The widespread New World corixid water boatman *Trichocorixa reticulata* (initially named a new subspecies, *T. verticalis saltoni*, in 1948) is common on and near

rocks and is often abundant in hypersaline shoreline pools at the Salton Sea and in saline waters elsewhere (Table VII; Barlow 1958a; Lebo et al. 1982; Oglesby pers. obs.). Water boatmen have been found in salinities as high as 47‰ in the Salton Sea and in much higher salinities in shoreline pools, to at least 70‰, and in mud volcano pools up to 105‰ (Barlow 1958a; Parker and Knight 1992; Oglesby pers. obs.). *T. reticulata* has been found in salinities as high as 190‰ in San Francisco Bay salt ponds (Balling and Resh 1984). Hart et al. (1998) cited a laboratory experiment in which *T. reticulata* survived in 300‰, and a thesis by Cox which reported that *T. reticulata* reproduced over a range from 5 to 148‰; the Salton Sea Authority (2000) cited water boatmen reproducing at field salinities as high as 100‰. *T. reticulata* is an excellent osmoregulator to at least 100‰, but is never collected in pure freshwater, apparently due to osmoregulatory failure at really low salinities (Sanguinetti 1980). Its distribution relative to the horohaliniacum has not been studied.

Water boatmen rest on the bottom, but swim rapidly away from shadows and potential predators (the Salton Sea Authority [2000] is in error in calling them surface-dwelling). Adults can fly, and so can abandon pools that have become too saline. The *Los Angeles Times* (3 April 1989) reported that after a massive winter die-off of tilapia in the Salton Sea, “unprecedented swarms” of water boatmen, presumably released from fish predation, “took wing and descended on homes and vehicles for miles around.” During unusually wet years, when the salinity of the Great Salt Lake drops significantly (from 100 to 50‰), *T. reticulata* becomes much more common, reducing *Artemia* dry biomass from 720 to 2 mg·mg<sup>-1</sup>·m<sup>-3</sup> and causing a 10X reduction in community filtration rate, a 4X decrease in water clarity, and perhaps a decrease in soluble nutrients. Invertebrate predators may be important in structuring simple food webs such as those in saline lakes (Wurtsbaugh 1992).

At the Salton Sea *T. reticulata* is omnivorous, feeding on small algal and other cells (>140 µm), small insects, detritus, and other zoobenthos. It thus competes with



*Gammarus mucronatus* for food (Lebo et al. 1982; Simpson et al. 1998). *G. mucronatus* is also a predator on *T. reticulata* (Simpson et al. 1998). Hammer (1986) reviewed the many studies on the physiology and reproduction of *Trichocorixa reticulata*. The life cycle is discussed by Jones (1985).

Brine flies may be abundant. *Ephydra riparia* (Ephydriidae) is the most common, but shoreline flies of other families (e.g. Heleidae) are also present; both are present in shoreline pools (Table VII; Barlow 1958a; Oglesby pers. obs.). In laboratory microcosms, *E. riparia* larval and adult densities increased at higher salinities, surviving well from 17 to 65‰ (Simpson et al. 1998). At the Salton Sea, brine flies have been found at salinities as high as 43‰, and have been reported in other salt lakes with salinities as high as 300‰ (Simpson et al. 1998). *Ephydra* spp. are strongly hypo-osmotic when adapted to higher salinities (as high as 330‰ in the Great Salt Lake: Salton Sea Authority 2000), and hyperosmotic when living in salinities below the horohalinicum (Hammer 1986). Larvae feed on algae. Hammer (1986) reviewed a number of studies on the biology of *Ephydra* spp. Many other Salton Trough aquatic insects are listed in Table VII.

Empty marine gastropod and bivalve mollusc shells are often found along the Salton Sea shoreline in areas frequented by fishers, but no living molluscs are known from the Sea itself. Beached shells are presumably from molluscs brought in as live bait. Commonest are shells of the cockle *Protothaca staminea*, the jackknife clam *Tagelus* spp., and both species of mussels found along the California coastline, the native *Mytilus californianus* and the introduced Old World *M. gallo-provincialis* (see McDonald et al. 1991 for evidence that true *M. edulis* does not occur on the US West Coast). But one time we found 11 empty shells of the tropical Indo-Pacific marine snail *Rhinoclavus vertegus*, whose local provenance is unknown (Oglesby pers. obs.). A report of a live octopus found in the 1970s has not been repeated (Horvitz 2000; J. Carlton pers. comm.; J. Fitch pers. comm.); no octopus prey live in the Sea. Euryhaline clams and snails live in

drains and shoreline ponds, and their shells may wash into the Sea, especially *Corbicula* and *Thiara* (Table I).

Two species of Old World freshwater snails in the prosobranch family Thiariidae (sometimes called Melaniidae) are common to abundant in some shoreline pools, most drains, springs, and other desert waters throughout the Coachella Valley and probably also the Imperial Valley, *Thiara (Tarebia) granifera mawiensis* and *Thiara (Melanoides) tuberculata*. Current taxonomic practice is to put both species in the same genus, *Thiara*, but many, especially parasitologists, continue to separate the two species into two genera, here treated as subgenera (Taylor 1981).

*Thiara granifera* is native to southeast Asia, China, and much of Polynesia including Hawai'i. It has been widely introduced throughout the world. *T. granifera* was first found in the US in Lithia Spring, Florida, and was believed to have been initially introduced to mainland US from Hawai'i ~1940 (Edmondson 1959). It was later reported in drainages associated with the San Antonio Zoo in Texas (Murray 1964 and later publications). Carolina Biological Supply Company listed *T. granifera* in its 1964 catalog, but the listing was later deleted (Murray 1971b). Murray (1971b) found both thiariid species for sale in aquarium shops "in many areas of the country." Both *Thiara* species were probably widely dispersed through the aquarium trade and from there into springs and streams around the country (R. T. Abbott 1952; Murray 1971b; Roessler et al. 1977). The earliest published California record (1969) of *T. granifera* is from the Avenue 82 drain on the northwest side of the Salton Sea (Taylor 1981; D. Taylor, pers. comm.), but A. Schoenherr (pers. comm.) said that he had seen this snail in Coachella Valley drains even earlier. R. T. Abbott (1952) provided a detailed description of the external and internal anatomy of *T. granifera*.

*Thiara tuberculata* is slightly larger than *T. granifera* (2 to 4 cm in the Coachella Valley: Oglesby pers. obs.; rarely to 7 to 8 cm in Texas: Murray 1975). Its native distribution in the Old World is from Africa to southeast Asia and some of the western

Indo-Pacific islands; it too is widely introduced outside its original range. In the US its distribution now includes at least Maryland, Florida, Louisiana, Texas, Oregon, Nevada, Arizona, and California, where it was first reported in 1972 in a drainage ditch near the Salton Sea (Murray 1964, 1971b; Murray and Wopschall 1965b; Dundee and Paine 1977; Roessler et al. 1977; Taylor 1981; Riggs 1984; Williams et al. 1985; Hershler 1998). *T. tuberculata* was first noticed in Whitefield Creek in the Salton Sea State Recreation Area in 1988, where it was rare compared to *T. granifera* (Oglesby 1993). Search revealed an immense population in the concrete-lined Cleveland Street Spillway in North Shore, along with sometimes equally dense populations of *T. granifera*, up to many thousands-m<sup>-2</sup> (Oglesby 1993, pers. obs.; M. Fastnow pers. comm.; A. Oglesby, pers. comm.). Mixed populations of both *Thiara* species are found in many, perhaps most, drains throughout the Coachella Valley (Oglesby 1993, pers. obs.). We have not explored the Imperial Valley for either species.

*Thiara tuberculata* may outcompete native snails and rare fishes in desert springs, seeps, and streams in the western US, including several species of pupfish (*Cyprinodon* spp.) and rare native snails. In San Antonio, Texas, both thiarid species invaded the type locality of the native snail *Goniobasis comalensis* (Pleuroceridae), which has since become extremely rare (Murray 1970). *T. tuberculata* was introduced to the Caribbean island of Martinique in 1979, followed by rapid colonization of the entire island (Pointier et al. 1998), and is also on the nearby island of Guadeloupe (Pointier and Augustin 1999). Neither thiarid species outcompeted the other on Martinique, and there seemed to be no adverse effects on native aquatic biota, except for several species of *Biomphalaria*, intermediate hosts of schistosomiasis (see below). Pointier (1999) regarded the introductions of both thiarid species into the Caribbean as beneficial, as there has been a great reduction in human schistosomiasis due to successful competition with *Biomphalaria* spp.

Both thiarids are primarily apomictic parthenogenetic live-bearers, releasing tiny

(1 to 2 mm) shelled (up to 4 whorls) snails at the rate of one every day or two from the brood pouch, a diverticulum from the mantle cavity (R. T. Abbott 1952; Oglesby pers. obs.). The brood pouch may contain over 200 juveniles in a full range of developmental stages (R. T. Abbott 1952). Parthenogenetic populations of *Thiara tuberculata* are entirely female, and can be either diploid or polyploid. The rare males (3% of an Indian population) are only polyploid; no males have been found in diploid populations (Jacob 1957, 1958). Stoddart (1983) described from 0% to 30% males in different populations of *T. tuberculata* (as *T. balonnensis*) in Australia. Though rare, Australian males did participate in reproduction in sexual populations, as indicated by parent-offspring and allele-frequency analyses (Jarne and Delay 1991; Hauser et al. 1992; Jarne and Stadler 1995). Males have also been reported in some populations of *T. granifera* (Chaniotis et al. 1980b; Murray 1982; Heller and Farstev 1990; Brande et al. 1996). It is not easy to distinguish the sexes externally in either species. *T. tuberculata* becomes reproductively mature when the shell aperture attains 3.5 mm; they live only 2 yr in Hong Kong, usually breeding only the second season (Dudgeon 1989); R. T. Abbott (1952) came to the same conclusion about a number of populations in Guam and Florida. In several Caribbean islands, *T. granifera* lives  $\sim 3^{1/2}$  yr (Pointier et al. 1993b).

Shiroma (1990) studied reproduction in *Thiara granifera* as a function of salinity (test range: Whitefield Creek water at 3‰ to Salton Sea water of 30‰), counting both numbers of juveniles in the brood pouch and the rate at which juveniles were released from the brood pouch. Maximal reproductive rate was at 10‰ ( $\sim 1$  juvenile·d<sup>-1</sup>), declining only a little at lower and higher salinities. Reproduction was successful at 30‰; more casual observations suggest suggests successful reproduction at considerably higher salinities (Oglesby pers. obs.). High salinities in the range found in the Salton Sea (up to 47‰) may not be limiting to reproduction of either *Thiara* species (Oglesby pers. obs.).

Because of their parthenogenicity and viviparity, both thiarids are highly dispersible. We always find snails in our wading shoes, and A. Schoenherr (pers. comm.)

While they are usually described as freshwater snails, Salton Trough populations of both thiarids are extremely euryhaline. The upper salinity limit for *Thiara granifera* in the mini-estuary of Whitefield Creek (~12 to 14‰) is markedly lower than its laboratory tolerance of the same waters, up to 30‰ for several months, up to 65‰, and even higher for shorter periods of time (Oglesby 1980, 1993, pers. obs.; Fastnow 1989; Robinson 1993). There are no published reports of *T. granifera* tolerating high salinities in the field away from the Salton Trough or in any other laboratory. *T. tuberculata* has been reported living in low salinities in Louisiana (up to 3‰: Dundee and Paine 1977), United Arab Emirates (~6 to 7‰: Ismail and Arif 1993), and Florida (up to 3 to 6‰, but with one record of 30‰ in a tidal mangrove swamp: Russo 1974; Roessler et al. 1977).

Ranges of laboratory salinity tolerance are 0 to 65‰ for Salton Trough *Thiara granifera*, and 0 to 90‰ for *T. tuberculata*, ranges which would be notable for an animal of marine evolutionary origin, but which are especially noteworthy as these two species, their genus (or genera), and their family Thiariidae (or Melaniidae) are of evolutionarily freshwater origin (Morrison 1954). Below ~10‰ (approximately the Salton Sea horohalinity) down to laboratory tap water of 0‰, extracellular fluids of both species are well regulated, being strongly hyperosmotic and hyperionic to the medium. Like many estuarine polychaetes and other euryhaline invertebrates of evolutionarily marine origin, above the horohalinity both species of *Thiara* are hyperosmotic osmoconformers. Extraorganismal water in the mantle cavity is neither osmotically nor ionically regulated, but the fluid of the brood pouch is strongly regulated in snails living in low salinities (Christ 1980; Swift 1986). Salinity tolerance of *T. tuberculata* is higher than that of *T. granifera*, and, remarkably, *T. tuberculata* appears to hyporegulate at salinities in excess of 65‰. Regulation begins to break down at ~80‰, and no snails survived above 90‰ (Christ 1980; Oglesby 1980, 1993; Swift 1986; Robinson 1993; Oglesby and Fastnow pers. obs.). Clearly, high salinity is no barrier to colonization of the Salton Sea or its shoreline pools by either thiarid.

Oxygen consumption of Salton Trough *T. granifera* did not change between 0 and 20‰, declined only slightly at higher salinities, and was still strong at 45‰, the highest salinity tested (Bauriedel 1990). Oxygen consumption increased with study temperature, as one would expect.

Both species of thiarids tolerate hypoxic conditions well. *T. tuberculata* withstands anaerobic conditions: 98% survival after 24 hr and 25% survival after 48 hr; the latter revived without apparent damage when returned to normoxic water (Von Brand et al. 1950). Murray (1964) reported that *T. granifera* in Texas not only tolerated low  $pO_2$ , but appeared to grow better in hypoxic waters. *T. granifera* is also highly tolerant of hypoxia, surviving in closed bottles for at least 4 d at  $0.8 \text{ mg}\cdot\text{l}^{-1} \text{ O}_2$ , and with unlimited survival from  $2.5 \text{ mg}\cdot\text{l}^{-1} \text{ O}_2$  to 100%  $\text{O}_2$  saturation (Fastnow 1989). One population of *T. tuberculata* lives in a sulfide-rich stream in Israel where  $\text{H}_2\text{S}$  ranged from 0.1 to  $7.3 \text{ mg}\cdot\text{l}^{-1}$ ; in the laboratory, adult snails survived “oxygen-depleted” water with up to  $3.4 \text{ mg}\cdot\text{l}^{-1} \text{ H}_2\text{S}$  (Heller and Ehrlich 1995). Juveniles were less tolerant of high sulfide waters. Both in the Salton Trough and in the laboratory, *T. granifera* and *T. tuberculata* do not climb above the water surface, suggesting that they do not breathe air (Oglesby pers. obs.). *T. granifera* does not survive desiccation well (Chaniotis et al. 1980a), but *T. tuberculata* is moderately tolerant of desiccation (Dudgeon 1989). There is no indication in these studies that  $pO_2$  would limit the distribution of either thiarid species at the Salton Sea, at least in shallow waters.

Both species of *Thiara* are eurythermal. Studies (Texas: Murray 1971; Florida: R. T. Abbott 1952; Puerto Rico: Chaniotis et al. 1980a; Guam: R. T. Abbott 1952; Salton Trough: Oglesby pers. obs.) indicate that *T. granifera* can survive from 7 to at least  $40^\circ\text{C}$ . Salton Trough thiarids are found in waters that get no colder than  $\sim 10^\circ\text{C}$ ; they can be found in waters at least as warm as  $37^\circ\text{C}$  (Oglesby pers. obs.). The actual range of temperatures at the Salton Sea is unlikely to limit the distribution of either species of *Thiara*.



Both thiarid species feed on detritus, bacteria, microalgae, and decaying macrophytes. They are typical of herbivorous prosobranchs in having a crystalline style to assist in digestion (R. T. Abbott 1952; Fish 1955; Roessler et al. 1977; Dudgeon and Yipp 1983; Oglesby pers. obs.). These feeding habits may put them in competition with other detritivores, perhaps including desert pupfish.

Taken together, these laboratory physiological investigations indicate that both species of *Thiara* could live in the Salton Sea -- extremes of salinity,  $pO_2$ , and temperature in the Sea are all well within physiological limits of both species. Why, then, don't they live in the Salton Sea? Fastnow (1989) experimentally maintained *Thiara granifera* in small wire mesh cages (15 cm cubes) in a shoreline *Typha* pool with a very silty bottom at the mouth of Whitefield Creek; salinity, temperature, and  $pO_2$  were all well within physiological limits, but this pool did not have thiarids at this time. Most caged snails died within 3 to 4 wk, but some caged snails were still alive after >2 mo, when the experiment was terminated. These experiments were conducted in fall and spring, not summer when water temperatures would have been at their highest and  $pO_2$  perhaps at its lowest. Fastnow's (1989) results suggest that the soft silty substrate in this particular pool was unsuitable for snails (they were always found on the cage sides or plant stems, not on the silty substrate). Lack of a suitable substrate may be an explanation for their absence in the Salton Sea proper.

There are potential snail predators in the Salton Trough such as tilapia (another tilapia, in Zimbabwe, *Sargochromis codringtoni*, readily eats *Thiara tuberculata* as well as other snails: Chimbari et al. 1997), Louisiana red crayfish, and terrestrial-based predators such as raccoons (*Procyon lotor*), herons, egrets, rails, and white-faced ibis (*Plegadis chihi*). We find broken shells in probable bird feces along dikes beside drains inhabited by snails. None of these potential predators has a salinity boundary around 10 to 14‰, the upper salinity limit we have found for both thiarids in the Coachella Valley. It seems doubtful that predation keeps either thiarid species from colonizing the Salton

Sea or the estuaries of drains. Why neither thiarid colonizes any part of the Salton Sea itself remains a mystery.

Cockerell (1945) mentioned the presence of unidentified foraminiferan protozoans in the Salton Sea. F. L. Rogers (1949) listed 13 genera of benthic Foraminifera in shallow sediments of the Salton Sea; Arnal (1958, 1961) discussed distribution patterns and some ecological aspects of 20 species in 15 genera in the Salton Sea. Foraminifera were more abundant near shore and in river deltas than offshore, a distribution Arnal (1961) attributed to lower sediment *pH* in the deeper parts of the Sea. Linsley and Carpelan (1961a) reported foraminiferans in shoreline sands and barnacle shell debris. Both groups reported a number of malformed tests. Because of their taxonomic affinities to Gulf of Mexico species, Arnal (1961) suggested that most foraminiferan introductions into the Salton Sea came by way of ballast water in Navy seaplanes from Texas during the 1940s (Table V).

Linsley and Carpelan (1961a) and Simpson et al. (1988) listed a number of other benthic and demersal protozoans in the Salton Sea, particularly ciliates and a large flagellate; we find ciliates in bluegreen algal mats and in shoreline pools (Table V; Small and Gebler 2000; Oglesby pers. obs.). Ciliates are most abundant at the boundary between surface oxidized and subsurface reduced layers of sediments (Simpson et al. 1988; Small and Gebler 2000). Hurlbert et al. (2000) and Small and Gebler (2000) identified over 40 ciliate species (Table V). Most benthic ciliates feed on diatoms or bacteria, but not apparently on dinoflagellates.

Arnal (1958) reported the presence of testate amoebae of two genera. Linsley and Carpelan (1961a) also reported amoebas and radiolarians, concluding that biomass represented by protozoans was small, relative to total algae and detritus. Forty-five different species of naked or lobose amoebas, at densities ranging from 14,500 to 237,000 cells·l<sup>-1</sup> were identified by Rogerson and Hauer (2000) (Table V). Hurlbert et al. (2000) pointed out that these amoebae, which feed on organic detritus and bacteria tightly bound

to sediment particles, may be ecologically important in the Salton Sea.

Linsley and Carpelan (1961a) and Dill and Cordone (1997) listed known introductions of invertebrates into the Salton Sea as of the late 1950s, nearly all of which failed to establish. Surely many more invertebrate species have been introduced during the past century, both accidentally and on purpose, for which official records are lacking.

**Desert springs, streams, seeps, irrigation canals, drainage ditches, and other desert freshwater and athalassic saline habitats.**\_\_These aquatic habitats have an expectable array of aquatic plants (Table VI) and aquatic invertebrates (Table VII); both tables are surely incomplete. Dominant in unlined sections of the Coachella Canal (salinity 0.5 to 0.9‰) were Asiatic river clams, the hydropsychid caddisfly *Smicridea utico*, the oligochaetes *Aelosoma* sp. and *Chaetogaster* sp., and chironomid midges. Concrete-lined portions of the canal supported large populations of *S. utico* and the lepidopteran larva *Parargyractis confusalis* (Marsh and Stinemetz 1983).

A preliminary, non-quantitative, report of invertebrates in San Sebastian Marsh in San Felipe Creek was provided by Lebo et al. (1982). Temporally and spatially variable marsh salinities (~4 to 5‰ up to ~9‰, with some salinities as high as 30‰) may be representative of habitats of invertebrates in drains. Overall insect diversity was low, higher on muddy and silty substrates and lower on harder sands and muds.

Not much work has been done anywhere on smaller, less conspicuous, invertebrates, such as worms, and there have been few studies even elsewhere of the ecology or physiology of these euryhaline freshwater invertebrates.

## 2. *Amphibians, Reptiles, and Mammals*

**Amphibians.**\_\_No amphibians are known from the Salton Sea itself, but several species are found in drains and canals, springs, streams, and marshes close to the Sea, a few of which are slightly euryhaline (Table IX). See McClanahan et al. (1994) for a discussion of adaptations of desert anurans to desert life. The most widespread and commonest anuran is the introduced bullfrog (*Rana catesbeiana*), a large frog native to the

(Cyprinodontidae). The only native fish now present in the Salton Sea, *C. macularius* initially colonized the present Salton Sea as its waters rose over desert springs, streams, and oases from 1905 to 1907. Desert pupfish were formerly abundant along the shoreline of the Salton Sea, in shoreline pools, in freshwater springs, streams such as Whitefield Creek, and in drains, as well as in drainages leading to the lower Colorado River. B. W. Walker et al. (1961a) wrote, "Pupfish are everywhere about the shores of the Salton Sea where there is quiet water," a statement that unfortunately is no longer remotely true.

Introduction of competitors and predators, especially sailfin mollies, mosquitofish, tilapia, and bullfrogs, has led to a precipitous decline in desert pupfish abundance everywhere in the Salton Trough in the past 30 yr. Black (1980) estimated that the ratio of predators and competitors to desert pupfish in drains and shoreline pools varied from 2:1 to as high as 188:1. Desert pupfish were formerly abundant in springs, notably Fish Springs (now capped) near Desert Shores, but became extinct in all springs by the 1970s. *Cyprinodon macularius* was placed on both federal and state lists of Endangered species in 1986.

For a number of years, the only known significant natural *Cyprinodon macularius* habitat was 23 km<sup>2</sup> San Sebastian Marsh at the confluence of San Felipe, Fish, Carrizo, and Coyote Creeks (Black 1980; Lebo et al. 1982; Lindsay 2001). San Sebastian Marsh was designated a National Natural Landmark in 1971 by the US National Park Service and as an Area of Critical Environmental Concern and an Outstanding Natural Area 1975 by the US Bureau of Land Management. About 18 km of San Felipe Creek were designated as critical habitat for desert pupfish by the US Fish and Wildlife Service, together with a 34 m wide riparian buffer zone (US Bureau of Land Management 1986, 1988). The Bureau has now banned off-road vehicles from the vicinity of the marsh and has done some habitat enhancement for desert pupfish (US Bureau of Land Management *Newsbeat* April 1989). Bullfrogs and tilapia are both present in San Felipe Creek and have been recorded from San Sebastian Marsh. The Bureau proposed a fish barrier on San Felipe

Creek downstream from the marsh to prevent upstream migration of tilapia (US Bureau of Land Management 1988), though tilapia were already present in the marsh and the barrier would not affect bullfrogs.

A population of *Cyprinodon macularius* in México's Ciénega de Santa Clara (Santa Clara Slough) (Fig. 6) in the degraded delta of the Colorado River derives from a 1976 introduction of fish from a refugium at the Boyce Thompson Arboretum, Superior AZ (Fradkin 1981; Turner 1983; Schoenherr 1993b; Zengel and Glenn 1996). The Ciénega is a severely degraded wetland fed only by saline waste US irrigation water ( $\sim 144,000$  acre-feet $\cdot$ yr $^{-1}$ , 3 to 5 ‰) diverted to the Wellton-Mohawk Drain from agriculture in the Gila River valley in southern Arizona (Fig. 6). Rinne and Guenther (1979) and Mellink and Ferreira-Bartrina (2000) wrote that the Ciénega's desert pupfish population was thriving, but worried that at least nine species of exotic fish had entered the Ciénega through the Bypass Drain from the Wellton-Mohawk Drain, any or all of which could prove to be competitors and predators.

More recently it has become recognized that *Cyprinodon macularius* is much more widespread in the Salton Trough than usually believed, though never abundant. Desert pupfish, along with sailfin mollies and tilapia, were collected in the Whitewater River near its mouth (Feldmeth 1980), presumably from a natural population. Native desert pupfish populations are now known in upper Salt Creek and Oasis Springs Ecological Reserve south of Bat Caves Buttes (Black 1980; Schoenherr 1988; Schoenherr and Feldmeth 1993). It is presumed that desert pupfish provided the name for Fish Creek (one of the tributaries of San Sebastian Marsh), but there have been no fish of any species in Fish Creek since at least the violent floods of 1916 (Lindsay 2001). Managed demonstration populations of desert pupfish are maintained at Salton Sea State Recreation Area, Anza-Borrego Desert State Park, and Living Desert Reserve in Palm Desert (Black 1980; Schoenherr 1988; Lindsay 20001; Oglesby pers. obs.). The Nature Conservancy restored desert pupfish to Dos Palmas and Thousand Palms Oases, but

since both tilapia and bullfrogs are also present in these springs, their desert pupfish populations are not secure. Desert pupfish are present in at least several drains in both the Imperial and Coachella Valleys (Department of Fish and Game; Lau and Boehm 1991; A. Schoenherr pers. comm.; Oglesby pers. obs.). In recent years small desert pupfish populations have been found in the concrete-lined Cleveland Street Spillway near North Shore and in Whitefield Creek in the Salton Sea State Recreation Area (Oglesby pers. obs.). *C. macularius* is widely distributed in northern Sonora and the Colorado Delta in México as well as in southern Arizona (Hendrickson and Romero 1989). How many of these populations were of *C. eremus* (then called a subspecies of *C. macularius*, see below) was not stated. Populations, with one exception, were low as desert pupfish coexisted with both predators and competitors. The exception was at Cerro Prieto, in a pond with an unusual chemical composition that excluded other fish; desert pupfish were abundant (Hendrickson and Romero 1989).

Reasons why so many species of desert fishes are endangered include: often highly restricted distribution (for many species, just a single spring), damage to riparian habitats by cattle overgrazing and tree cutting, habitat damage from groundwater pumping, surface water diversions for agriculture, drainage of springs, channelization of streams, introduction of competitor and predator fish and other vertebrates, and vandalism (Williams and Sada 1985; Williams et al. 1985).

Turner (1983, 1984) studied allozyme variation in four natural populations of *Cyprinodon macularius* from the Salton Trough, comparing them with each other and with allozyme patterns of the same subspecies from the Ciénega de Santa Clara and *C. eremus* from Quitobaquito Spring in southern Arizona (recently elevated to separate species status: Echelle et al. 2000) and the nearby Río Sonoyta in Arizona and Sonora, México; he also studied *C. macularius* from four artificial refugia. He concluded that genetic divergence of different populations “has almost certainly been overestimated,” and that refugium populations differed little from wild populations. Turner (1984) also



concluded that these several natural and refugium populations did not go through any significant genetic bottlenecks and that genetic drift has not been an important process affecting desert pupfish populations. Dunham and Minckley (1998) expressed concern that the limited genetic differentiation of both natural and refugium populations of *C. macularius* would make full recovery to healthy populations difficult.

Desert pupfish are small and chunky, adults no greater than 3 to 6 cm long. Non-breeding *Cyprinodon macularius* form loose schools of similar size for diurnal foraging. They feed unselectively on detritus, algae, and small invertebrates; in the Salton Sea and adjacent waters, prey invertebrates include ostracods, copepods, pileworms, insect larvae (especially chironomids and mosquitoes), and molluscs; they also sometimes eat their own eggs and fry (Moyle 1976; Lebo et al. 1982). Desert pupfish are easily reared in laboratory aquaria over a wide range of salinities and temperatures, permitting detailed studies of their morphological, physiological, and genetic adaptations. Aquarium-raised desert pupfish feed on a variety of readily available foods: *Artemia* larvae, enchytraeid and tubificid oligochaetes, copepods, cladocerans, beef liver, fresh lettuce, spinach, and commercial fish foods (Kinne 1960; Kinne and Kinne 1962; Crear and Haydock 1971).

Few fish can live in such extreme salinity conditions as *Cyprinodon macularius*: adults can live in salinities from freshwater to 68‰ while juveniles can withstand up to 90‰ (Barlow 1958b; Kinne 1960). Spawning occurs from freshwater to 70‰ (Kinne and Kinne 1962). Euryhalinity declines with age, as adults cannot withstand as sudden and extreme salinity transfers as can juveniles (Kinne 1960). Desert pupfish tolerate higher salinities than all other native and introduced freshwater fish, so perhaps as Salton Sea salinity rises, killing less euryhaline fishes, desert pupfish may again become the dominant Salton Sea fish, a situation that Swift et al. (1993) believed has repeated itself many times in the thousands of years of history of desiccating lakes in the Salton Trough.

Schoenherr and Feldmeth (1993) summarized studies on thermal relations of several southwest pupfish species: "Thermal tolerances vary with acclimation

temperature and season. Species from constant temperature habitats have narrower ranges of thermal tolerances [than those from thermally variable waters], and those tolerances are inherited." Adult *Cyprinodon macularius* can withstand temperatures from 4.5 to 44.6°C and  $pO_2$  from saturation down to 0.13 mg·l<sup>-1</sup> (Kinne 1960; Sweet and Kinne 1964; Crear and Haydock 1971; Moyle 1976; Black 1980; Schoenherr 1993b; Schoenherr and Feldmeth 1993). Kinne (1960) and Sweet and Kinne (1964) documented irreversible phenotypic developmental differences as well as differences in growth rates, food intake, assimilation efficiency, and activity in Salton Sea desert pupfish raised in different but stable combinations of temperature and salinity. In the laboratory, the critical thermal maximum was 44.6°C, the highest known for any teleost fish (Schoenherr and Feldmeth 1993). Desert pupfish avoid the highest temperatures in shoreline pools on hot summer days; if they had cooler temperatures available, they were never observed in waters warmer than 37°C. Winter behavior patterns were somewhat different (Barlow 1958a).

Desert pupfish collected in freshwater were frequently infected with an ectoparasitic copepod in the family Lernaeidae. Crear and Haydock (1971) speculated that the parasite was introduced to the Salton Trough from aquarium fish. Infected fish were weak and usually died soon after collection. No lernaeid parasites were found in desert pupfish collected from more saline waters (Crear and Haydock 1971).

Desert pupfish reproductive behavior attracts much attention (Cowles 1934; Barlow 1961; Moyle 1976). Territorial males, blue in their breeding colors, make nests in algal patches in shallow water from mid-spring to late summer. After an elaborate courtship ritual a female is induced to lay one or a few eggs in the nest, which are immediately fertilized; the male then chases away the female. After several females have spawned in a male's nest, he pugnaciously guards the nest until the eggs hatch. In the warm temperatures of their normal habitats, including the Salton Trough, desert pupfish can complete their entire life cycle in 1 yr, but most breed in their second summer (Moyle

1976). Juvenile tilapia can completely disrupt the stereotyped courtship of desert pupfish, curtailing reproduction (Schoenherr 1993b).

Desert pupfish habitat requirements include a sand-silt substrate, abundance of rooted aquatic plants and filamentous algae (not available in the Salton Sea itself), water shallower than 30 cm, minimal surface flow ( $<0.25 \text{ m}^3\cdot\text{s}^{-1}$ ), and water temperatures above freezing in winter (Black 1980). Desert pupfish living in shoreline pools and streams swim along the Salton Sea shoreline and can colonize adjacent waters (Sutton 2000).

The viviparous mosquitofish *Gambusia affinis* (Poeciliidae), native to the southeastern US, has been widely introduced in the West and elsewhere for mosquito control; it was initially introduced into California in 1922, and mosquito control districts supply large numbers on the slightest demand. Mosquitofish are one of the commonest fish in the “minnow” array found in canals and drains, shoreline pools, and calm, shallow areas of the Salton Sea, especially near drain mouths (Barlow 1958a; B. W. Walker et al. 1961a; Oglesby pers. obs.). Moyle (1976) summarized studies on the great thermal tolerance (4 to  $37.3^\circ\text{C}$ ) of *G. affinis*. Mosquitofish are mostly omnivorous surface feeders (which permits them to live in hypoxic waters), preying on insects, small crustaceans, and amphibian tadpoles; however, they compete with desert pupfish for food (Black 1980) and may prey on desert pupfish eggs and fry. Desert pupfish would be at least as potent in mosquito control (Kennedy 1976; Moyle 1976; Williams and Sada 1985).

Mosquitofish usually complete their reproductive cycle in 1 yr, particularly if the water is warm, and usually die the summer they reach sexual maturity. Mosquitofish are fecund and population growth can be very rapid. Copulation is preceded by a stereotyped courtship display (Moyle 1976).

The Salton Sea population of longjaw mudsuckers, *Gillichthys mirabilis* (Gobiidae) dates from a California Department of Fish and Game introduction of ~500

fish in 1930 from San Diego Bay, in support of the attempt to establish striped bass (Anonymous 1931a, 1958; B. W. Walker et al. 1961a). Longjaw mudsuckers are euryhaline, able to survive being transferred directly from saltwater into freshwater, and *vice versa*. Their high salinity limit is 82.5‰ (B. W. Walker et al. 1961a; Barlow 1963; Owens et al. 1977). They can grow as long as 14 cm. Longjaw mudsuckers can tolerate freshwater but do not maintain permanent populations there (Moyle 1976).

While widespread in the Salton Sea, longjaw mudsucker distribution is patchy and mostly restricted to quiet shallows and occasionally shoreline pools. Adult longjaw mudsuckers feed primarily on pileworms, other benthic invertebrates, and small fish including desert pupfish. Younger fish feed on insects as well, with up to 10% of the diet being nematodes. Newly hatched fingerlings are zooplanktivores. Reproduction is in shallow water, from December through June. Females may spawn up to 3 times-yr<sup>-1</sup> in the Salton Sea. After a stereotyped courtship, a female lays 4000 to 9000 eggs in a burrow in shallow water, guarded by the male until they hatch (Barlow 1958a, 1963; Whitney 1961b; Barlow and De Vlaming 1972; Courtois 1976; Moyle 1976; Loretz 1979; Swift et al. 1993).

Occasionally fed upon by orangemouth corvina, the chief importance of longjaw mudsuckers at the Salton Sea is as orangemouth corvina bait. However, most bait longjaw mudsuckers sold in California, including by Salton Trough bait shops, are trapped from lagoons along the Pacific Coast of Baja California (Dill and Cordone 1997), raising the risk of introduction of undesirable fish species and parasites (see below).

*Poecilia latipinna* (sailfin molly, Poeciliidae) is the very common, conspicuous, schooling “minnow” with a iridescent green tail and dorsal fin, but with color variations all the way to rich black; adults reach >12 cm. Introduced ~1964 as escapees from tropical fish farms or as released by aquarists who tired of their pets, this euryhaline freshwater fish (native from South Carolina to the Yucatán Peninsula in México) has established huge populations (as much as 20 million fish standing crop) along the shallow margins of the

Salton Sea, in drains, and some larger shoreline pools. Sailfin mollies accounted for as much as 98% of all fish collected in shoreline pools and along the Salton Sea shoreline, and are serious competitors and predators on native desert pupfish (Black 1980). Sailfin mollies live in salinities as high as 87‰ and can tolerate up to 92.2‰ for several weeks (Nordlie et al. 1992). At the Salton Sea, adult sailfin mollies feed primarily on detritus and bacteria (86% by volume) and algae (14%), rarely invertebrates. Sailfin mollies are livebearers, with Salton Sea fish producing between 20 and 60 young per female; one large female contained 141 embryos (Moyle 1976; Trexler 1985).

The native, cosmopolitan euryhaline striped (or gray) mullet, *Mugil cephalus* (Mugilidae), migrated into the Salton Sea from the Gulf of California after the Sea's formation in 1905 to 1907. Reaching 4.5 to 5.5 kg, mullet were the only fish legally taken from the Salton Sea by commercial interests, first in 1915 to 1921, reaching a peak landing of 41,370 kg in 1918, and then again from 1942 to 1953, when commercial fishing was banned to protect the newly introduced sport fish. By then, mullet catches were too low to sustain commercial exploitation. The history of commercial mullet fishing in the Salton Sea was described by Thompson and Bryant (1920), Dill and Cordone (1977), and Costa-Pierce (1998a). Catadromous adults spawning in the Gulf of California migrated to the Salton Sea by way of the Colorado River and irrigation canals, but there is no evidence they ever spawned in the Sea, despite its salinity which was then about the same as the ocean. When permanent headgates for the All-American Canal were established in 1942 above the 7 m high Imperial Dam upstream from Yuma, migration of striped mullet from the Gulf of California was blocked. Mullet seen in the Salton Sea since that year presumably entered the Sea prior to 1942. Several mullet taken by fishers in the mid-1990s indicate that a few mullet can still reach the Sea (Horvitz 2000).

Mullet filter-feed on plankton to a small extent but feed primarily on benthic algae, particularly diatoms (Hendricks 1961b; B. W. Walker et al. 1961a; Moyle 1976; Eggold and Motta 1992; Cardona et al. 1996). Mullet are euryhaline, adaptively changing

the number and activity of gill chloride cells and  $\text{Na}^+\text{-K}^+$  ATPase in response to salinity (Murashige et al. 1991; Ciccotti et al. 1995; Hotos and Vlahos 1998).

See Table VIII for a list of fish of the Salton Trough, a table that is probably incomplete for "freshwater" fish. Table 25 in B. W. Walker et al. (1961a), Table 2 in Dill and Cordone (1997), and Table 1 in Costa-Pierce (1998a) list the many known fish introductions into the Salton Sea up to the late 1950s; nearly all have been failures. These lists were expanded by Swift et al. (1993). Introductions of other fish species probably takes place frequently, when people bring live bait to the Salton Sea or dump their aquaria.

The various studies discussed above indicate that reproduction of Salton Sea sport fish is likely to be seriously diminished when salinities reach 40 to 45‰, a concentration which was exceeded by the late 1990s. But even if the major part of the Salton Sea exceeds 40 to 45‰ during the entire year, there might still be adequate reproduction by fish migrating into lower salinity estuarine areas near the mouths of the Alamo, New, and Whitewater Rivers and larger drains. There is some indication that orangemouth corvina now breed preferentially near the New and Alamo river mouths. Developmental stages of all these species are more sensitive to higher salinities than are adults; thus, lower-salinity estuarine habitats might serve as nurseries, with fish dispersing into the Sea once they reach a more high-salinity tolerant subadult or adult stage. There is no diminishing of sport fish catch in 1999 and 2000.

A problem of unknown magnitude beginning in the 1980s is illegal fishing for orangemouth corvina and tilapia, conducted primarily by southeast Asian immigrants using gill nets. For example, in 1983, 18 people were charged with gill netting 3200 kg tilapia ( $\approx 2250$  fish); Department of Fish and Game personnel said the fish were to be sold live in markets in San Diego, Orange, and Los Angeles Counties. "Our information is that some people have made as much as \$9000 on a single weekend by selling fish illegally taken from the Salton Sea," said Warden Laret in November 1982. As another example, in



expand. Many are euryhaline and have expanded their ranges to other drains and canals via the Salton Sea (Mearns 1975; Schoenherr 1979; Oglesby pers. obs.). Table VIII lists species known or believed to be inhabitants of canals, drains, and other "fresh" waters of the Imperial and Coachella Valleys; not listed are species now believed to be extinct or at least non-breeding. For more detailed lists and discussions of these fish, see B. W. Walker (1961), Mearns (1976), Moyle (1976), Swift et al. (1993), and Dill and Cordone (1997). Of the species listed in Table VIII, only the desert pupfish and razorback sucker are native to the Salton Trough.

King Street drain in the Coachella Valley receives both agricultural wastewater at  $\sim 22^{\circ}\text{C}$  and thermal well water at  $42^{\circ}\text{C}$ , producing a strong thermal gradient;  $p\text{O}_2$  is at or near saturation. Five species of fish (*Cyprinella lutrensis* [as *Notropis*], *Cyprinodon macularius*, *Gambusia affinis*, *Poecilia latipinna*, and *P. sphenops*) inhabited the canal and displayed different thermal preferenda. Desert pupfish inhabited the warmest part of the canal, up to  $39^{\circ}\text{C}$ . Mosquitofish appeared at  $32^{\circ}\text{C}$ , and the remaining three species at 26 to  $22^{\circ}\text{C}$ . There was an almost complete separation of the five species in terms of both thermal and microhabitat preferenda (Schoenherr 1979). This result does not really conflict with those of Mearns (1976) for the Johnson Street drain, where a similar array of fish coexisted in a non-thermal gradient. King Street drain was completely remodeled by bulldozer after *chubasco*-caused flooding in 1976, which simplified microhabitats and changed the thermal pattern but not the gradient itself. The original five species persisted along with newly introduced tilapia, but with reduced niche separation (Schoenherr 1979).

After the failure of introduced tilapia to control aquatic weeds, particularly the rapidly growing -- up to  $25\text{ cm}\cdot\text{d}^{-1}$  -- Eurasian *Hydrilla verticillata* (Table VI), and based on research by its Aquatic Weed Control Facility and fish hatchery near El Centro, Imperial Irrigation District obtained permission from California Department of Fish and Game to introduce triploid (sterile) grass carp (*Ctenopharyngodon idella*), originally from east Asia (Imperial Irrigation District Public Relations Office 1990). Introduced into

1988, two men were seriously injured when their car caught fire on State Highway 86 in the Salton Sea State Recreation Area, flipped over, and spilled 136 kg ( $\approx$ 30 fish,  $\sim$ 12 over the then-limit of nine) of orangemouth corvina onto the road. Department of Fish and Game is attempting to educate the southeast Asian immigrant community in southern California about California fishing law and the importance of conservation, as traditional fishing procedures used in the former Indo-China are illegal in California. The paucity of reports of illegal fishing in the Salton Sea in the 1990s may reflect a genuine reduction in poaching, or just reductions in State funding for Department of Fish and Game surveillance and enforcement (information from news articles in the *Pomona CA Progress Bulletin* and *Los Angeles Times*).

Nevertheless, the Salton Sea still maintains a superb sport fishery, even if many fishers have deserted it because of unfounded rumors. Jim Matthews, outdoors columnist for the *Ontario CA Inland Valley Daily Bulletin*, wrote on 3 June 1999: "Where would you go fishing this weekend? My first pick is the Salton Sea. It is easily the most productive fishery in the nation, producing more fish per surface acre than -- well -- anywhere. This is the place to take the kids and truly catch a mess of fish. If you fish with nightcrawler pieces from shore, you will catch dozens -- no, hundreds -- of tilapia and bairdiella. Fish from a boat, float tube, or wade out to your armpits and make long casts, and you will catch corvina to [2.7 or 3.6 kg] on mudsuckers. . . . All three species are great eating."

**Fish in springs, streams, seeps, canals, ditches, and other desert freshwater and athalassic saline habitats.**\_\_Collections of fish in drains and canals in the Imperial and Coachella Valleys, waters somewhat saline (2 to 6‰ and sometimes higher) due to saline groundwater seepage and agricultural runoff, provide a number of records of introduced fish -- cyprinids, centrarchids, ictalurids, and tropical fish "normally" found in domestic aquaria (Table VIII, likely incomplete). It can be expected that breeding populations are or will become established and that ranges of many of these fish will

canals at 0.3 to 0.5 kg, adult grass carp reach 11 to 18 kg and >1 m long. Biologists and engineers with the District regard the experiment as a great success, and note that (unlike tilapia), grass carp do not turn carnivorous when they deplete intra-canal vegetation: rather, they leap out of the water and eat Bermuda grass (*Cynodon dactylon*, Poaceae) growing at the water's edge. Over 200,000 grass carp had been stocked in canals by 1999, ~20,000 to 25,000·yr<sup>-1</sup>. Grass carp have established breeding populations in several other river systems in the US, including the Columbia River, the Trinity River in Texas, and the Mississippi River, apparently derived from a few fertile diploid individuals mixed in with stocked sterile triploids (Bain 1993; Raibley et al. 1995; Elder and Murphy 1997; Loch and Bonar 1999). Since grass carp eat plants also fed upon by waterfowl (McKnight and Hepp 1995), care must be taken not to contaminate wildfowl management ponds in the Imperial Valley with this competitive fish.

It is not yet known whether grass carp will also eat the noxious floating fern *Salvinia molesta* (Table VI) following its 1999 introduction into the Colorado River and All-American Canal (*Los Angeles Times* 23 September 1999). *S. molesta* is, after the water hyacinth *Eichhornia crassipes*, the most widespread aquatic weed in the world (Oliver 1993; Room and Fernando 1992). An aquatic beetle, the weevil *Cyrtobagous salviniae* has been used effectively in biological control of salvinia elsewhere in the world (Cilliers 1991) and should be considered for the Salton Trough if can be demonstrated that it will not feed on other, desirable plants. Both hydrilla and salvinia are readily spread by boaters.

In 1980 hybrids between grass carp and *Hypophthalmichthys nobilis* (bighead carp) were planted in several waterways in the Coachella Valley (Swift et al., 1993). The original 18,000 triploid grass carp cost \$75,000 in 1985 (still cheaper than the \$100,000 it costs to clean the canals mechanically), and live a number of years, so that restocking does not need to be done annually. Imperial Irrigation District established its own grass carp hatchery in 1988, producing 10,000 to 20,000 stockable fish·yr<sup>-1</sup> (Imperial Irrigation

District Public Information Office 1990). It is illegal in California to catch or possess grass carp.

Mearns (1976) predicted that introduced tropical fish would not likely threaten Salton Sea sport fish, but that tropicals very likely would become major competitors with the native *Cyprinodon macularius*. This pessimistic prediction has become reality, as documented by Schoenherr (1979, 1981, 1988) and Department of Fish and Game. Swift et al. (1993) and Dill and Cordone (1997) provided detailed reviews on introduced fish species in southern California. Swift et al. (1993) regarded as "introductions" native California fish introduced outside their native range; Dill and Cordone (1997) ignored intra-state introductions.

### 5. Birds

"Birds are often completely ignored in limnological studies in spite of the fact that they may play very important roles in a lake's ecology" (Hammer 1986). The marshes and riparian vegetation of the Salton Sea edges, rivers, lakes, springs, seeps, canals, and drains provide an oasis of habitat for water-related birds amid the broad cultivated fields of the Imperial and Coachella Valleys and the surrounding Colorado Desert.

There are two wildlife refuges along the Sea's shoreline: the federal Sonny Bono Salton Sea National Wildlife Refuge at the south end of the Sea (US Fish and Wildlife Service 2000), and the state Imperial Wildlife Management Area (Wister Unit, 1580 ha, along the southeast margin of the Sea; Finney-Ramer Unit, 1820 ha, along the Alamo River; Hazard Unit, adjacent to and managed by the federal refuge) (Gillilan 1971; Nathanson 1972). The federal refuge, established in 1930, originally consisted of 5,789 ha bordering a considerably smaller Salton Sea. The refuge later leased an additional 5,931 ha from Imperial Irrigation District for its present refuge. Because of flooding, only ~432 ha of manageable habitat remain. The state's Imperial Wildlife Refuge was formed in 1954. Both refuges provide shallow waters and abundant food to attract wintering waterfowl away from agricultural fields to reduce crop depredation. Both refuges allow fishing and

seasonal bird hunting (chiefly ducks, geese, doves). Wister's hunting use has varied from ~11,000 hunter-d-yr<sup>-1</sup> to ~5,000 hunter-d-yr<sup>-1</sup>, with the current level ~8000 hunter-d-yr<sup>-1</sup> (Salton Sea Authority 2000). Both refuges have become sites of major recreation, with bird watching now the major use. Refuge personnel buy high-quality irrigation water to dilute used agricultural water in the refuges -- a short-term solution to high salinity that is very expensive.

More than 400 bird species have been recorded at the Salton Sea (US Fish and Wildlife Service 1997; Shuford et al. 1999), including a number of rarities observed nowhere else in the western US. This number is over half the total number of birds species recorded for all of North America north of the Mexican border, and is rivaled only by the number of birds recorded for the Texas coast of the Gulf of Mexico. The Salton Sea area is the major center of avian diversity in the American west. Checklists of birds are available from the federal refuge and the Salton Sea State Recreation Area visitor center, though they can never be complete nor up to date (US Fish and Wildlife Service 1997; Shuford et al. 1999).

Salton Trough bird life falls into several important categories:

- Resident species of desert plant communities, most abundant near water and agricultural lands, as well as residents of the Salton Sea shoreline and adjacent marshes. Additional species are resident in agricultural fields and towns.
- Winter visitors, notably grebes, ducks, geese, shorebirds, and other migratory birds attracted to water and cultivated fields which provide food and shelter.
- Spring and fall migrants along the Pacific Flyway.
- Summer visitants, many of which breed, sometimes in large numbers.

With an increasing number of birders present during the intense heat of the summer, it is becoming apparent that many bird species regularly disperse northwards in late summer after breeding in México, some in large numbers, others exceedingly rare. These include blue-footed booby (*Sula nebouxii*), magnificent frigatebird (*Fregata*

*magnificens*), roseate spoonbill (*Ajaia ajaia*), wood stork (*Mycteria americana*), Heermann's gull (*Larus heermanni*), laughing gull (*Larus atricilla*, which bred in a few years from the 1920s through 1957), and yellow-legged gull (*Larus livens*). Amazingly, there are several recent records of the Laysan albatross (*Phoebastria immutabilis*), normally an open Pacific ocean bird. Some of these late summer visitors have recently established breeding populations, including brown pelican (*Pelecanus occidentalis*) and black skimmer (*Rhynchops niger* (Table X). Late summer *chubascos* may even force open ocean birds such as boobies (*Sula* spp.), storm-petrels (*Oceanodroma* spp., *Oceanites* spp.), and jaegers (*Stercorarius* spp.) onto the Sea (Kaufman 1977; Patten and Minnich 1997). We may expect additional reports of accidental rarities as the number of summer birders continues to rise.

Colonial nesting species at the Salton Sea include brown pelican (*Pelecanus occidentalis*, since 1996), white pelican (*Pelecanus erythrorhynchos*, not since 1957), double-crested cormorant (*Phalacrocorax auritus*, since ~1907), great blue heron (*Ardea herodias*, since ~1907), great egret (*Ardea alba*, since ~1961), snowy egret (*Egretta thula*, since ~1978), little blue heron (*Egretta caerulea*, once in 1979, near Seeley), tricolored heron (*Egretta tricolor*, once in 1994, at Ramer Lake), cattle egret (*Bulbulcus ibis*, since 1970), black-crowned night heron (*Nycticorax nycticorax*, since 1986), white-faced ibis (*Plegadis chihi*, sporadic breeding since 1950s), western snowy plover (*Charadrius alexandrinus*), laughing gull (*Larus atricilla*, since 1920s, but not in recent years), California gull (*Larus californicus*, since 1997), gull-billed tern (*Sterna nilotica* since 1927), elegant tern (*Sterna elegans*), Caspian tern (*Sterna caspia*, since 1920s-1930s, ceased in 1950s, with recolonization in 1992), Forster's tern (*Sterna forsteri*, since 1970), and black skimmer (*Rhynchops niger*, since 1973). Note that many of these species colonized the Sea relatively recently. Ground-nesting colonial waterbirds must contend with one of the world's hottest and most rigorous places to nest and raise chicks. The cattle egret is a natural introduction to the Western Hemisphere from Africa in the 1930s.



It was first recorded from the Salton Trough in 1963, and first nested in the Imperial Valley, at the New River delta, in 1970. Cattle egrets soon displaced snowy egrets from many tree and snag nesting sites, and are now the most common ardeid in the Salton Trough (Platter 1976; Small 1994; Shuford et al. 1999). See Shuford et al. (1999) for details on colonial nesting birds at the Salton Sea.

Pelicans, cormorants (which also nest in trees), snowy plovers, gulls, terns, and black skimmers all nest on the ground, either on islets or barnacle shell "sand" bars (Small 1994), both of which are vulnerable both to land-based predators such as: raccoons (*Procyon lotor*), striped skunks (*Mephitis mephitis*), coyotes (*Canis latrans*), kit foxes (*Vulpes macrotis arsipus*), domestic dogs (*Canis familiaris*), and feral house cats (*Felis catus*), etc., and to inundation by seasonally rising Salton Sea waters. In 1995, federal refuge personnel created five artificial islets in three shallow waterfowl management ponds, normally drained during the summer, managing water levels to maintain islet status. The immediate and happy result is that the large majority of the Salton Sea's gull-billed terns (now ~180 pairs) and black skimmers nest on these islets; in 1997 Caspian terns began nesting. Refuge personnel (pers. comm.) reported that this project has continued to be successful and is expected to expand with the creation of more managed nesting islets.

Birding on both federal and state wildlife refuges in Imperial County is big business: birders from around the world spent \$3.1 during the year September 1993 through August 1994 (Ornithological Council 1998). That year avian enthusiasts came from 7 countries, 31 states, and 20 California counties.

**Benthic-feeding birds.**—American avocets (*Recurvirostra americana*) and black-necked stilts (*Himantopus mexicanus*), both of which breed in the Salton Trough in large numbers, and many other smaller, mostly migratory, shorebirds (Charadriiformes) probe-feed on small invertebrates (worms, crustaceans, insects) along the Salton Sea shoreline, in shoreline pools, drowned fields, and in other waters shallow enough to wade

in. American avocets sweep and filter the water above the substrate with their upwards-curved bills. The rare summer visitant roseate spoonbill is a zooplankton feeder. Some 44 species of shorebirds have been found at the Salton Sea, four or five of which breed. Vast numbers appear during migration. The Salton Sea is one of the most important sites along the Pacific Flyway for wintering and migrant species, with over >10,000 individuals each season; as many as 90,000 individuals have been estimated for April. Eleven species exceeded 1000 in at least one season (Shuford et al. 1999). The great abundance of wintering and migratory shorebirds in the Colorado delta has led to its recognition by the Western Hemisphere Shorebird Reserve Network (Mellink and Ferreira-Bartrina 2000). It is unlikely that any of these avian planktivores and benthic feeders, however abundant, have any significant ecological effect on overall ecology of the Salton Sea itself, except perhaps in certain marginal areas (Oglesby pers. obs.).

From many hundreds of thousands to 3 to 4 million eared grebes winter (November through April) on the Salton Sea, as much as 90% of the world's population of this species. Eared grebes at the Sea feed primarily on pileworms, small insects, and crustaceans (Jehl 1996, 1997, 2000; Warnock 1999; Kuperman et al. 2000). See below for discussion of major grebe mortality events.

Thirty-six species of swans, geese, and ducks have been recorded from the Salton Sea area, most occurring as migrants and winter visitors; only five species have been confirmed as breeders. The Salton Trough is second only to the Central Valley for wintering waterfowl. Commonest are snow (*Chen caerulescens*) and Ross geese (*Chen rossii*), ruddy ducks (*Oxyura jamaicensis*), northern pintail (*Anas acuta*), northern shovelers (*Anas clypeata*), American wigeon (*Anas americana*), green-wing teal (*Anas crecca*), Canada goose (*Branta canadensis*), scaup (*Aythya marila* and *A. affinis*), and canvasback (*Aythya valisneria*) (Shuford et al. 19989).

**Piscivorous birds.**—At all times of the year, piscivorous birds are abundant, both along the Salton Sea shoreline and on the open Sea itself.

A few brown pelicans (federally listed as Endangered in 1970) from the Gulf of California often summered at the Salton beginning many years ago after nesting in the Gulf of California, with numbers increasing in recent years. Brown pelicans first overwintered in 1987, and began breeding on Mullet Island in 1996. This colony is the only breeding site away from the Pacific Ocean coastline (including the Gulf of California), but constitutes only a tiny fraction of the total brown pelican population in the eastern Pacific Ocean. Since the mid-1990s, summer post-breeding populations of brown pelicans regularly reach 1000 to 2000 birds, with 10 to 20 birds overwintering (Imperial Irrigation District 1994; Anderson et al. 2000).

White pelicans, which breed at inland saline lakes throughout the west, have always been present in the Salton Trough as they migrated to winter in the Colorado Delta; they still use the Delta when there is water present. White pelicans began breeding at the Salton Sea as soon as it formed in 1905 to 1907, using small islets near the five volcanic buttes -- this was the southernmost known nesting colony (Grinnell 1908). The last confirmed breeding was in 1957, after which the last few breeding islets were inundated by the rising Salton Sea. Several thousand (2000 to 17,000) white pelicans winter at the Salton Sea, most of the western US population (Friend 1998), but numbers seem to have declined in recent years, as they have over all of western North America due to habitat loss and human disturbance. Both pelican species feed primarily on tilapia, with white pelicans able to take larger fish (up to 2 kg) than brown pelicans (up to 1 kg) (Imperial Irrigation District 1994).

Double-crested cormorants have declined regionally because of pesticides; predation of eggs and young by crows, ravens, and gulls; habitat losses; and human disturbance. Cormorants have bred on islets and snag trees at the Salton Sea since at least 1980 and probably since the formation of the Salton Sea in 1905 (an old name for Mullet Island is Cormorant Island). About 10,000 cormorants are now resident, with their major nesting location on Mullet Island (as many as 4500 nests -- the largest breeding colony on

the West Coast); other Salton Sea breeding colonies include the Whitewater River delta and near the Wister Unit of the state game refuge. Cormorants feed and roost both at the Salton Sea and at Finney and Ramer Lakes. They also feed at the New and Alamo Rivers (Imperial Irrigation District 1994).

Ospreys are open-water piscivores, but are uncommon at the Salton Sea. Bald eagles are also piscivores, usually robbing other birds (kleptoparasitism); as many as 1 to 3 winter at the Salton Sea (Imperial Irrigation District 1994).

Shoreline-associated piscivores additionally include a number of species of herons and egrets, white-faced ibis, several species of rails, and wood storks. Despite statements to the contrary (e.g. US Bureau of Reclamation 1998) cattle egrets are not piscivores; they are terrestrial birds, eating insects, spiders, other terrestrial invertebrates, lizards, and mice, but only a few fish (Platter 1976). Black skimmers feed on surface fish on the wing, but do so only in very nearshore waters, not the open sea. Black skimmer populations, nesting colonies, and reproductive success vary greatly in size from year to year (Molina 1996). Up to 40% of the California population nests at the Salton Sea (Friend 1999).

While feeding of these piscivores has been little studied at the Salton Sea (for example: What fish species and sizes do they feed on? What is the effect of predation on the population biology of their prey?), piscivorous birds may have a significant impact as top predators in Salton Sea food webs (Oglesby pers. obs.).

For four years beginning in 1987, US Fish and Wildlife Service made annual counts of active nests of great blue herons, great egrets, snowy egrets, cattle egrets, and double-crested cormorants in the Imperial Valley. This breeding census presented a dismaying picture: a steady decline through the four year study period, and apparently no young produced at all in 1990. Fish populations in drains and in the Salton Sea had not comparably declined, suggesting that food was not limiting the four piscivores. A major problem in assessing potential adverse effects from pollutants is the fact that these

species feed not only on the Sea and but also in lakes, canals, irrigation drains, riparian habitats, and irrigated fields. Cattle egrets do not eat fish, and their nesting crashed similarly to those of the piscivores. US Fish and Wildlife Service believed that trace metal buildup might have been responsible, presumably derived from runoff into the closed Salton Sea, though in fact trace metal concentrations are not elevated in the Sea (see below). Nevertheless, all five species are still abundant at the Salton Sea (Oglesby pers. obs.). High winds can cause significant nest failure in heron and egret nesting colonies in trees in the federal wildlife refuge (Barnum 2000).

Recent proposals for “saving” the Salton Sea have focused only on five species on the federal list of Endangered species: brown pelican, bald eagle, peregrine falcon (delisted in 1999), Yuma clapper rail, and California least tern (Table X). For only one of these species (Yuma clapper rail, ~300 breeding pairs, about 40% of state’s population: Friend: 1999) is the Salton Sea population critical. Brown pelicans have recently started to breed at the Sea but coastal colonies will always be much more productive. California least tern, osprey, and bald eagle are rare visitants. It is a serious mistake for planners to focus so narrowly on these five species: Table X lists 68 rare species which are on either or both federal and California lists of Endangered, Threatened, and Special Concern species, because of declining ranges, declining populations, nest parasitism, competition, or combinations thereof. About 20 of these rare species are intimately tied to the Salton Sea and riparian habitats. All five alternatives for “restoration” of the Salton Sea presented by Salton Sea Authority (2000) (see below) have the acknowledged potential for significant adverse impacts, mostly localized, on Salton Sea-related birds. If planning for “restoration” of the Salton Sea involved planning to maintain and improve populations of all 67 of these rare species, all 400+ Salton Trough avian species would greatly benefit.

#### *6. Food Chains and Webs*

The main food chains in the Salton Sea leading to the four sport fish are short and unusual in composition: there is no significant zooplanktivore. Most phyto- and

zooplankton, feces, and dead fish sink to the bottom and become rich organic detritus. The only major detritus feeder is the vastly abundant pileworm, *Nereis succinea*. The quasi-marine food chains leading to Salton Sea sport fish are fragile and could be easily upset, particularly by introductions of new fish species, such as a major zooplanktivore or another top carnivore. The low diversity of the Salton Sea could easily be disrupted, as each successive link is vital to the survival of species in higher trophic levels: there are no alternate trophic pathways.

In the 1950s, a research group headed by B. W. Walker from the University of California at Los Angeles studied the ecology of the Salton Sea for 4 yr in conjunction with Department of Fish and Game fish introductions. Their report (B. W. Walker 1961a), though now representing work >45 yr old, is the most recent and comprehensive, and perforce still the best, survey of the biology of the Salton Sea. The ecological roles of more recent introductions, such as tilapia, the amphipod *Gammarus mucronatus*, and the polychaete *Streblospio benedicti* have not yet been well studied. B. W. Walker et al. (1961b), Young (1970), Isaacs (1972, 1973), Hogg (1973), Kim (1973), Lange and Hurley (1975), and Mearns (1979) discussed overall trophic relations in the Salton Sea. None of these papers could address the ecosystem of the 1990s. A group headed by Stuart Hurlbert at San Diego State University is comprehensively studying Salton Sea ecology beginning in 1999 (D. Dexter pers. comm.; S. Hurlbert, pers. comm.). Few of the resulting papers have so far been published.

The major food chains in the Salton Sea are:

1. Phytoplankton , herbivorous zooplankton , death of plankton + feces , bacterial decay forming organic detritus on the bottom plus bacteria and other benthic micro-organisms , detritivores (*Nereis succinea*, *Gammarus mucronatus*) , benthic-feeding organisms (fish, birds, especially eared grebes) , fish and birds that feed on benthic feeding organisms. This detritus-based food chain is at least unusual in large lakes, and may be unique, though detritus-based food chains are common in estuaries, where planktonic



food chains are usually also important. The Salton Sea lacks planktivorous fish, except for the mostly irrelevant threadfin shad.

2. The orangemouth corvina food chain in the Salton Sea is: phytoplankton , herbivorous zooplankton , death of plankton + feces , bacterial decay forming organic detritus on the bottom plus bacteria and other benthic micro-organisms , detritivores (*Nereis succinea*, *Gammarus mucronatus*) , benthic-feeding fishes (bairdiella, tilapia?, young orangemouth corvina) , piscivores (larger orangemouth corvina, birds)
3. The sargo food chain seems to be: phytoplankton , herbivorous zooplankton , benthic *Balanus amphitrite* and amphipods , sargo.
4. The tilapia food chain seems to be: phytoplankton , herbivorous zooplankton , death of plankton + feces , bacterial decay forming organic detritus on the bottom , organic debris, benthic algae, pileworms, insects, crustaceans, small fish , tilapia , brown and white pelicans, other piscivorous birds.
5. A minor, seasonal variation for the one pelagic planktivore, threadfin shad: phytoplankton , herbivorous zooplankton (adults, larvae) , plankton feeding fish (threadfin shad) , orangemouth corvina, many birds.

B. W. Walker et al. (1961b) strongly warned against further introductions of top-of-the-food-chain carnivorous fishes unless the newly developing fishery in the 1950s did not succeed, and advised great caution in introductions of any other animals or plants to the Salton Sea. Their one exception was based on their concern that the pileworm *Nereis succinea* is the major trophic link between plankton/detritus and the sport fishes. They suggested introducing several species of mysid and amphipod crustaceans and perhaps other polychaetes to become alternate food sources for the fish. Fortunately, tilapia, introduced in the 1970s, seem to have augmented the sport fishery of the Sea rather than disrupting it. Curiously, Costa-Pierce and Riedel (2000) and Riedel and Costa-Pierce (2000) suggested stocking new species of predatory game fish, without discussing the likely adverse effect -- perhaps severe -- on the popular fishery for orangemouth corvina

and the other sport fishes. It is important to keep these warnings in mind in discussions of proposals to stabilize elevation and salinity of the Salton Sea.

### **Major Fish and Bird Mortality Events: Toxins, Pathogens, and Parasites**

Fish kills and bird-die offs have been known in the Salton Sea since its formation in 1905 to 1907 (Cohen et al. 1999; Friend 2000c), and have continued regularly ever since. We have seen sometimes massive kills of bairdiella, tilapia, eared grebes, puddle ducks, ruddy ducks (*Oxyura jamaicensis*), geese, and coots (*Fulica americana*) both in summer and winter since 1968 (Oglesby pers. obs.). Many recent writers believe that fish and bird die-offs have become more frequent and more severe in the 1990s, and that they are indicative of an increasingly stressed Salton Sea ecosystem (e.g., Cohen et al. 1999; Cohn 2000; Friend 1999, 2000c). But it is not at all clear whether the recent, well-publicized mortality events represent real increased mortality, or that a now-sensitized press is publicizing "ordinary" mortality more than before, when even large die-offs were neglected except for refuge and state park personnel, fishers, residents, and regular visitors (Costa-Pierce 1998a; Oglesby pers. obs.).

Many, if not most, fish kills at the Salton Sea over the past century have been caused by: (1) hypoxia created by wind-driven mixis, especially during the summer, bringing oxygen-deficient and sometimes  $S^{2-}$ -rich and  $NH_4^{+}$ -rich hypolimnetic water to the entire water column. Hypoxic fish kills have also been attributed directly to intense algal blooms (Salton Sea Authority 2000; many other reviewers, and popular writers), although the evidence for this is not persuasive. (2) Food deprivation in bairdiella during the summer when pileworms vanish from deeper waters. This mortality may propagate up the food chain. (3) Low temperatures adversely affecting tilapia in winter (see above). Often, bird and fish mortality events at the Salton Sea simultaneously occur at other lakes and marshes in the western US (Costa-Pierce 1998a), suggesting that region-wide issues are involved, rather than just at the Salton Sea.

A headline in the *Los Angeles Times* for 12 August 1999 was "7.6 million fish die in a day at Salton Sea." The fish were tilapia. The *Times* went on to say, "Residents contend that despite the numbers [the deaths are] just as much a part of the Salton Sea as summer heat. Some scientists, however, say the die-off is yet another omen of the sea's demise, and they warn that the end may be approaching faster than expected." Costa-Pierce was quoted: "The Salton Sea is dying. Our response plan needs to be rapid, or I give it a couple of years before we have massive die-offs year round. This is just the beginning." Such a sudden, one-time die-off is unlikely to have been the result of chronic or gradually changing factors such as salinity, temperature, algal blooms, or contaminants from agricultural or industrial wastes. Most likely, the August 1999 die-off was the result of a rapid wind-caused turnover of the Sea, bringing hypoxic hypolimnetic water to the surface and reducing  $pO_2$  in the entire water column to below the hypoxia threshold of tilapia. A longtime resident was quoted: "They keep saying this is unprecedented. But we've been here over 20 years and every time that water churns up in the summer, we have dead fish. You have to live here to understand."

Jim Matthews, Outdoors columnist for the Ontario CA *Inland Valley Daily Bulletin*) pointed out on 12 August 1999: "The die-off mostly affected tilapia on the northeast end of the sea and was a drop in the bucket compared to what the sea holds. At the same time the die-off was taking place, the corvina action on the other side and south end was the best it has been in over a decade. This is the best fishing anywhere right now." The figure of 7.6 million dead tilapia must also be questioned. While available accounts gave no information as to how total deaths were estimated, probably the figure was based on counts on short stretches of beach at the northwest Salton Sea, scaled upwards to cover the entire shoreline. This procedure would vastly over-estimate the total since east and southeast shorelines had few dead fish.

Large-scale mortality events involving eared grebes have been documented in the West, including both Mono and Great Salt Lakes, for more than a century, attributed to

disease, inadequate pre-migration fattening, and adverse weather during migration (Jehl 1996). Jehl observed that a three-year meromixis period in Mono Lake beginning in 1996 led to reduced weight gain during fall migration and apparently more stress on the grebes when they wintered at the Salton Sea; they did fine in 1999 (Little 2000).

**Toxins.**—In winter 1991-1992, a large number of eared grebes and some other wintering waterbirds washed up dead along the Salton Sea shoreline, estimated at >150,000 dead grebes, ~10% of the grebes wintering that year on the Sea (Jehl 1996; Warnock 1999; Franson et al. 2000; US Geological Survey National Wildlife Health Center 2000). Living and dead birds were concentrated at the mouths of large drains and the three rivers, and scavengers were very active, according to federal refuge personnel (deBuys 1999). The cause of the 1991 to 1992 grebe deaths was controversial right from the start, with toxic algae (the pelagic bluegreen alga *Microcystis*), Hg, and Se all being held responsible. A decade later, there is still no evidence for microcystin (or anything else) being specifically responsible.

Reifel et al. (2000) used an *Artemia* bioassay to see if a number of potentially toxic Salton Sea phytoplankters (listed in Table V) would be toxic to fish or birds. Some of these algae were toxic in an *Artemia* assay, but had no effect on mice. The most studied of these was the raphidiophyte *Chattonella marina*, which produces both brevetoxins and superoxide radicals and can cause massive die-offs in aquaculture facilities as well as in the nearshore ocean, notably Japan and Australia (Coe et al. 2000; Tiffany et al. 2000). At the Salton Sea, *C. marina* blooms up to 600 cells·ml<sup>-1</sup> from April through November, when the water is in excess of ~24°C (Horvitz 2000) with characteristic damage to fish gills. Tiffany et al. (2000) thought that the absence of this alga in the plankton during winter means that it overwinters as cysts in the sediment. The studies by Reifel et al. (2000) were negative as regards any algal toxicity to fish.

The main conclusions are that there is no positive evidence for toxic algal blooms at the Salton Sea, and that mortality events in fish and piscivorous birds are not caused by

toxins, despite popular belief. Nevertheless, investigators continue to explore the potential for algal toxins to cause major problems in Salton Sea biota (Faulkner 1998).

**Pathogens.**\_\_Waterbird die-offs have occurred regularly for many decades at the Sea, and those caused by several pathogens have been well-studied at the Salton Sea or elsewhere (Shuford et al. 1999).

Newcastle virus killed a number of double-crested cormorants and some Caspian terns in 1997 and 1998, killing ~1600 cormorants and 100 Caspian terns; these were largest kills in entire US attributed to Newcastle disease (Kaiser 1999; Daszak et al. 2000; Friend 2000; US Geological Survey National Wildlife Health Center 2000). Despite many reports to the contrary, Shuford et al. (1999) concluded that it was not possible to determine the age of affected cormorants and terns -- they may well not have been nestlings but one or two years old. Newcastle virus type C was unknown in double-crested cormorants west of the Rocky Mountains until 1977 (Shuford et al. 1999). The Salton Sea cormorant strain of Newcastle virus is the mesogenic strain, but is different from the one that causes serious disease in parrots and galliform birds such as chickens (velogenic strain), first identified in the US in 1944. Newcastle virus is a paramyxovirus, a group of often virulent viruses that cause such diseases as rinderpest in cattle, canine distemper, and human measles. Newcastle virus is readily transmitted by ingestion, inhalation of aerosols, and contact with infected hosts and contaminated materials. It can remain infective for weeks in nature over a wide range of pH and temperature, and in litter, soil, and carcasses for at least 255 d. Humans may get a mild, self-limiting infection (U.S. Geological Survey National Wildlife Health Center 2000). Immediate removal of bird carcasses is important in control of outbreaks; workers must exercise strict sanitation to prevent transmission to other birds.

Avian (fowl, chicken) cholera has caused sometimes large bird kills at the Salton Sea for many years, chiefly in ducks and geese, especially snow and Ross geese; ~60,000 to 100,000 snow geese winter at the Salton Sea, along with a small number of Ross geese.

This disease is primarily present in winter. Avian cholera is a long-known avian disease caused by the bacterium *Pasturella multocida* Type 1, unrelated to the bacterium that causes human cholera and related diseases (*Vibrio* spp.). In 1880 to 1882 Louis Pasteur used chicken *P. multocida* in establishing both the germ theory of disease and the value of vaccination. Though well known as a poultry disease, avian cholera in wild waterbirds was first reported in North America in 1944 near San Francisco and Texas, and at the Salton Sea in 1979; it is now widespread in the US.

*Pasturella multocida* is highly contagious and easily transmitted by direct contact between birds as well as by contaminated soil, food, and water. It is also virulent, killing birds in as few as 6 to 12 hr after infection, and often causing mortalities of >50%. Sick birds are lethargic, poorly coordinated, and erratic in flight (dying birds may just fall from the sky). *P. multocida* does not over-summer in the absence of vulnerable birds; rather, the Salton Sea and all other wintering sites are reinfected every year by now-immune migratory birds who survived avian cholera in their northerly breeding grounds (US Geological Survey National Wildlife Health Center 2000). *P. multocida* was found in 21% of Salton Sea eared grebe carcasses necropsied since 1991 (Franson et al. 2000; US Geological Survey National Wildlife Health Center 2000). Immediate removal of carcasses is important in control of outbreaks; workers must exercise strict sanitation to prevent transmission to other birds.

A large late-summer 1996 bird kill -- >8500 white pelicans (~15% of the entire population of this species in the west), ~2000 brown pelicans (~20% of the state's population), and >4500 birds of ~60 other species -- was eventually attributed to avian botulism. Avian botulism is caused by the anaerobic bacterium *Clostridium botulinum* Type C and, to a much lesser extent, Type E (not the human botulism strains A, B, and F: A. Oglesby pers. comm.). Type C is cosmopolitan, found in ducks and geese, shorebirds, colonial waterbirds, and a few others; scavenging birds such as turkey vultures (*Cathartes aurea*) are resistant. Type E is found in gulls and loons and has been reported



so far only from the Great Lakes region. At the Salton Sea, avian botulism is well known in puddle ducks and coots, both of which eat decaying vegetation. *Clostridium botulinum* is a strict anaerobe which forms dormant spores which can survive for years under anaerobic conditions in soil and organic matter in wetlands, including carcasses. Spores are highly resistant to environmental stresses such as extreme temperature and desiccation (US Geological Survey National Wildlife Health Center 2000).

Transmission of avian botulism at the Salton Sea is attributed to ingestion of spores found in a wide range of living and dead vertebrates, such as tilapia, and invertebrates, especially, maggots of flesh flies (Sarcophagidae) and blowflies (Calliphoridae). In 1996 sick brown pelicans were found with botulinum-infected tilapia in their guts (Costa-Pierce and Riedel 2000). Up to 50,000 maggots can occur in one bird carcass; ingesting as few as 3 to 5 infected maggots can kill a duck. Bacteriophage-infected *Clostridium botulinum* produce a paralytic neurotoxin, botulinum, which is transmitted directly to birds in their food. The resultant muscle paralysis leads to inability to hold the neck up ("limberneck") and then to death by drowning, respiratory failure, altered salt and water balance, or predation. Control of avian botulism necessitates quick removal of fish and bird carcasses. Early treatment can save diseased birds, but since this is expensive, it is usually reserved only for endangered species (US Geological Survey National Wildlife Health Center 2000).

Anywhere from a few hundred to tens of thousands of ducks die from avian botulism each year at the Salton Sea. Nationwide, from a few 100,000s to over a million birds may die each year; the disease seems to be increasing everywhere, not just at the Salton Sea (Shuford et al. 1999). Avian botulism has long been present in late spring and summer at the Sonny Bono Salton Sea National Wildlife Refuge, though never before to the extent seen in July to September 1996, and not before then to any significant extent in fish-eating birds. The 1996 connection seems to be massive acute infections in Salton Sea tilapia with *Vibrio* (*Photobacterium*) *alginoliticus*, a bacterium well known for causing

fish kills in waters with extreme conditions such as high temperature, high salinity, pollution, or overcrowding. Humans can develop rashes after eating *V. alginolyticus*-infected fish. *V. alginolyticus* has been found at the same Salton Sea sites as *C. botulinum* Type C, and, in one case, a mixed infection of both species in one fish. Other species of bacteria were cultured from partially decomposed tilapia, including *V. damsela*, *Pseudomonas (Shewanella) putrefaciens* and a *Bacillus* sp. (US Geological Survey National Wildlife Health Center 2000).

The link between acute *Vibrio alginolyticus* infection in tilapia and avian botulism is not established. US Geological Survey National Wildlife Health Center (2000) biologists suspect that *V. alginolyticus* may produce anaerobic conditions in fish guts that allow *Clostridium botulinum* spores to germinate and produce botulinum. Avian botulism is probably spread directly to fish-eating birds which ingest maggots while feeding on botulinum-infected fish carcasses, or rotting tilapia with *C. botulinum* in their guts, though wild pelicans rarely eat dead fish (*New York Times* 24 March 1998; deBuys 1999; US Geological Survey National Wildlife Health Center 2000; US Fish and Wildlife Service 2000; a number of articles in the *Los Angeles Times*). A few brown pelicans infected with avian botulism were found after the large August 1999 die-off of tilapia. Another die-off of brown and white pelicans occurred in summer 2000, though apparently there was no significant fish mortality and no other birds were affected; several hundred pelicans were released in November on the sea coast after rehabilitation (*Los Angeles Times* 10 July 2000, 30 August 2000; KNBC-TV local news November 2000; US Fish and Wildlife Service 2000). No other outbreak of avian botulism has equaled the 1996 one.

While many writers (e.g. Rocke and Nol 2000) state that avian botulism is only newly recorded from the Salton Sea, we have seen sometimes large numbers of herbivorous ducks and coots that died from avian botulism on and near the federal wildlife refuges since at least the late 1960s (federal refuge personnel, pers. comm.), and Shuford et al. (1999) stated that the disease has been present since at least 1939. What seems to

be new is that piscivorous birds are now involved (Rocke and Nol 2000; US Geological Survey National Wildlife Health Center 2000). Franson et al. (2000) found only 2% of eared grebe carcasses necropsied since 1991 to be positive for avian botulism, but most grebes migrate north before the avian botulism season of late spring and summer.

A few avian deaths from *Salmonella* infections have been recently reported (Shuford et al. 1999; Friend 2000c), but may have been overlooked prior to the late 1990s. Avian salmonellosis is usually recorded in passerine birds at bird feeders, spread both from food to bird and from bird to bird (US Geological Survey National Wildlife Health Center 2000). A kill of 4,500 cattle egrets and some other ardeids in the Imperial Valley in 1989 was attributed to salmonellosis (Shuford et al. 1999; Salton Sea Authority 2000).

The dinoflagellate *Amyloodinium ocellatum* is a major fish pathogen in aquaculture facilities, home marine aquaria, and in tropical and sub-tropical ocean nearshore environments. Fish deaths can occur within 12 hr of initial infection in laboratory cultures, though most infected fish usually live several days. Long-lived (4 to 6 wk at least) flagellated dinospores are the dispersal, reproductive, and infective stage; the trophic stage is ectoparasitic. The species also develops cysts. The life cycle can be completed in ~1 wk. Infected fish exude mucus from their gills, breath rapidly, and gasp for air due to extensive gill epithelial damage (US Geological Survey National Wildlife Health Center 2000). At the Salton Sea, tilapia seem to be the major fish infected with *A. ocellatum* (Friend 2000c). Infections were high on Salton Sea fish during spring and summer 1997 to 1999, with up to 100% of examined fish infected with *A. ocellatum*. Gills and skin are often severely damaged, which can readily lead to respiratory failure as well as secondary infections by other pathogens such as bacteria, viruses, and fungi (Kuperman and Matey 1999, 2000). In September 1997, a large tilapia kill (>1 million fish) was attributed to *A. ocellatum* (US Geological Survey National Wildlife Health Center 2000). It is not yet known whether this pathogen has any significant effect on

tilapia population biology, and its potential for damage to the Salton Sea ecosystem is unknown.

**Parasites.**—Several monogenetic and digenetic flukes have been reported in Salton Sea fish (Table VII). Barlow (1963) wrote, “The Salton Sea [longjaw mudsuckers] at times are heavily infested with a monogenetic trematode [on the gills], but so are coastal populations.” It would be easy to introduce additional coastal parasites to Salton Sea fish with longjaw mudsucker bait imported from Baja California, if appropriate intermediate hosts are also present in the Sea. Introductions of fish from any source could introduce parasites such as nematodes, tapeworms, flukes, and diverse crustaceans. Fish to be introduced should be screened for parasitemia.

Because of recent reports of “unprecedented” fish and bird die-offs, there has been increased study of fish parasites that might be causative. Kuperman and Matey (2000), noting that environmentally-stressed fish are more susceptible to parasitic infections and can infect predators and scavengers such as birds and mammals, studied ectoparasites of both major Salton Sea fish and invertebrates (Tables V, VII). Ectoparasites were common around the shoreline on young tilapia, orangemouth corvina, bairdiella, and longjaw mudsuckers, as well as pileworms and copepods. The dinoflagellate gill parasite *Amyloodinium ocellatum* (see above), the peritrich ciliate skin parasite *Ambiphyra ameiuri*, the flagellate gill parasite *Cryptobia branchialis*, (involved in an autumn 1997 outbreak at Bombay Beach), and two species of the skin and gill monogenetic trematode *Gyrodactylus*, *G. olsoni* and *G. imperialis*, were identified. The skin and parapodia of the pileworm *Nereis succinea* were parasitized by the peritrich ciliate *Epistylus* sp., and the copepod *Apocyclops dengizicus* was parasitized by another peritrich, *Rhabdostyla vernalis*. These parasites often infect fish in aquaculture facilities elsewhere, where fish density is high. Gills and skin are often severely damaged, which can readily lead to respiratory failure as well as epithelial damage resulting in secondary infection (Kuperman and Matey 2000). The importance of these parasites to Salton Sea biota and ecology is

US southeast. Bullfrog tadpoles, which usually metamorphose after 2 yr (perhaps only 1 yr in warm desert waters), compete with desert pupfish and other aquatic animals for food, including tadpoles of native frogs and toads. Adult bullfrogs are carnivorous, serious predators of native amphibians, small fish including desert pupfish, and even baby waterbirds (Stebbins 1985). Bullfrogs are one of the most noxious introductions to the Salton Trough and to California in general.

See Table IX for other Salton Trough amphibians. Most native amphibian species are undergoing severe, even catastrophic, population declines, often attributed to bullfrogs and habitat destruction. A contributing factor may also be chytridiomycosis, first described in 1998 from dead amphibians on several continents, including *Rana* spp. and *Bufo* spp. in nearby Arizona and Colorado, including the rare *Rana yavapaiensis* (Daszak et al. 1999a, 2000), which may or may not be the correct name of the never-to-be identified euryhaline "*Rana pipiens*" studied by Ruibal (1959, 1963) in San Sebastian Marsh. Chytrids are ubiquitous fungi that lack hyphae and metabolize such polymers as keratin, a major component of amphibian skin; *Batrachochytridium dendrobatidis* seems to be the species involved in the arid Southwest.

**Reptiles.**\_\_No reptiles are known from the Salton Sea, but several species are found in drains and canals. See Table IX.

**Mammals.**\_\_There are no aquatic mammals in the Salton Sea, but one species occurs in drains and canals, often close to the Sea, the muskrat (*Ondatra zibethicus bernardi*). See Table IX.

California Department of Fish and Game issues lists of Colorado Desert Endangered, Rare, Threatened, and Special Concern species of invertebrates (only insects), plants, reptiles, and mammals. All these are terrestrial species with no connection to the Salton Sea or to aquatic habitats in the Desert, and so are not tabulated or discussed here.

### 3. The Sport Fish and Sport Fishery

Apparently California Department of Fish and Game cannot abide a body of water which lacks a viable sport fishery: "The vast expanse of the Salton Sea has long presented a challenge to California's Department of Fish and Game, but a lack of funds and manpower precluded any concerted attempt to establish game fish there until 1950" (Anonymous 1958). Fish and Game has introduced to nearly all California waters many alien species, including centrarchids, salmonids, and other fish from elsewhere in the US and the world, as well as California fish not native to that particular geographical area (Swift et al. 1993; Dill and Cordone 1997). The Salton Sea has been no exception. Fish and Game has at least three times made major attempts to introduce sport fish to the Sea; the first and second in the early 1930s were both failures. The third attempt, in the early 1950s, was spectacularly successful. There are very few species of fish in the Salton Sea, but those are extremely abundant, and within only a few years supported the most productive sport fishery in the state and probably the US. The Salton Sea State Recreation Area was established in 1955 along the eastern shore to provide camping and other amenities for the rapidly developing sport fishery (Laflin 1995, 1998). Only one Salton Sea fish, the tiny desert pupfish, is native; formerly abundant, it is now on both federal and state lists of Endangered species (see below). In the 1970s Fish and Game created several "fishing reefs," three of them piles of tires chained together ~1000 m offshore, and others made of car bodies (Stroud and Jenkins 1960; *Los Angeles Times* 29 March 1974). Artificial reefs, as well as drowned structures such as buildings and utility poles, concentrate fish, making these areas particularly attractive for fishers.

When the Salton Sea formed in 1905 to 1907, it was initially populated by freshwater fishes native or introduced to the Colorado River (Grinnell 1908; Evermann 1916; Coleman 1929; B. W. Walker et al. 1961a; Dill and Cordone 1997), although no complete survey was ever done. In 1916, the major Salton Sea fish (see Table VIII for scientific names) were all freshwater except for the migratory mullet: carp (introduced), striped mullet, humpback or razorback sucker, rainbow trout, bonytail, and desert



pupfish (Evermann 1916). By 1925, when the Salton Sea reached its lowest elevation and highest salinity through evaporation, all freshwater fish except striped mullet and the migratory, euryhaline ten-pounder or machete, *Elops affinis* (Elopidae), had died out. *Elops*, survived in the Salton Sea longer than most Colorado River fishes, supporting a modest sport fishery into the 1930s (Dill and Woodhill 1942; Swift et al. 1993; Dill and Cordon 1997). There was a “fabulous” commercial fishery for mullet beginning with the formation of the Salton Sea in 1907. Mullet as large as 9.5 kg were taken, and in 1918, a total of 41,370 kg was landed. Mullet made “huge” spawning runs to the Gulf by way of the New and Alamo rivers as late as the 1950s (Costa-Pierce 1998a). Mullet are still present in small numbers (see below), while *Elops* was believed extinct in California. However, recent reports indicate that *Elops* still occurs in the lower Colorado River, apparently as a consequence of several years of high river flow that connected the river to the Gulf of California (Bettaso and Young 1999).

In 1929 and 1930, Fish and Game attempted to introduce to the Salton Sea euryhaline striped bass (*Morone saxatilis*, Serranidae, native to the US East Coast but widely introduced elsewhere, including San Francisco Bay). In support of this attempt to create a sport fishery, in the late 1920s Game Warden Glidden tried to establish food sources for the striped bass, buying bucketsful of live bait in San Diego which he dumped into the Salton Sea. Introductions of striped bass in 1929 (from the San Joaquin River) and 1930 (from San Francisco Bay) did not succeed, but it is generally believed that the introductions of the pileworm *Nereis succinea* and the longjaw mudsucker *Gillichthys mirabilis* date to Warden Glidden’s bait purchases in 1929 (Anonymous 1929, 1930a,b, 1931a,b, 1932, 1958; B. W. Walker et al. 1961a).

In 1934, Fish and Game introduced 15,000 fingerlings of the Pacific northwest silver (coho) salmon (*Oncorhynchus kisutch*, Salmonidae), from a hatchery in the San Bernardino Mountains. None were ever seen again (B. W. Walker et al. 1961a; de Stanley 1976).

The third, and most serious, attempt by Fish and Game to create a sport fishery came in the early 1950s. Fish and Game personnel selected as their source the San Felipe area of the northern Gulf of California, and in scattershot fashion introduced small numbers of 30 different fish species as well as a number of marine invertebrates -- the only selection used was to eliminate species they thought might be detrimental in the Salton Sea (B. W. Walker 1961; Dill and Cordone 1997). de Stanley (1976) published several photographs of the transplant operation. Of these 30 species, only three were successful colonizers of the Salton Sea: bairdiella, sargo, and orangemouth corvina, the top carnivore in the Sea though nothing remarkable in the Gulf. None of the invertebrates survived. Within a few years of their introductions, these three species made the Salton Sea the most popular sport fishery in the state, with  $>1.5$  million use-d-yr<sup>-1</sup>. It was also the most productive fishery: from the 1960s through 1980s; fishers caught an average of 1.46 fish-hr<sup>-1</sup> (Black et al. 1985). Tilapia, introduced in the 1960s, made up the largest share of this fishery in more recent years (41%), with bairdiella and sargo next (both 28% of the total); orangemouth corvina account for only 3.5% of the total, because they are caught primarily from boats rather than from shore (Black et al. 1985). This fine sport fishery requires no hatcheries and is fully self-sustaining. With up to 2.6 million recreation d-yr<sup>-1</sup> in the late 1980s, sport fishers brought in as much as \$76 million to the local economy, the equivalent of over 1400 jobs in Riverside and Imperial Counties (CIC Research Inc. 1989).

Popular accounts of the sport fishes, how to catch them, and how to prepare them for eating have been published by St. Amant et al. (1978), Jansen et al. (1985), and Karr (1985). Karr (1985) made numerous errors on the history and biology of the Salton Sea itself, as did some of the expert orangemouth corvina fishers interviewed by Jansen et al. (1985). Curiously, some federal agencies deny the fact of the fine sport fishery, e.g. "The sport fishery at Salton Sea is nonexistent today" (US Fish and Wildlife Service, 1997). The Salton Sea Authority (2000) concluded, to its apparent surprise, that the sport

fishery was extraordinarily productive. Orangemouth corvina and tilapia are described both as growing faster and having shorter life spans in the Salton Sea than in their native waters. There is no elevated frequency of deformed fishes (Costa-Pierce et al. 2000). In other words, the sport fishery in 1999 to 2000 is in fine shape. In the following discussion, histories of introductions come from several chapters in B. W. Walker (1961a), summarized by Dill and Cordone (1997).

The Salton Sea population of the Gulf croaker or bairdiella, *Bairdiella icistia* (Sciaenidae), derives from introductions of only 67 individual fish (57 in 1950, 10 in 1951). Salton Sea bairdiella first spawned in 1952; there was explosive population growth in presence of the great pileworm food supply. Their population reached as high as ~10 million fish standing crop in the Sea within a few years, and now is the second most abundant sport fish in the Sea, after tilapia. Despite the small inoculum, bairdiella genetic diversity is high; there is no evidence for a founder effect or a genetic bottleneck (Beckwith 1987).

Bairdiella are panfish up to 30 cm long, found everywhere in the Sea; they occur occasionally in shoreline pools (Barlow 1958a). Bairdiella spend spring and summer near shore and move to open waters during late winter. They spawn from May to June; eggs float near the surface where early development also takes place (Haydock 1971). Young bairdiella are zooplanktivores; juveniles and adults feed primarily on benthic pileworms and serve as a major food for adult orangemouth corvina and perhaps tilapia (a detailed discussion of bairdiella food is given by Quast 1961). There is some invasion of the lower reaches of streams such as the Whitewater River (Whitney 1961a; Swift et al. 1993). At the Salton Sea bairdiella live up to 8 yr. Bairdiella often have massive summer die-offs from low  $pO_2$  and consequent reduced pileworm food supply, with up to 3 million deaths within a couple of months, beginning within a few years of their introduction. Whitney (1961b) concluded that in the summer, when bairdiella are food-limited by the great reduction in pileworm density and distribution, they may compete strongly with

juvenile orangemouth corvina, which also feed almost exclusively on pileworms (Quast 1961; Whitney 1961a; May 1975b, 1976; Riedel and Costa-Pierce 2000).

Growth of adult bairdiella is depressed at 45‰, and adults die at 75‰. Bairdiella hatching was successful at normal Salton Sea salinities (84% hatch success in 35‰) but declined at higher salinities (only 7% hatch in 45‰, the survivors dying within 60 hr). Fingerlings were more resistant, with 100% survival in 52.5‰ (US Department of the Interior and The Resources Agency of California 1969; Hanson 1970; Brocksen and Cole 1972; Lasker et al. 1972; May 1974, 1975a,b; Black 1981). Hanson (1970), Brocksen and Cole (1972), and Lasker et al. (1972) concluded that 40‰ exceeds the upper limit for successful bairdiella reproduction, but did not rule out higher limits after slow adaptation to higher salinities -- an ecologically and physiologically reasonable scenario -- or reproduction in lower salinity waters near the mouths of rivers and larger drains. Bairdiella fishing remains excellent, particularly by children; clearly, adequate reproduction and survival occur at 43 to 47‰.

Matsui et al. (1991a) studied ichthyoplankton in the Salton Sea in 1987 to 1989, finding that abundance of bairdiella larvae increased in each of 3 yr; conversely, abundance of sargo and orangemouth corvina larvae declined. Whitney (1961a) documented a number of developmental deformities in bairdiella in the 1950s, but did not identify any causes. Matsui et al. (1992) also found developmental defects in both field populations and laboratory-reared sciaenids (bairdiella, orangemouth corvina) in the 1990s. In neither case were any studies done to determine if mortalities had any significant effects on sciaenid population biology. Costa-Pierce et al. (2000) reported no deformities in adult sport fishes caught in the Sea.

The large Salton Sea population of sargo, *Anisotremus davidsoni* (Pomadysidae), is derived from an introduction in 1951 of just 65 fish; there was no early explosive population growth as with bairdiella. There is now a standing crop of ~5 million sargo in the Sea, but it is the least abundant of the four sport fishes (Riedel and Costa-Pierce

2000). Sargo commonly reach  $>1$  kg and  $>35$  cm in length; the state record in the 1970s was 1.9 kg (de Stanley 1976). Sargo are particularly abundant near the shoreline and submerged structures (Department of Fish and Game undated handout). Reproduction is little known, but spawning occurs in winter and spring. Sargo rarely live more than 3 yr (Riedel and Costa-Pierce 2000). Summer die-offs are not as intensive as with bairdiella. Sargo are an important sport fish ("a tasty dish:" de Stanley 1976), feeding on benthic invertebrates such as pileworms, barnacles, and amphipods (B. W. Walker et al. 1961a). Sargo did not figure prominently in the excellent sport fishery in 1999 and 2000.

Studies on effects of salinity on sargo development gave results similar to those for bairdiella, with 90% hatching success in 35‰ but only 8% success in 40‰ and no success in 45‰; fingerlings were somewhat more sensitive to higher salinities than were those of bairdiella. Growth of sargo adults is hampered at 45‰, and adults die at 62.5‰ (US Department of the Interior and The Resources Agency of California 1969; Hanson 1970; Brocksen and Cole 1972; Lasker et al. 1972; Black 1981; Matsui et al. 1991b). The sex ratio is approximately even (Riedel and Costa-Pierce 2000). Lasker et al. (1972) concluded that 40‰ exceeds the upper limit for successful sargo reproduction, but did not rule out either higher limits after gradual adaptation to higher salinities or reproduction in lower salinity waters associated with agricultural inflow.

The orangemouth corvina, *Cynoscion xanthulus* (Sciaenidae), is the premier sport fish of the Salton Sea, and thus of California. Salton Sea orangemouth corvina derive from several introductions in 1950 to 1956 of not more than 272 fish. In the 1970s and 1980s their standing crop population was 3 to 5 million fish, with  $\sim 1/2$  million caught-yr<sup>-1</sup>. "This fish is a gourmet's delight, for there is no finer tasting fish to be found anywhere, baked, broiled, fried, or smoked" (de Stanley 1976). Limit is 5·d<sup>-1</sup>, reduced from 9·d<sup>-1</sup> several years ago. Orangemouth corvina are schooling, open-water fish. Adult orangemouth corvina are piscivores, feeding on bairdiella, sargo, and tilapia at and near the bottom; fingerlings are zooplanktivores, while juveniles feed on small fish and benthic

pileworms. There is some invasion of the estuaries of the Whitewater and Alamo Rivers (Swift et al. 1993), apparently for breeding (Department of Fish and Game undated handout). Orangemouth corvina commonly reach 9 to 11 kg. The larger fish usually caught weigh from 7 to >11 kg. The record orangemouth corvina weighed 16.8 kg (length >1.14 m, girth >0.72 m); it was caught by Dick Van Dam, Jr., on 15 July 1988, near Red Hill -- a very impressive fish, estimated to be ~30 yr old (Horvitz 2000). While this 1988 record has not been topped, orangemouth corvina in the range of 12 to 14 kg and >1 m are still regularly caught. Reports of 18 to 23 kg orangemouth corvina are unconfirmed, and may just represent standard tall tales from fishers (Whitney 1961b; Lasker et al. 1972). A year-long creel census in the early 1980s indicated that the average orangemouth corvina taken from the Salton Sea was ~50 cm long, which is also the size they become sexually mature (Black et al. 1985). Black et al. (1985) expressed concern that "there may be a significant portion of the population being removed before it has an opportunity to spawn," and suggested that a minimum size limit be set. A minimum size limit of 45 cm was set in March 2000 (Oglesby pers. obs.), which is below the size at first reproduction (Whitney 1961b; Black et al. 1985; Prentice and Colura 1985). Orangemouth corvina fishing is best in the summer when the air is beastly and the water warm, but there are good bites during warm winters as well (e.g., 1999 to 2000: Matthews' Pick of the Week, Ontario CA *Inland Valley Daily Bulletin*).

Salinity resistance studies show that orangemouth corvina fingerlings are more resistant than those of either bairdiella or sargo, with 100% survival at 52.5‰, 91.4% hatch success at 57.5‰, and no survival at 62.5‰ (US Department of the Interior and The Resources Agency of California 1969; Hanson 1970; Brocksen and Cole 1972; Prentice 1985; Matsui et al. 1991c). When gradually adapted to freshwater in the laboratory, orangemouth corvina do not feed for the first week or so but afterwards resume normal feeding (Prentice 1985). Freshwater-adapted orangemouth corvina are excitable, and Prentice (1985) attributed their mortality to injury in collisions with the



tank and to subsequent fungal infections (*Saprolegnia*), rather than to low salinity itself. Orangemouth corvina exhibit stress when in freshwater, but continue to grow, though at about half the rate of fish maintained in seawater (Prentice 1985). Feeding activity of laboratory orangemouth corvina is “greatly decreased” at temperatures below 18 to 20°C (Prentice and Colura 1985).

Orangemouth corvina breeding is not well understood. A great increase in underwater sound was observed by hydrophone in the deepest part of the northern basin in the late spring. This huge increase in sound was attributed to the peak of reproduction by orangemouth corvina (Fish and Cummings 1972). The main breeding season at the Salton Sea is from April to August, with fingerlings still in the plankton in October (Matsui et al. 1991b). Prentice and Colura (1985) exposed a laboratory population of Salton Sea orangemouth corvina to cycles of temperature (varying from 16 to 28°C), salinity (varying from 17 to 33‰), and photoperiod (varying from 15:9 L:D to 9:15 L:D) “to simulate seasonal variations of the Salton Sea,” though salinity does not vary seasonally. Laboratory males became sexually mature at 50 cm, greatly increased their drumming, and could spawn; 60 cm laboratory females developed eggs, but could be induced to spawn only after injection of human chorionic gonadotrophic hormone. No fertilized eggs were obtained. Size at sexual maturity of laboratory populations is consistent with observations at the Salton Sea (Whitney 1961b). Laboratory spawning took place only during simulated summer conditions, somewhat later than Whitney (1961b) observed at the Salton Sea itself, in late May and June. In a later study, Prentice and Thomas (1987) reported successful spawning of orangemouth corvina in response to injection of several hormones, but did not indicate whether there was successful fertilization. Bumgardner et al. (1992) raised large numbers of orangemouth corvina to fingerling size in laboratory ponds. Orangemouth corvina sex ratio favors females in estuaries and males in the open sea, and is approximately equal near shore (Riedel and Costa-Pierce 2000).

The fourth major Salton Sea sport fish is the tilapia, an African cichlid. Tilapia have established an immense breeding population in the Salton Sea and in nearly every canal and ditch as well as in some streams and springs in the Valle de Mexicali, Imperial Valley, and Coachella Valley.

There has been much confusion as to which species of tilapia is (are) in the Salton Sea and canals and drains in the Coachella and Imperial Valleys. Fortunately, these taxonomic problems have been sorted out (Costa-Pierce and Doyle 1997; Costa-Pierce 1998a,b; Costa-Pierce and Riedel 2000; Riedel and Costa-Pierce 2000), though not all current workers are aware of these changes and may still use old names or even names of species never found in California. All tilapias are native to Africa, but have been widely introduced for aquaculture and other purposes around the world, arriving in California up to fourth-hand. Both Salton Trough tilapia species were introduced from countries outside of Africa (Table VIII). Members of the genus *Tilapia* are nest brooders, *Oreochromis* are female mouth-brooders, and *Sarotherodon* are male or bisexual mouthbrooders. While *Tilapia zillii* is readily separated from members of the genus *Oreochromis* by external morphological criteria, such criteria cannot be used successfully within *Oreochromis*. (Costa-Pierce and Doyle 1997; Costa-Pierce 1998a,b; Costa-Pierce and Riedel 2000; Riedel and Costa-Pierce 2000).

*Tilapia zillii* was the species name most often mentioned after tilapia first entered the Salton Sea, but this species apparently is no longer present in the Salton Sea itself, though it is still present in adjacent wetlands. *T. zillii* (Zill's or redbelly tilapia) was introduced into Imperial Valley drains in 1971 in an ill-advised attempt to control aquatic weeds (Costa-Pierce 1998a,b; Costa-Pierce and Doyle 1997). *T. zillii* is much more euryhaline, eurythermal, euryoxic, and euryphagic than originally believed on the basis of inadequate experimentation by a biologist for the Imperial Irrigation District (Hauser 1975a,b, 1977; Hauser and Legner 1975). Costa-Pierce and others recommend total eradication of *T. zillii*, finding it worthless for any useful purpose (aquatic weed control,

aquaculture, fishing), despite its euryplastic physiology and rapid growth rate (Costa-Pierce and Doyle 1997; Costa-Pierce 1998a,b; Costa-Pierce and Riedel 2000; Riedel and Costa-Pierce 2000).

Apparently the only tilapia species in the Salton Sea itself is *Oreochromis mossambicus* (Mozambique tilapia). It was introduced in the lower Colorado River near Yuma in 1964, and reached the Imperial Valley and Salton Sea a year later, by as many as three routes: an illegal aquarium route from a fish farm near Niland, invasion from Arizona irrigation canals by way of the Colorado River and Imperial Valley canals, and deliberate stocking (St. Amant 1966; Hoover and St. Amant 1970; Hoover 1971; Costa-Pierce and Doyle 1997; Costa-Pierce 1998a,b; Costa-Pierce and Riedel 2000). Genetic analysis of Salton Sea tilapia, using microsatellite DNA marker frequencies, shows considerable differentiation from "pure" African *O. mossambicus*, and some genetic inflow from *O. urolepis hornorum* (Wami River tilapia), even though the latter is not present in California; the California strain of Mozambique tilapia is clearly not pure *O. mossambicus*. It also has the highest heterozygosity of any tested California tilapiine strain, about the same as reference collections from Africa, indicating great genetic diversity. Along with carp (*Cyprinus carpio*), *O. mossambicus* is the most widely introduced exotic fish in the world, although it is generally regarded as not as valuable for aquaculture as *O. niloticus* (Costa-Pierce 1998a; Costa-Pierce and Doyle 1997). No genetic programs have been conducted to improve *O. mossambicus* for aquaculture; Costa-Pierce (1998b) concluded that it is premature to write this species off in favor of *O. niloticus*.

Other species of *Oreochromis*, -- the first two currently illegal in California -- *O. aureus* (blue or golden tilapia), *O. niloticus* (Nile tilapia), and *O. urolepis hornorum* (Wami River tilapia) do not seem to be feral in the Salton Trough (Costa-Pierce and Doyle 1997; Costa-Pierce 1998a,b; Costa-Pierce and Riedel 2000; Riedel and Costa-Pierce 2000). *O. niloticus* is present in the Colorado River near Blythe and thus has the ready

potential of invading the Salton Trough; it is also permitted in at least one aquaculture operation in Southern California, outside the Trough (Costa-Pierce and Doyle 1997). *O. niloticus* grows faster, has a larger size at first reproduction, and is more herbivorous than other tilapia species. *O. urolepis hornorum* is notable for the male-only progeny of hybrids of male *O. urolepis hornorum* with female *O. mossambicus*. *O. urolepis hornorum* has apparently never been imported to California (Costa-Pierce 1998a,b).

Both Salton Trough tilapia species are not just herbivores as originally believed: they are broad-spectrum omnivores that readily feed on all types of small organic particles, aquatic plants, small invertebrates (especially insects, crustaceans, and pileworms), and small fish including desert pupfish. Juvenile tilapia are more euryphagic than adults (Moyle 1976; Hart et al. 1998). The population of desert pupfish in the Salton Sea, canals, and drains has crashed, but only since introduction of tilapia; Costa-Pierce and Riedel (2000) attributed this great population reduction of desert pupfish specifically to *Tilapia zillii*, since desert pupfish share waters with *Oreochromis mossambicus*.

Tilapia are strongly euryhaline, swimming readily from the Salton Sea across the horohaliniacum into drains and rivers and back again. Salton Sea tilapia tolerate salinities from freshwater to at least 70‰; *T. zillii* handles direct transfer from freshwater to 35‰ seawater (Potts et al. 1967; Hammer 1986) while *O. mossambicus* needs a more gradual acclimation to extreme salinities (Costa-Pierce and Riedel 2000). Tilapia reproduce at salinities as high as 60‰, though not at 79‰ (Kültz and Onken 1993; Hart et al. 1998; Costa-Pierce and Doyle 1997; Costa-Pierce 1998; Costa-Pierce and Riedel 2000; Riedel and Costa-Pierce 2000). Both tilapia species are reported as living elsewhere in salinities as high as 74.9 to 134.4‰, but not reproducing higher than 63.6‰. When adapted to a range of salinities from freshwater to seawater, *O. mossambicus* shows adaptive changes in numbers and morphology of chloride cells, changes in chloride cell permeability, and changes in whole-body permeability (Kültz and Onken 1993; Bijvelds et al. 1997;

Miyazaki et al. 1998; Morgan et al. 1998; Vonck 1998; Hiroi et al. 1999; Uchida et al. 2000). There is evidence that at high salinities, tilapia have increased sensitivity to organic pollutants (Salton Sea Authority 2000).

*Tilapia zillii* will die at temperatures  $<7^{\circ}\text{C}$ . The lower limit for the more stenothermal *O. mossambicus* seems to be  $\sim 10$  to  $15^{\circ}\text{C}$ . Cold stress sets in at  $\sim 15^{\circ}\text{C}$ , with lethal temperatures  $\sim 5.5$  to  $12^{\circ}\text{C}$ . Winter tilapia kills at the Salton Sea are likely caused by low temperatures, both from the low temperature itself and perhaps from stress-induced greater sensitivity to pathogens. *O. mossambicus* can tolerate water as warm as  $40^{\circ}\text{C}$ , but grows optimally at 25 to  $37^{\circ}\text{C}$  (Costa-Pierce and Doyle 1997; Costa-Pierce 1998; Costa-Pierce and Riedel 2000). Developing *O. mossambicus* have deformities when raised at elevated temperatures of 28 and  $32^{\circ}\text{C}$ ; low temperatures lead to feminization (Wang and Tsai 2000). Since summer temperatures at the Salton Sea are warmer than  $32^{\circ}\text{C}$ , one might expect a proportion of deformed fish, but none have been reported. Tilapia are now an important food for adult orangemouth corvina (Hauser 1975a,b, 1977; Moyle 1976; Knaggs 1977; Schoenherr 1981).

*Tilapia zillii* breeds year-round whenever temperatures exceed  $15^{\circ}\text{C}$ . Female *T. zillii* lay their eggs in small nest depressions made by males in shallow water; one or both *T. zillii* parents guard the nest until the eggs hatch. *Oreochromis mossambicus* females brood up to 400 eggs in their mouths. In the Salton Sea, the sex ratio of *O. mossambicus* is strongly skewed toward males, as much as 7:1. A side-scan sonar image of the 1946 wrecked Grumman Avenger at  $\sim 16$  m showed a striking and dense pattern of apparent pits  $\sim 0.7$  to 1 m across surrounding the downed plane, but these features were not commented upon (*Los Angeles Times*, 15 June 1999). Both B. Costa-Pierce (pers. comm.) and S. Hurlbert (pers. comm.) thought these pits were tilapia nests, in which case there must still be a species of the benthic-brooding genus *Tilapia* present in the Salton Sea. Tilapia, particularly *O. mossambicus*, can breed at 90 d from hatching and every 60 d thereafter (Karr 1985) or at 60 d from hatching and every 35 d thereafter (Jansen et al.

1985), and so have an immense potential for rapid population growth, even after a major die-off.

Year-round, *Oreochromis mossambicus* is most common near the shoreline and in estuarine areas offshore from the mouths of the New and Alamo Rivers. This distribution makes them easily caught by shoreline fishers. Shoreline tilapia are more concentrated near the bottom during the summer, and occupy the entire water column in winter; open Sea tilapia rarely are caught near the bottom at any time (Costa-Pierce and Riedel 2000). Mozambique tilapia do not colonize the two rivers much, perhaps because of their high silt loads and rapid currents (Costa-Pierce and Riedel 2000). The Salton Sea produces as much as 3,600 kg tilapia·ha<sup>-1</sup>·yr<sup>-1</sup>, as much as 3X to 4X higher than several locations in the Philippines and Sri Lanka cited by Costa-Pierce and Riedel (2000). Most of these caught tilapia were >1 yr old, younger than at most other locations in the world; California Mozambique tilapia also grow much more slowly. At the Salton Sea they rarely exceed 2 yr in age (Riedel and Costa-Pierce 2000).

Costa-Pierce and Riedel (2000), Riedel and Costa-Pierce (2000), and Salton Sea Authority (2000) proposed a commercial harvest for Salton Sea tilapia, taking older fish and permitting younger fish to grow faster, thus increasing the overall productivity of the fishery while reducing Sea PO<sub>4</sub><sup>3-</sup> and thus hypereutrophication. This approach is likely to be futile, based as it is on unsupported assumptions and inadequate science (see above).

Costa-Pierce and Doyle (1997) warned against using Salton Sea tilapia as sources for aquaculture broodstock because of the likelihood of disease, and also warned against importation of any tilapia from elsewhere until it is known for sure that they would not transmit the pathogenic bacterium *Streptococcus*, which could cause severe disease both in aquaculture ponds and in the Salton Sea. *Streptococcus* is already known from Salton Sea *Oreochromis mossambicus* (Costa-Pierce 1998). Newly imported tilapia species or even different stocks of the two species already present might adversely impact the Salton



Sea's unusual fish community and its productive fishery.

Salton Sea tilapia are subject to sometimes immense die-offs, apparently from low water temperature in the winter and from low  $pO_2$  and high  $pH_2S$  after wind-caused summer breakdowns of thermal stratification (see below). Nevertheless, tilapia standing crop has been estimated as high as 100 million in the Sea. Tilapia have become the most popular sport fish of the Salton Sea, reaching ~2 kg and 40 cm; they are easily caught from shore using simple baits (Oglesby per. obs).

Some 40 aquaculture facilities in both the Imperial and Coachella Valleys raise tilapia (chiefly *Oreochromis mossambicus*), immensely popular in Asian, méxicano, and puertoriceño communities; recipes are increasingly presented to mainstream fish cooks by magazines and newspapers (*Sunset Mag.* May 1991: 162, 164). Salton Trough tilapia aquaculture produces ~13 million  $kg \cdot yr^{-1}$ , ~40% of national production. Fish are ready for market at 8 mo when they have reached 2.2 to 3.3 kg; growth is enhanced by culture in geothermal waters as warm as 47 to 61°C (Boardman 1998). About 11,000 to 15,400 kg are shipped live each week for sale to markets in Los Angeles and San Francisco. Salton Trough tilapia production increased 8% from 1997 to 1998, and is expected to continue to increase (Costa-Pierce and Doyle 2000; California Aquaculture Association). California is the largest domestic producer of tilapia. Even so, imported tilapia (28.2 million kg in 1996) are over 3 times that produced in US aquaculture, and still rising (Costa-Pierce and Riedel 2000).

Other organisms grown in Salton Trough aquaculture facilities include tropical fish for home aquarists, several species of catfish (Ictaluridae), largemouth bass (*Micropterus salmoides*), hybrid striped bass, rainbow trout (*Oncorhynchus mykiss*, Salmonidae), "shrimp," and several groups of algae such as the halophile red chlorophyte *Dunaliella* and the cyanobacterium *Spirulina*. Many of these aquaculture facilities, particularly in the Coachella Valley near the mouth of the Whitewater River, are also used as migratory duck hunting clubs in the winter. The Imperial Irrigation District is beginning to use duck

hunting ponds in its projects to increase the acreage of wetlands in the Salton Trough, maintaining them with water during the summer rather than letting them be drained, reducing inflows to the Salton Sea by  $\sim 8,400$  acre-feet-yr<sup>-1</sup> (Imperial Irrigation District 1998).

Rumors persist about the presence in the Salton Sea of one or a few giant totoabas (*Totoaba macdonaldi*, Sciaenidae), a splendid fish that can reach  $\sim 2$  m long and  $< 60$  kg and supposedly introduced in the 1950s from the Gulf of California where the species is now seriously endangered Mellink and Ferreira-Bartrina (2000). There is no evidence to support this myth.

#### 4. Other Fish

**Planktivorous fishes.**\_\_Euryhaline and migratory threadfin shad (*Dorosoma petenense*, Clupeidae) is the only planktivorous fish in the Sea, but is not important in the Salton Sea ecosystem though it is readily fed upon by carnivorous fish (Devries et al. 1991; Garvey et al. 1998). Threadfin shad were introduced from the Tennessee River in 1954 “on the optimistic assumption that they were the ideal forage fish for California reservoirs and should greatly improve growth rates of game fishes” (Moyle 1976). Threadfin shad entered the Salton Sea in 1955, only 8 mo after introduction of just 1020 fish into Lake Havasu behind Parker Dam on the Colorado River. *D. petenense* is an obligate planktivore, filter-feeding on both phyto- and zooplankton. Threadfin shad are of some seasonal importance as food for Salton Sea orangemouth corvina, but migrate back into the Colorado River to breed. Threadfin shad are most abundant along the eastern shoreline, particularly near freshwater inlets; both the New and Alamo Rivers harbor small populations (Costa-Pierce et al. 2000). Native habitat for threadfin shad is streams entering the Gulf of Mexico from the US south to Belize (Hendricks 1961a; B. W. Walker et al. 1961a; Moyle 1976; Dill and Cordone 1997).

**Non-planktivorous fish.**\_\_Of the remaining species of fish in the Salton Sea (Table VIII), the one of greatest interest is the desert pupfish, *Cyprinodon macularius*

not known.

### Is the Salton Sea Polluted?

Much concern has been expressed in the popular media as well as more scientific publications (e.g., Schoenherr 1993a; Kaiser 1999, 2000) about contamination of Salton Sea biota, especially sport fish and birds, with pesticides, herbicides, and trace elements brought in by drainage from non-operative sewage systems in Mexicali, agriculture, cattle feed lots, municipalities, and Mexicali *maquiladoras*. Wambaugh (1992) in *Fugitive Nights* summarized this view: "Many of the migrant workers, particularly Asian boat people, liked to fish the salt water for local corvina, using illegal gill nets. The cops figured that anybody hungry enough to eat the mutant fish from that selenium-loaded water -- polluted by agricultural waste -- should be welcome to it." Reality is quite different. The popular story about heavy pollution in the Salton Sea is poorly supported by direct measurements. There should have been no surprise at the release of a 1999 report by the Salton Sea Authority (see below) that there were few to no pesticide residues or trace elements in Salton Sea biota. The high input of agricultural fertilizers leads to high primary and thus high secondary production, not pollution (González et al. 1998; Salton Sea Authority 2000).

There are major problems in interpreting published data on potential pollutants:

- (1) raw data are presented in sometimes immensely elaborate and unwieldy tables, with little or no synthesis or interpretation in accompanying text;
- (2) no lower detection limits are provided for most analyses (is "<5" units at or below the limit of detection?);
- (3) only rarely are any criteria or standards for concentrations potentially hazardous to wildlife or human public health presented (Should we be worried about a report of 135 units?);
- (4) no statistical analyses were done, and, apparently often, only one sample per site or creature was analyzed;
- (5) no analysis of variability was presented;
- (6) no statistical comparisons were made (re 4, 5, and 6: Is "15 units" in this animal from this site at this

time significantly different from “9 units” from that animal at that site at that time?); (7) for the same reasons, it is often impossible to determine temporal or spatial trends; (8) units vary; (9) only sometimes is it stated whether the units are per wet weight or per dry weight; (10) there may be other, unstated, differences in analytical techniques that may lead to different results. Holdren (1999) assumed that if the testing agency were reputable and if standard analytical techniques were used, the results would be valid (“While no information was given on analytical methods used, the data were considered good because of the agencies participating in the study.” “Data was [*sic*] produced with acceptable methods.”). In fact, about all one can say is that some numbers are larger than others, but it is often not possible to determine whether such differences are biologically meaningful.

**Pesticides.**\_\_In the 1970s, ~1800 metric ton·yr<sup>-1</sup> of 120 different insecticides and herbicides were used on fields in the Imperial and Coachella valleys (US Department of the Interior and The Resources Agency of California 1974a,b; Layton and Ermak 1976). Concentrations of pesticides and their metabolites in drains and at the mouths of the New and Alamo Rivers were low, usually well below measured LD50 concentrations for fish (Swajian 1976). Nevertheless, Department of Fish and Game documented six fish kills, totaling ~54,000 dead fish in the decade 1965 to 1975, in drains in Imperial and Coachella Valleys from pesticides and other toxic agricultural wastes (Swajian 1976). The seemingly higher incidence of fish kills towards the end of the reporting period may reflect greater awareness of the problem (Swajian 1976). A spill of the insecticide thiodan in July 1996 killed 10,000 to 15,000 fish near the Hazard Unit of the Imperial Game Refuge (US Fish and Wildlife Service 1997). Many insecticides are toxic to humans and fish, and must be monitored in Salton Sea biota carefully, including using appropriate statistical analyses.

Hogg (1973) analyzed Salton Sea biota and sediments for several pesticides commonly used in the Imperial Valley. He found the organochlorine insecticide DDT

(1,1,1-trichloro-2,2-*bis* (*p*-chlorophenyl)-ethane) or its metabolites in 92% of all samples from the Salton Sea, and dieldrin in 42%. There was a non-significant south to north gradient in pesticide concentrations, and considerable seasonal variability, which Hogg attributed to fluctuations in pesticide application and to variability in runoff. While biological magnification in Salton Sea food chains was present, it was not marked. Hogg's conclusion was that these low pesticide concentrations posed no hazard to human health nor to the health of the Salton Sea biota.

A report in the early 1970s discussed what was then known about pesticide contamination of the Salton Sea and its biota, including fish. No data were given (US Department of the Interior and The Resources Agency of California 1974a,b). The conclusion was, "In all cases pesticide levels were found to be low, and it was concluded that there was no damage to fish from pesticide accumulation." The same report summarized a 1972 study which tested fish for pesticides: "The ranges of pesticide concentrations found were extremely low." DDT metabolites are very stable, persisting in the environment long after application. Even though DDT application was banned in 1972 in the US and in 1983 by México, concentrations of its more stable metabolite DDD (1,1-dichloro-2,2-*bis* (*p*-chlorophenyl)-ethane) in 1986 to 1987 as high as 50 to 60 mg·kg<sup>-1</sup> were found in drain sediments, but Salton Sea sediments had only 2.4 mg·kg<sup>-1</sup> (Setmire et al. 1990; Setmire et al. 1993), in agreement with Hogg (1973). DDT is a contaminant in dicofol, an acaricide used on cotton (Cagle 1998), so that there is still a certain level of DDT input into US agricultural drains and the Salton Sea. See Imperial Irrigation District (1994) and LFR (1999) for data on a number of pesticides; only chlordane, DDT and some of its stable metabolites, and toxaphene exceeded Food and Drug Administration or National Academy of Science guidelines, and then only in a few fish from only a few locations, none from the Salton Sea itself.

Imperial Irrigation District (1994) summarized several studies on organochlorine concentrations in drain and Salton Sea waters, sediments, and biota. Except for stable

DDT metabolites, concentrations were almost always below detection limits. Except for redbfin shiners from the Whitewater River delta, total DDT (including its metabolites) was below federal guidelines; other fish tested were mosquitofish, sailfin mollies, and tilapia. Benthic invertebrates in drains had higher concentrations than those from the Salton Sea, up to 8 to 20 times as high, with Asiatic river clams from Vail Drain being the highest; by striking contrast, Asiatic river clams from Wister Drain, which receives no agricultural drainwater, had no detectable organochlorines. Bioaccumulation tests with Asiatic river clams showed that DDE concentrations correlated to increased drain flows. Alamo and New Rivers had higher organochlorine concentrations than did agricultural wastewaters in canals and drains by factors of 10 or more (California Regional Water Quality Control Board, Colorado River Basin 1991; Imperial Irrigation District 1994), perhaps reflecting high inputs from México. Recent studies showed four metabolites of DDT and three other pesticides were somewhat in excess of federal standards (Setmire 2000). Three volatile organics were also in excess of federal standards: tetrachloroethylene, methylene chloride, and n-nitrosophenylalanine.

Elevated concentrations of the DDT metabolite DDE were found in black-crowned night herons and great egrets nesting near the Salton Sea, correlated with slightly thinned egg shells. Both species could have fed either in the Salton Sea or in the many drains or both. DDE in night heron eggs was slightly higher than the concentration associated with reduced night heron reproductive success elsewhere in the US (Ohlendorf and Marois 1990). There are no reports of reduced night heron nesting success at the Salton Sea, where they remain abundant (Oglesby pers. obs). Cattle egrets nesting in the Valle de Mexicali had somewhat elevated DDE concentrations, slightly thinned eggshells, and reduced hatching success, but they are insectivores and do not feed in the Salton Sea or drains (Mora 1991). Mora (1991) concluded that their reduced hatching success was caused by factors other than organochlorine pesticides.

The Salton Sea Authority (2000) concluded that available data demonstrated a



long-term decline in maximum concentrations of both pesticides and organics in the Salton Sea and its sediments, with the most recent studies finding such compounds below the concentration of detection.

**Selenium.**—The major potential pollutant of concern in the Salton Sea is the non-metallic element selenium. A cofactor in the enzyme glutathione peroxidase, Se is required for human nutrition at a concentration of  $0.04 \text{ mg}\cdot\text{g}^{-1}$ ; it is beneficial to human up to  $0.1 \text{ mg}\cdot\text{g}^{-1}$ , and toxic above  $4 \text{ mg}\cdot\text{g}^{-1}$  (Cagle 1998).

It is unfortunate that the literature on purported Se problems in the Imperial Valley and Salton Sea rarely discuss the many serious problems experienced by nesting birds at Kesterson National Wildlife Refuge in the San Joaquin Valley. Agricultural waste waters brought high concentrations of Se to shallow ponds and marshes at Kesterson, where many water-related birds spent the winter and bred during the summer. The problem was recognized beginning in 1983 by a very high frequency of unhatched eggs and deformed chicks, most of which died soon after hatching. Kesterson was closed, and a number of remedial treatments were applied, based on extensive scientific research. The initially-favored soil removal plan was demonstrated to be ineffective in protecting ephemeral pools often favored by water birds. Groundwater was protected from Se contamination by natural biogeochemical immobilization. Upland vegetation did not much concentrate Se, and was regarded as safe. For these reasons, no attempt was made to remove Se-contaminated soils; low-lying pools were filled to prevent birds from nesting, as aquatic food chains did lead to Se bioaccumulation. Important conclusions included: (1) naturally-occurring biogeochemical processes can be the cornerstone of effective remedial strategies; (2) “safe concentrations” of toxic constituents based on total elemental analyses may be misleading, and species-specific goals difficult to define; and (3) scientific research and fast-track remedial activities must go hand-in-hand to achieve cost-effective, risk-based remedial strategies (Harris 1991; Benson et al. 1993; Presser 1994). Bacterial pathways which convert Se to less-toxic organic species or which

volatilize Se may be useful (Combs et al. 1996; Losi and Frankenberger 1997; Hanson et al. 1998; Setmire and Schroeder 1998; Gao et al. 2000). The Salton Sea Authority (2000), ignoring this extensive literature, made no recommendations concerning lowering Se concentrations in agricultural waters.

Various studies indicate that soils of the Salton Trough are not the source of its Se. Colorado River water is  $\sim 2 \mu\text{g Se}\cdot\text{l}^{-1}$ , the Se being derived from erosion of sediments in the river's Upper Basin (Setmire and Schroeder 1998; Setmire 2000).

In the Imperial Valley, Se is concentrated by evaporation and leaching in agricultural fields (Craig 1966; Cagle 1998) so that Se is much higher in agricultural drainwater than in incoming Colorado River water, concentrations in the Whitewater River (which receives little agricultural waste) being lower than in the New and Alamo Rivers (Setmire et al. 1990; California Regional Water Quality Control Board, Colorado River Basin 1991; Colorado River Board of California 1992; Setmire and Schroeder 1998; Salton Sea Authority 2000). Concentrations of Se in the Salton Sea are as much as 50% lower than in the rivers, apparently because Se is rapidly removed from the water column at the mouths of rivers and drains by benthic bacteria, sedimentation, and aerosolization (Setmire and Schroeder 1998; Setmire et al., 2000; see below).

Drain sediments were always low in Se, within baseline ranges for soils in the western US. Concentrations in Salton Sea sediments were higher, as much as three times higher in a composite sample from the Sea (Salton Sea Authority 2000). Curiously, highest Se concentrations in sediments were in the northern two-thirds of the Sea, with lower concentrations found in the southern third, which receives most of the direct agricultural drainage.

Se in Salton Sea biota is rarely concentrated enough to be of any concern either to public health or to bird reproduction, though Se concentrations in biota from rivers and drains can be markedly higher. The highest concentrations of Se in plants,  $1.1 \text{ mg}\cdot\text{g}^{-1}$ , was found in sago pondweed (*Potamogeton pectinatus*), an important waterfowl food. At

Kesterson concentrations of Se in bird food plants ranged as high as  $310 \text{ mg}\cdot\text{g}^{-1}$  (Setmire et al. 1990; Setmire and Schroeder 1998; Schoenherr 1993a).

With a few unexplained exceptions, invertebrates in both drains and the Salton Sea had low concentrations of Se, all below the minimum  $10 \text{ mg}\cdot\text{g}^{-1}$  dietary concentration that produced waterbird abnormalities in laboratory experiments (Imperial Irrigation District 1994).

Se in Salton Sea fish (*bairdiella*, *orangemouth corvina*, *sargo*, *tilapia*) taken near the mouth of the Alamo River were higher than concentrations in fish taken upstream in the river, but usually not higher than public health criteria. One composite sample of *orangemouth corvina* was  $20 \text{ mg Se}\cdot\text{g}^{-1}$ , considerably higher than the value reported by the state in 1986 and 10 times the "level of concern" in the state's health advisory (see below). *Tilapia* from drains ranged as high as  $17 \text{ mg Se}\cdot\text{g}^{-1}$  (Alamo River delta), a value considered detrimental to reproduction in fish-eating birds and higher than in other fish in these drains. Highest Se concentrations in mosquitofish and sailfin mollies came from populations in San Felipe Creek, which receives no irrigation wastewater (Saiki 1990; Imperial Irrigation District 1994; Setmire and Schroeder 1998; Setmire et al. 2000).

Interpretation of Se analyses in water-related birds is greatly complicated by the fact that most waterbirds feed in several habitats: in the Salton Sea itself, the major rivers and freshwater lakes (e.g., Finney and Ramer lakes and farm ponds), agricultural canals and drains, and agricultural fields, sometimes in the same day. The relative times spent feeding in each habitat are not known, and may vary with season. Therefore, it is not possible to conclude where a given bird or even species obtained its Se load. Some reports state that the cattle egret is a piscivore and so interpret Se loading as if from aquatic food chains, which is incorrect.

Reported Se concentrations were higher than background in several species of Salton Trough birds, but well below concentrations found in deformed birds at Kesterson; most values from birds that feed away from the Salton Sea were well below the threshold

for reduced reproduction and survival. Se concentrations in Salton Sea-feeding birds were somewhat higher, but not threatening. There was evidence of bioaccumulation at higher trophic levels, with Sea piscivores such as black-crowned night herons and pelicans at greatest risk (Imperial Irrigation District 1994; Setmire and Schroeder 1998; Shuford et al. 1999; Setmire et al. 2000). Both brown and white pelicans from the Salton Sea had elevated Se concentrations compared with the same species from Sea World in San Diego (Bruehler and de Peyster 1999), which might make them more susceptible to botulism and other diseases, but no causal relationship has been established. A 1995 US Fish and Wildlife Service study attributed a 4% reduction of reproductive success of black-necked stilts to elevated concentrations of Se and worried that desert pupfish reproduction might also be affected (*Los Angeles Times* 25 April 1995). Neither seems to have actually occurred.

In 1986, the California Department of Health Services announced that analyses of “edible flesh” from all four species of Salton Sea sport fish “indicate the presence of selenium at concentrations sufficiently high to warrant issuance of a health advisory for people who consume these fish.” Reported Se concentrations ranged from 1.7 to 3.8  $\text{mg}\cdot\text{g}^{-1}$  dry weight based on single tests of composites of 5 to 6 individual fish per species, effectively a sample size of one. Although there is no officially set public health standard for Se, Department of Health Services regarded 2  $\text{mg}\cdot\text{g}^{-1}$  dry weight Se as representing a “level of concern” with respect to human consumption. The health advisory stated that total consumption of any of the four fish species should not exceed one 124.4 g portion  $\cdot 2 \text{ wk}^{-1}$  and that fish consumption should be avoided altogether by women of childbearing age and children under 15. Many residents, fishers, and biologists regarded with skepticism both the timing of this health advisory and also the data upon which it was based (Pomona CA *Progress Bulletin* 4 July 1986), as the advisory coincided with requests by Imperial Irrigation District and Metropolitan Water District effectively to abandon the Salton Sea as a fishery resource in favor of its continued use as

an agricultural wastewater sump. No cases of human Se poisoning have been reported from eating Salton Sea fish (Salton Sea Authority 2000). Now 20 yr old, the health advisory has not been lifted, despite more recent data that suggest that it is unnecessary.

Methods to control Se in the Salton Sea watershed would be most effective if they dealt with Se at its point of highest concentration -- subsurface agricultural drains (tile drains), which provide about a third of the flow in Imperial Valley surface drains. Se in tile drain waters is diluted by tailwater and leakage from canals so that the overall average of drainwater is diluted by ~67%. Some methods effective in preventing pesticides from entering drains also reduce the amount of tailwater. Since tailwater is an important source of relatively low Se waters, removing it from the drains may cause overall Se concentrations to increase (California Regional Water Quality Control Board, Colorado River Basin 1991).

Setmire et al. (1990) concluded that some as-yet-unknown mechanism in the Alamo and New River mouths was removing Se from the water and concentrating it in Sea sediments, which they said is the first step in incorporation of Se into Salton Sea food webs. Se can be metabolized by benthic bacteria and sequestered in sediments, such as flocculated silts that precipitate (Postma 1967) at the mouths of the New and Alamo Rivers: the sediments of river mouths at the Salton Sea are a Se sink, receiving Se at a rate of 9 to 10 metric tons-yr<sup>-1</sup>, amongst the largest known Se sinks in the world (Cagle 1998). Dredging sediments for dikes could resuspend this sequestered Se and so adversely affect Salton Sea food webs (Cagle 1998). Similarly, should the Salton Sea become significantly lower in elevation, these silts, now exposed to air, could lead to Se-enriched particles readily moved by winds.

Bacteria can reduce Se to selenite or hydrogen selenite -- less soluble than selenate; much of the reduction in concentration of Se in the Salton Sea (as compared with drain and river water) might be attributed to this cause (Cagle 1998; Salton Sea Authority 2000; Schroeder and Orem 2000). Incorporation of Se into organics may be capable of

volatilizing Se or precipitating Se with organic detritus (Salton Sea Authority 2000), though Swan and Orem (2000) concluded that atmospheric loss is not now important.

**Other Trace Elements.**—Values for most other trace elements in Salton Sea sediments are usually also within baseline ranges (Setmire et al. 1990; Imperial Irrigation District 1994; Holdren 1998; LFR 1999; Setmire 2000; Swan and Orem 2000). According to LFR (1999), Bechtel National Inc. in 1997 studied contamination at the closed Salton Sea Naval Test Base. An aeroballistic target area in the Sea had been used for testing atomic weapons in the 1940s through 1960s, with ~3750 test units (non-explosive, non-radioactive) dropped -- stainless steel casings filled with arming, fusing, and firing components, including lead/acid (until the 1950s) and nickel/cadmium (after 1950s) batteries, and minor amounts of Al, Cu, brass, rubber, concrete, and lead or stainless steel ballast. These test units usually broke apart on impact, scattering debris over wide areas. A MK-6 “fly-around” radioactive test unit with 55 kg U was lost in the Sea. Approximately 4545 kg were recovered from one area, but much debris still remains. No systematic attempt has been made to decontaminate this aeroballistic site. According to LFR (1999), Bechtel National in 1997 found somewhat elevated concentrations of As, Cd, Mo, Se, U, Va, and W at this site, but concluded that these elements were naturally occurring except for Cd, and that in view of the low concentrations, no additional actions need be taken.

Boron concentrations in water and sediments were high enough to cause reproductive impairment in birds, though there have been no reports of avian developmental abnormalities at the Salton Sea. In several studies summarized by Imperial Irrigation District (1994), only B in pileworms was elevated. Other invertebrates had concentrations at or below background. Salton Sea water had concentrations only slightly over the  $10 \text{ mg B} \cdot \text{l}^{-1}$  considered safe. Summarized analyses for fish reported  $25 \text{ } \mu\text{g B} \cdot \text{g}^{-1}$  dry weight in mosquitofish, similar to values at Kesterson in 1985. Salton Sea bairdiella had 5 to  $8.3 \text{ } \mu\text{g B} \cdot \text{g}^{-1}$  dry weight, as did freshwater fish taken from rivers and drains



(Imperial Irrigation District 1994). Some birds had elevated concentrations of B, chiefly those that feed on vegetation such as filamentous algae, though Setmire et al. (1993) also speculated that piscivores might also accumulate B. The important conclusion is that boron is not a problem at the Salton Sea.

Elevated concentrations of Cr, Ni, and Zn were found in Whitewater River sediments; Setmire et al. (1990) asserted that these concentrations were not associated with agriculture. Numerically, Setmire's (2000) results were similar to Setmire's study of 10 yr earlier. Over 25 trace metals have been detected in the New River at the international boundary. Those that exceeded federal standards in at least one sample were Ag, As, B, Ba, Cd, Cr, Mn, Ni, Pb, Se, Tl, U, W, and Zn (Setmire et al. 1990; Setmire and Stroud 1990; Setmire et al. 1993; Setmire 2000). Bradford et al. (1990) found no elevation in Salton Sea water concentrations of U, V, or Mo. Hg concentrations were elevated in fish-eating birds. Concentrations of other trace elements in biota were not regarded as indicating hazard (Setmire et al. 2000). Vogl et al. (2000) found somewhat elevated concentrations of Cd, Cu, Mo, Ni, Se, and Zn, with Mo and Se most elevated, particularly in the northern Salton Sea. These elements were also elevated in the top 0.3 m of sediments. Vogl et al. (2000) also detected very low concentrations of a number of volatile organics, which they concluded were the result of ordinary biological processes in the Sea. Again, the important conclusion is that trace element contamination is not a problem at the Salton Sea.

Only a few studies have looked at how Salton Sea biota uptake trace metals. In laboratory experiments, the detritus feeder *Nereis succinea*, the herbivore and carnivore *Trichocorixa reticulata*, and the zooplanktivore *Balanus amphitrite* obtained trace metals, including Se (as selenate), from their food, not from the water column (Thomas et al. 1999; Wang et al. 1999a,b,c). Fialkowski and Newman (1998) analyzed seven trace metals in Salton Sea *Balanus amphitrite*, finding that concentrations both in brooded lipid-rich eggs and in adults varied between collection sites and were least where organic inputs

were highest; concentrations were lower, sometimes markedly so, than in an estuarine population in Mission Bay, San Diego. They concluded “that the [Salton Sea], contrary to expectations, has not been severely contaminated by heavy metals.” J. P. Skrupa of the US Fish and Wildlife Service is quoted in a recent, undated handout from the Salton Sea State Recreation Area as saying, “No human health problems have been noted from eating Salton Sea fish.”

**Other Pollution Issues.**—In 1999 a proposal was put forward to import some 7730 metric tons of Hg-rich toxic sludge from Taiwan and then illegally dumped in Cambodia, and to dump it in a 640-acre toxic waste site owned and operated by Safety-Kleen near Westmorland in the Imperial Valley. Vertical permeability of the deep Colorado River sediments in the Imperial Valley is not high (Hely et al. 1966; Layton and Ermak 1976; Salton Sea Authority 2000), but with the proximity of this dump to the New River, it is still easy to imagine waste Hg seeping first into the New River and then being carried to the Salton Sea. In April 1999 the US Environmental Protection Agency rescinded its tentative approval for dumping this Taiwan/Cambodian waste (*Los Angeles Times* early April 1999). Residents of nearby Westmorland were elated. But what is the fate of other toxic wastes dumped in this site?

It was discovered in 1999 that Inland Container Corporation (now Inland Paper Board and Packaging) of Ontario CA was the source for illegal dumping of ~4545 metric tons of industrial wastes (shredded plastics, cellulose fibers) in “former wetlands” in the Coachella Valley adjacent to the Salton Sea. If these wastes had entered the Sea, the cellulose would be degraded by bacteria and fungi while lowering  $pO_2$ , and the undegradable plastic particles would cause serious problems for any fish and birds that ingest them, and perhaps for some invertebrates. The actual dumper was a sub-contractor, two of whose employees were convicted and sent to prison for 30 mo each. Inland Paper Board and Packaging volunteered to pay ~\$1 million to clean up the mess, and is suing to get repayment from both the contractor and sub-contractor (*Los Angeles*

*Times* 14 December 1999; D. Reynolds and S. Householder pers. comm.). This incident serves as a warning about the perennial dangers of illegal dumping at the Salton Sea and adjacent wetlands.

The first part of a major study of the Salton Sea authorized by Congress in late 1998 was released in May 1999 by the Salton Sea Authority. Local newspapers (*Los Angeles Times* 23 May 1999; *Ontario CA Inland Valley Daily Bulletin* 24 May 1999) exulted over the good news. The more alarmist *Daily Bulletin's* headline was "Study: Salton Sea, state's largest lake, free of pesticides." Because of negative publicity about contamination over the past several decades, the Salton Sea Authority had expected to "find elevated concentrations of pesticides, herbicides and metals, but we instead found almost no trace. This is good news." Executive Director Kirk of the Salton Sea Authority, was quoted, "Despite popular conception, the Salton Sea is not dead." There was no explanation of why Director Kirk thought the Salton Sea should have been "dead," as all evidence indicates that this hypereutrophic lake is biologically flourishing (see above). The *Los Angeles Times* concluded, "If the Salton Sea is not a cesspool of pesticides, it could mean that cleaning up the sea, which still a difficult, dirty and expensive undertaking, may not be as daunting as once feared." Then-Interior Secretary Babbitt was quoted, "The sea is much more vibrant and complex than people have thought."

The Salton Sea Authority's May 1999 report suggested that the shallowness of the sea and the turbulence kicked up by desert winds serve to dilute incoming pesticides. Much more likely, pesticides, trace elements, and other contaminants flowing into the Salton Sea are associated with clay particles, which in freshwater are repelled from each other by negative charges and so remain in suspension. These clay particles flocculate and settle out as benthic sediments when the negative charges are neutralized by the higher salt concentrations of the Salton Sea, just as in conventional estuaries elsewhere (Postma 1967).

Overall, it appears that Jim Matthews (Ontario CA *Inland Valley Daily Bulletin* 3 June 1999) is correct when he alerts fishers: “Don’t worry about the water (it’s cleaner than Santa Monica Bay), and the fish are fine to eat.”

### Public Health

Popular accounts often worry that the Salton Sea and its inflowing rivers and drains are a source of major public health problems, such as sewage pollution and concomitant pathogenic fecal bacterial and viruses, industrial pollution that inputs toxic trace elements into the Salton Sea (see above), and agricultural inputs of pesticides (see above), as well as other possible pathogens. Potential routes of transmission to humans include inhalation into the lungs, ingestion into the gut, skin contact, vectors, trauma, and physiological stress. So far, none of these has proved to be at all dangerous to human health, as concentrations of all potential pathogens and toxic substances turn out to be very low in the Salton Sea and its biota, including edible fish (though sometimes high in the New River and other agricultural wastewaters: see above); infested or infected humans have not been reported. Known pathogens of Salton Sea birds, such as Newcastle virus, avian cholera, and avian botulism, do not usually affect humans (see above). *Vibrio vulnificus* is present in sick and dying Salton Sea fish, and while it can cause sometimes severe disease in humans, does not seem to have done so at the Salton Sea (Salton Sea Authority 2000).

Mandated regular tests for coliform bacterial concentrations -- an index of fecal and sewage contamination -- rarely exceed minimum criteria for concern, though they can be high in the New, Alamo, and Whitewater Rivers (Salton Sea Authority 2000). The usual test does not distinguish between fecal coliforms from humans and those from domestic and wild birds or mammals. High coliform concentrations have been detected in the New River just downstream from Mexicali, which has no viable sewage system. Fecal coliforms and streptococci have been consistently detected at the international boundary,

often greatly in excess of US standards (Setmire 2000). These bacteria are killed or diluted by the time New River water reaches the Salton Sea (Salton Sea Authority 2000). Coliform bacterial counts at the mouth of the New River and in the Salton Sea are usually below concentrations considered hazardous for humans (Riverside County Health Department, no date), though in the 1960s Imperial County posted ~5 km of the Salton Sea shoreline from the New River mouth north to Bombay Beach as “unfit for water-contact sports,” and Riverside County similarly posted an area near the mouth of the Whitewater River (US Department of the Interior and The Resources Agency of California 1969, 1974a,b). Coliform bacteria in the Salton Sea itself are unlikely to be of human origin, but rather from soil bacteria and the many water-related birds. One would not expect significant sewage contamination of the Salton Sea, since its periphery is so sparsely populated. The Salton Sea is a Class I water, suitable for body contact.

The New River is well known for high pathogen counts at the international border, whose source is probably Mexicali, which lacks a viable sewage treatment system. Pathogens recovered from New River water in Calexico include the bacteria responsible for “food poisoning” gut infections (*Salmonella* spp., *Shigella* spp.), typhoid (*Salmonella typhi*), *Aeromonas* spp. and cholera (*Vibrio cholerae*), as well as the viruses that cause meningitis and polio. There are no positive records for other human bacterial and viral pathogens, either in the New River or in the Salton Sea (*Los Angeles Times* 4 November 1995; Wolcott and Berlowski 2000). Many illegal immigrants swim the New River to enter the U.S. where there is a break in the 3.5 m border wall at Calexico, hiding in foam patches and “often” suffering illness from drinking the foul water (Ontario CA *Inland Valley Daily Bulletin* 30 January 2000).

Mosquitoes carry a number of arboviruses, including those causing western equine encephalomyelitis (Togaviridae) and St. Louis encephalitis (Flaviviridae). These encephalitides have been detected in Salton Trough *Culex tarsalis* and *Aedes dorsalis*, but not in humans. The last known human case of western equine encephalomyelitis in the

Trough, which was fatal, was in 1938 (Coachella Valley Mosquito and Vector Control District 1997; Salton Sea Authority 2000), but 2 to 16% of current residents who visited clinics and hospitals for any reason had antibodies to one or both encephalitides, though they had not been sick (Reisen et al. 1996). Both viruses maintain a primary enzootic transmission cycle involving wild birds and mosquitoes, but mammals are also infected. Vector mosquitoes, primarily *C. tarsalis*, breed in salt marshes in the Coachella Valley and elsewhere and may often be abundant, especially from late spring through early autumn, with the most cases in August and September (Reisen and Lothrop 1995; Reisen et al. 1995, 1998; Coachella Valley Mosquito and Vector Control District 1997; Oglesby pers. obs.). Species, unidentified, of culicid larvae and pupae have been found in the concrete-lined Cleveland Street Spillway, Whitefield Creek, and shoreline pools (Table VII). There are reports of encephalitis-infected mosquitoes in the southern Imperial Valley and even one, unconfirmed, human case associated with the New River (Cagle 1998).

All species of *Anopheles* mosquitoes are vectors for malaria, once common throughout California. Several species of *Anopheles* have been reported from the Salton Trough (Mullens and Dada 1992; Reisen et al. 1999), but no recent cases of malaria are known. But a traveler or immigrant who contracted malaria elsewhere and who relapsed from *Plasmodium vivax* could lead to a localized indigenous outbreak, as has been documented several times in immigrant camps and adjacent communities in San Diego County and the San Joaquin Valley, as well as in a Girl Scout camp in the Sierra Nevada (A. Oglesby pers. comm.). Humans have recently changed their habits, reducing their exposure to vector mosquitoes: they stay indoor at dusk watching television, rather than being bitten by (infected) mosquitoes while outside (A. Oglesby, pers. comm.). Nevertheless, the potential for a malarial outbreak at anytime exists.

Both species of the prosobranch snail *Thiara* are intermediate hosts for a diversity of digenetic flukes in both the Old and New Worlds, including some serious human



parasites. For example, *T. tuberculata* in Visakhapatnam, India, harbors 19 species of larval trematodes from 10 families (Madhavi et al. 1997). In many parts of the world, both thiarids and parasites are introductions, including the Salton Trough. Larvae of the digenetic trematode *Paragonimus* sp. (lung fluke) were found infesting one specimen of *T. granifera* from Whitefield Creek in summer 1988 (Oglesby pers. obs.). *P. westermanni* is a serious human parasite common in much of southern and eastern Asia and adjacent Pacific islands. The life cycle of *P. westermanni* involves a carnivorous mammal (humans) in which flukes reach sexual maturity in the lungs and release eggs which enter the esophagus and are eliminated with feces. Eggs hatch into swimming miracidia larvae which enter freshwater snails (*T. granifera* and other gastropod species in Asia: Davis et al. 1994) as first intermediate host. Swimming cercarial larvae emerge from snails after significant asexual reproduction in the snail's digestive diverticulum and gonads, and enter a largish crustacean (freshwater crabs in Asia) as second intermediate host, which is then eaten uncooked by the human host-to-be (Noble et al. 1989).

Both *Thiara granifera* (first intermediate host) and Louisiana red crayfish (potential second intermediate host) co-occur in agricultural drains and springs around the Salton Sea (Tables I, VII), but it is unlikely that enough humans (potential definitive host) eat raw crayfish and then defecate into these waters to maintain a parasite life cycle involving humans. More likely, the definitive mammalian host of this as yet unidentified species of *Paragonimus* is a local carnivore such as raccoon, kit fox, or coyote (Noble et al. 1989; Oglesby pers. obs.). A New World human lung fluke, *Paragonimus mexicanus*, afflicts freshwater crab-eaters, and has been found in desiccated pre-Colombian mummies in Central America (Pringle 1998).

The San Antonio Zoo, Texas, populations of both *Thiara granifera* and *T. tuberculata* harbor rediae and release cercariae of *Philophthalmus megalurus*, an eye fluke which infests nictitating membranes of birds and occasionally mammals. There are a few known cases of human infestation with eye flukes in Asia, but none yet known from the

US. The entire life cycle operates at the San Antonio Zoo, with the definitive hosts there being waterfowl (Murray and Stewart 1968; Murray and Haines 1969; Murray 1971; Kotrla 1975, 1977, 1983; Kotrla and Murray 1980). Alicata (1962) described in detail the life cycle of another avian eye fluke, *P. gralli*, whose host is *T. granifera* in Hawai'i.

*Thiara tuberculata* is an important intermediate host in Asia for the Chinese liver fluke *Opisthorchis sinensis*. Many species of fish, including poeciliid fish such as sailfin mollies (abundant in the Salton Trough) serve as second intermediate hosts (Dundee and Paine 1977). Dundee and Paine (1977) worried that all species involved in the Chinese liver fluke life cycle were present in Louisiana, including Southeast Asian immigrants who may have brought the flukes with them and who eat raw fish. The same would be the true in the Salton Trough. McCullough and Malek (1984) concluded that establishment of a human Chinese liver fluke life cycle was unlikely in Louisiana, but stated that not enough information was available to be certain. A population of *T. granifera* was found in Echo Park Lake in Los Angeles, which was then drained and the snails eliminated because of worry about human parasites (C. Coney, pers. comm.).

Another introduced human parasite life cycle might be present at the Salton Trough. Basch et al. (1975) found the snail *Biomphalaria obstructa* in the Coachella Valley (Table I). *B. obstructa* is a first intermediate host for the blood fluke *Schistosoma mansoni*, whose cercariae infest humans after burrowing into the skin. A Yemeni strain of *S. mansoni* was raised in Salton Trough *B. obstructa* in the laboratory (Basch et al. 1975). About 50% of Yemeni agricultural workers in the San Joaquin valley were infected with *S. mansoni* in 1972. None of 100 *B. obstructa* collected from the Coachella Valley harbored schistosome rediae or cercariae, so it is unlikely that the parasite life cycle is now established in the Salton Trough (Basch et al. 1975). Furthermore, since both species of *Thiara* can outcompete several species of *Biomphalaria* and thus have reduced or eliminated schistosomiasis on several Caribbean islands (Giboda et al. 1997), the spread of *B. obstructa* in the Coachella Valley may be severely restricted.

As Cohen et al. (1999) observed, protecting public health is not a component of any current Salton Sea “restoration” plan (e.g., Salton Sea Authority 2000).

### **Cleaning up the New River**

Many serious human pathogens (see above) and other potentially harmful substances have been found in the New River at the international boundary (see above). Abundant foam at the border is caused by detergents, and often contains high fecal coliform and *Streptococcus* concentrations (see Moore [2000] for color photos of New River trash). Large floating patches of foam can be seen north of Calipatria, downstream, where the New River falls over a small weir (Oglesby pers. obs.). Curiously, the New River here at Calipatria is no longer signed about pollution.

Trace element and pesticide concentrations in the southern, upstream, part of the New River are high. Comparisons with contaminant concentrations in Salton Sea biota show that the latter may contain low concentrations of some pesticides and trace metals, but not high enough to cause adverse health effects from eating either New River or Salton Sea biota. However, the Public Health Service recommends that no one eat anything from the New River because of its many human pathogens (US Public Health Service Agency for Toxic Substances and Disease Registry 1996; see above).

Because of its notorious contamination, plans have been developed to “clean up” the New River, potentially the largest point source of pollutants to the Salton Sea, and one of the most polluted rivers in the US. A pact was signed in January 1987 between the US and México, pledging US dollars to help build a sewage treatment plant for Mexicali (population ~800,000 to 1 million), most of whose untreated sewage is now discharged directly into the New River just before it enters the US. Congress appropriated \$5 million for a dozen “quick fix” repairs to the Mexicali sewer system, and \$47.5 million was allotted to the International Boundary and Water Commission for anti-pollution efforts along the border, with much of that US sum being proposed to build an

entirely new Mexicali sewage system (*Los Angeles Times* 11 April 1975, 4 November 1995, 7 August 2000; *Time Magazine* 20 April 1987; Anonymous 1989; Fortner 2000; *USA Today* 11 May 2000; Moore 2000).

Additionally, a New River test purification project (New River Wetlands Project), under the auspices of a Citizen's Congressional Task Force guided by Department of Fish and Game for 12 federal state and county agencies and legislators, is being constructed at a site ~8 km downstream (northwest) of El Centro (Moore 2000). Low levees will force New River water to spread into two marshy ponds constructed adjacent to the river; the first pond is for silt settlement, the second for wetland treatment of organic pollutants, lowering nutrient concentrations in water to be returned to the New River. Monitoring will be by the Imperial Irrigation District. US Bureau of Land Management biologists estimated that 4.2 km of river marsh land would clean the river entirely, but due to the New River's extreme concentration of pollutants, the project allowed for >8 km of marsh flow before the river enters the Salton Sea. Costs are expected to be modest. If the current pilot project is effective, plans call for 40 two-pond purification wetlands to be constructed along the entire lengths of both New and Alamo Rivers, including a 121-152 ha site just downstream from Finney and Ramer Lakes on the Alamo River. It is expected that these ponds will develop into new wetlands valuable for wildlife and increased hunting, fishing, birding, and other forms of recreation (*Los Angeles Times* 7 August 2000; Moore 2000).

Nothing is being done to allay trace metal and human pathogen pollution from Mexican domestic sewage, industry, and *maquiladoras* (Anonymous 1989). The New River at Calexico is anoxic, hence no fish (*Los Angeles Times* 7 August 2000).

Detoxification now occurs as the New River travels the 96 km from Calexico to the Salton Sea, so that river water entering the Salton Sea is nowhere near as polluted as it is in Calexico. The 1974 Feasibility Study discussed bacterial concentrations in the Salton Sea, but presented no data (US Department of the Interior and The Resources Agency of

California 1974a,b). Federal and state testing programs continue to reveal the magnitude of the New River pollution problem, and official concern has increased since ratification of the North American Free Trade Agreement. Lawsuits are threatened by Imperial County against the US Environmental Protection Agency, which has recently become more aggressive in dealing with the New River. But the remoteness of the Imperial Valley to Washington DC, its sparse population (only 130,000 people), and federal, state, and local budget problems all conspire to limit effective actions. Imperial County Supervisor Van De Graaff said in 1995, "When all is said and done about the New River, there's been a lot more said than done" (*Los Angeles Times* 4 November 1995).

### **Energy Development at the Salton Sea**

**Geothermal energy.**—The Imperial Valley and Valle de Mexicali are valuable for geothermal energy development because of high temperature groundwaters near the surface, associated with the northernmost two of the East Pacific Rise crustal spreading centers, the Brawley Seismic Zone and Cerro Prieto. The first geothermal wells in the Salton Trough were developed in 1927 and 1928 at Mullet Island (California Department of Water Resources 1970; Lande 1979), but were soon abandoned. Drilling east of Mullet Island again took place in 1933 through 1954, but was equally unsuccessful (Sturz et al. 1998). After two successful test wells were drilled in 1957 and 1958 near Red Hill and Alamo Butte, geothermal explorations began in earnest and still continue for ways to exploit geological heat for production of electricity (Shinn 1976; Lande 1979; Black 1981). The nine geothermal plants in the Imperial Valley produced 380 MW in 1999, ~7% of California's total energy (Lindsay and Hample, 1998; *Los Angeles Times* 24 January 2000).

Discharge of geothermal waste brines to the Sea is prohibited by the California Regional Water Quality Board Colorado River Basin Region (Resolution No. 63-14 and later resolutions). Nevertheless, spills do occur. In April 1976 geothermal wastes in an

evaporation pond spilled into a drain near Red Hill Marina, causing a large kill of otherwise healthy orangemouth corvina both in the drain and adjacent Salton Sea (Phelps and Anspaugh 1976; R. Ireland, pers. comm.). At a 1981 US Bureau of Land Management hearing on proposed oil and gas leases (see below), the Union Oil District Operations Manager strongly denied the fact of any such spill (pers. comm.). Later R. Miller (pers. comm.), Imperial County Planning Director, wrote that Imperial County, the California Division of Oil and Gas, and the Department of Fish and Game “had no record of any spills contaminating the Salton Sea,” but went on to say that there are “some unofficial personal accounts” that a holding pond leaked into a drain, and that two other wells “as a matter of normal operations, discharged some of their fluids into the drain system and thus into the sea.” R. Zortman (pers. comm.), El Centro Resource Area Manager, US Bureau of Land Management, wrote, “The fish kill identified in your letter was the result of flow testing of the geothermal resource.” In other words, the spill and associated orangemouth corvina kill did not happen, but the spill and resultant fish kill were the result of normal operations. Whether or not this 1976 fish kill really took place (I am sure that it did), it and many Endangered green sea turtle (*Chelonia mydas agassizii*) deaths in Laguna Ojo de Liebre from a spill of salt works brine in December 1997 (A. Hershowitz, pers. comm.) serve as warnings that brine spills, whether from geothermal energy development or other diked evaporation ponds (see below) could seriously damage the biota of the Salton Sea.

At several locations in the volcanic buttes area geothermal facilities have been developed, cooperative ventures of private energy companies and the US Department of Energy. Unlike the Geysers facility north of San Francisco (one of two other geothermal facilities in California) with its energy source clean superheated steam, underground temperatures in the Salton Trough are lower, from 61°C to over 260°C (Boardman 1998). Geothermal fluids in the Imperial Valley are amongst the most saline natural liquids known, from 200‰ to as high as 330‰, and have high concentrations of trace metals



(White et al. 1963; Phelps and Anspaugh 1976; Helgeson 1968; Lindsay and Hample 1998). Imperial Valley drill depths vary from ~750 to 1000 m to as deep as ~2470 m. High salinities cause continuing problems of corrosion of metal fixtures and brine disposal (Shinn 1976). Injection of waste brines into the ground is now used for disposal, a practice which helps avert soil subsidence and which should also avert damage to aquatic biota. If brine spills can be controlled, environmentally the greatest problem may be negative interactions between the festoons of high-voltage power lines and migratory waterbirds (Leitner and Grant 1978). Layton (1978a,b) and Black (1981) worried that the necessary utilization of freshwater by geothermal facilities would reduce water inflow to the Salton Sea and thus exacerbate Salton Sea salinity problems.

In 1983 the Department of Fish and Game authorized Bear Creek Mining Co. to use >50% of the Wister Unit of the Imperial Wildlife Area for geothermal energy exploration. Much concern was expressed about adverse effects of geothermal drilling in a wildlife refuge, both as to direct effects of noise and light disturbance on nesting of the Endangered Yuma clapper rail and other birds, and effects of spills of hot geothermal brines into managed waterfowl ponds. But a Department of Fish and Game geothermal expert defended this permission: "To put it simply, we decided it was safer to have them inside the refuge -- where we could control them -- than to have them outside. This way we can tell them exactly how to run their operation, and we can shut them down when we need to" (*Los Angeles Times* 10 June 1983; F. Worthley, pers. comm.).

In 1982, Imperial County authorized 44,922 ha for geothermal energy development. Actual production has gone from a single 10 MW facility in 1985 to >200 MW from nine facilities in 1999. By 1990, at least 60 production wells and hundreds of exploration wells had been drilled (Norris and Webb 1990). The Imperial Valley, the "Saudi Arabia of geothermal," is estimated to support >1000 MW of electrical power production (US Bureau of Land Management *Newsbeat*, November-December 1995; Lindsay and Hample, 1998). See the books by Butler and Pick (1982) and Lindsay and

Hample (1998) for detailed discussions of problems and prospects for geothermal energy development in the Imperial Valley.

Reprocessing technology is now used to salvage trace metals from Imperial Valley geothermal brines, reducing their environmental impacts. In September 1998 a contract was awarded for a \$148 million plant to recover 27,300 metric ton·yr<sup>-1</sup> of Zn. The plant was expected to be operational in mid-2000 (Premuzic et al. 1997; Kohler-Antablin 1999).

**Solar ponds.**—The Salton Sea has been proposed as the site of a solar pond for electricity generation. In 1980, a pilot solar pond project was proposed for the Navy's Salton Sea Test Base, using Israeli technology and starting with a 5 MW plant that would cost \$20 million. At that price, 1 KW would cost \$4000 in 1980 dollars, about twice that of now-uneconomic nuclear power plants. Promoters hoped that future solar ponds could generate electricity at 1/3 to 1/4 this initial cost. If the pilot experiment is successful, a solar pond of ~1/4 the area of the entire Sea is envisioned, located at the shallow southern end (Black 1981; WESTEC Services 1981). No solar pond has yet been constructed.

**Manure energy.**—Feed lots in the Imperial and Coachella Valleys accommodate ~450,000 cattle (*Bos taurus*), primarily in the winter as cattle have a difficult time during intense summer heat. A single cow can drop 680 kg manure·yr<sup>-1</sup>, a total of ~31 million kg·yr<sup>-1</sup> for the Salton Trough. Cattle manure is a significant source of phytoplankton nutrients in the New and Alamo Rivers and thus of the Salton Sea. Beginning in 1988 Phillips Cattle Company in El Centro operated a \$47 million experimental plant which burns cattle manure for electricity, offering a seemingly practical solution as to what to do with all that dung. This manure plant ground to a sticky halt in torrential rains in 1993, and the plant switched to more expensive natural gas. In 1994 the US Energy Commission denied an appeal from Phillips, which in effect prevented the manure electricity plant from starting up again unless the company repaid some \$6 to \$9 million

to Southern California Edison (*Los Angeles Times* 22 February 1992). A 26 February 1994 *Los Angeles Times* news item suggested that the manure plant might go bankrupt if forced to repay all this money in a lump sum. But what else can be done to rid the Salton Trough of so much manure which contaminates surface and groundwaters with phytoplankton nutrients and organics whose decomposition lowers  $pO_2$ , and stimulates growth of bacteria?

**Other energy proposals.**—The Salton Sea has been studied by the US Bureau of Land Management for natural gas and petroleum production using both onshore wells and offshore artificial “islands” (*Los Angeles Times* 13 March 1981; US Bureau of Land Management 1982). The Bureau, after preparing an inadequate Final Environmental Assessment and after holding a 1981 public hearing in which nearly everyone spoke in opposition (US Bureau of Land Management 1982; US Bureau of Land Management Decision Option Document 10 June 1982; Matthews 1982; Oglesby pers. obs.), authorized 57 noncompetitive leases to Chevron, but no drilling has yet taken place. The controversy over these proposed leases immediately led to the 1980 formation of the Salton Sea Fish and Wildlife Club, a group of fishers and residents who advocate preservation of the integrity of the Salton Sea ecosystem and its fine sport fishery (*Los Angeles Times* 13 March 1981).

No one state or federal agency coordinates these, and other, energy explorations and developments in and near the Salton Sea. No proposal analyses cumulative effects of these diverse energy developments. All energy developments are vulnerable to earthquake damage, particularly those involving evaporating brines stored in diked ponds. Earthquake-damaged energy facilities and broken dikes might well send toxic materials or brines into the Salton Sea. Even if dikes were not breached, earthquake-generated seiches in brine ponds might cause saline water to overtop the dikes and enter the Sea.

### **Water Politics and the Salton Sea**

“Water is the life blood of California politics,” goes a popular saying. The Salton Sea and its remarkable sport fishery have little impact on water politics in California. Fishers are for the most part lower-income families from urban southern California (in 1982, 42% were from Los Angeles County) and have limited political clout. “The Salton Sea is the resort of the ghetto,” wrote R. A. Jones in the *Los Angeles Times* (23 May 1989).

The Salton Sea itself has no priority to receive water from any source. Drainage and seepage waters that maintain the Sea are officially incidental results of other “beneficial” uses of water, governed by compacts, agreements, court decrees, and federal and state laws (US Department of the Interior and The Resources Agency of California 1969). The Imperial Irrigation District and Coachella Valley Water District, whose water goes primarily to agriculture and ultimately into the Salton Sea, and the Metropolitan Water District which pumps Colorado River water to urban and suburban communities (but little to agriculture) from San Diego to Santa Barbara and from the coast inland to San Bernardino and Riverside, are politically powerful and have a profound interest in keeping the Salton Sea as a sump for wastewater.

“During modern times, uses and control of water still inspire more vocal violence, legal controversy, editorial polemics, and political rhetoric than any other subject,” wrote Gulick (1991) about the Snake and Columbia rivers in the Pacific Northwest, but he could equally well be describing the Colorado River. He continued, “Two basic assumptions were treated as sacred: the first, that dams meant progress; the second, that irrigation rights exceeded all others.”

“Agricultural interests take the position that there was literally no aquatic habitat in these valleys prior to the advent of irrigated agriculture; that the agricultural drainage systems were developed as a necessary means of surface and subsurface drainage to maintain soil-salinity control; that it is by virtue of agricultural funding and development that the aquatic habitats exist; [and] that any aquatic or wildlife resources associated with

the drains are at most corollary benefits of the primary purpose of these drains" (Swajian 1976).

This widely held belief that aquatic and riparian ecosystems of the Salton Trough are totally artificial and so are of reduced or no biological value ignores the fact that the extensive and productive riparian forests, lagoons, sloughs, and wetlands of the broad Colorado delta in México have been totally destroyed by the final, complete diversion of Colorado River water upstream from Morelos Dam (1.6 km south of the international border), primarily for agriculture in the Salton Trough (Sykes 1926; Kniffen 1932; Leopold 1949; Fradkin 1981; *Los Angeles Times* 26 December 2000). Since completion of Morelos Dam in 1950 and diversion of water into the Canal Central to irrigate the Valle de Mexicali, the Colorado River now disappears completely within a few km downstream of the dam -- "a river no more" according to Fradkin (1981) -- only to reappear further south because of return, saline, flows from Mexican agriculture. Colorado River water now rarely reaches the Gulf of California, leading to significant ecological changes in the northern Gulf and loss of important fisheries, including the near extinction of the totoaba, the world's smallest porpoise, the vaquita (*Phocoena sinus*), and an important shrimp fishery in the northern Gulf (Hendricks 1961b; Fradkin 1981; Weatherford and Brown 1986a; Mellink and Ferreira-Bartrina 2000). There was a 95% reduction in intertidal clam density in delta mudflats since Hoover Dam was closed in 1936, from 50 clams·m<sup>-2</sup> down to 3·m<sup>-2</sup> (Kowalewski et al. 2000).

These formerly highly productive Colorado Delta wetlands supported a great abundance of resident and migratory wildlife that no longer inhabit the Delta; see Aldo Leopold's 1949 *A Sand County Almanac* for a fine description of the Delta in 1922. As deBuys (1999) and Mellink and Ferreira-Bartrina (2000) observed, even in 1922, much of the Delta was already severely degraded by US water diversions and developments in the early 20th century, and by increased siltation as a consequence of intensive trapping of the beavers (*Castor canadensis*) in the river during the 19th century. An overview of the

current status of Delta wetlands and riparian forests, and the northern Gulf of California, was given by Cohen et al. (1999) who concluded that there are still many hectares of high-quality wildlife habitat, which would be adversely affected by any further reductions in Colorado River flows. By contrast, Mellink and Ferreira-Bartrina (2000) and the *Los Angeles Times* (26 December 2000) concluded that the many changes in favor of agriculture and the loss of Colorado River water -- loss of the dense riparian forests, reduction and extinction of many native species, and introductions of alien species -- have totally altered most of the delta, except for a few relict locations. Further diversions of water from the River, for whatever reason, would only worsen these problems in México's part of the delta (*Los Angeles Times* 26 December 2000)

Even in the pre-irrigation Imperial and Coachella Valleys there were riparian habitats along the three rivers and a number of ponds and freshwater lakes, all host to water-related wildlife. Most of these aquatic systems vanished with the 1905 to 1907 overflow of the Colorado River into the Salton Trough, but others have been remade into valuable aquatic habitats, including Finney and Ramer lakes (see above).

With the destruction of the vast Colorado River Delta wetlands in México, resident and migratory wetland birds now use the ecosystems of the Salton Sea and surrounding areas. One can view the Salton Sea and its adjacent riparian areas as partial substitutes for the loss of Colorado Delta wetlands. "The Salton Sea, despite its artificial genesis, serves as de facto mitigation on a regional if not continental scale for the 92 to 99% of wetlands that have been destroyed in the region" (Ornithological Council 1998).

It was only as recently as 1982 that the Salton Sea was officially recognized as having "unique and valuable fish and wildlife resources and associated recreational values" (California Fish and Game Commission 1982). The Commission, while continuing to designate the Salton Sea primarily "as a repository for agricultural drainage water," recommended policies to:

- Preserve the biological integrity of the Salton Sea and its associated wetland



habitats.

- Protect and perpetuate the diverse fish and wildlife resources of the Salton Sea ecosystem for use and enjoyment of present and future generations.
- Prevent or alleviate those aspects of projects, developments, and activities which would or do exert adverse impacts on habitats and fish and wildlife resources of Salton Sea ecosystem.
- Urge the formation of a multi-agency task force with instructions to prepare a program designed to stabilize Salton Sea salinity and elevation permanently at concentrations which will sustain and perpetuate existing fish and wildlife resources concomitant with energy development and related projects.

The Commission did not reconcile the contradictory nature of these policies.

The Colorado River is surely the most scrutinized, most controversial, most dammed, most regulated, most negotiated, most legislated, and most litigated river in the US (Hundley 1986) -- "The River of Contention," according to former Interior Secretary Babbitt (*Los Angeles Times* 18 December 1999). According to the California doctrine of prior appropriation, the Imperial Irrigation District and the Coachella Valley Water District have prior water rights ("first in time, first in right") to Colorado River water over the Metropolitan Water District that provides domestic water to the 16 million people in urban and suburban coastal southern California. The contradictory California doctrine of riparian rights, by which owners of land adjacent to a stream must be allowed to divert all the water they can practicably use, does not apply significantly in the Imperial and Coachella Valleys. However, a June 2000 decision by the US Supreme Court allowed the Quechan Indian tribe to pursue its claim to 79,000 acre-feet of Colorado River water if it can prove it owns 6178 ha along the River at its Ft. Yuma Reservation (*Los Angeles Times* 20 June 2000). Even though the amount of water involved is low, only ~1% of the River's average flow, that value was not been factored into the allocation of River water to the states and water agencies by the 1922 Colorado

River Compact. Where will this additional water allotment come from?

Between 1961 and 1985, diversions into the Salton Trough by Imperial Valley Irrigation District and Coachella Valley Water District averaged  $\sim 3.5$  million acre-feet-yr<sup>-1</sup> (out of a total California allotment of 4.4 million acre-feet-yr<sup>-1</sup>), with another 0.3 million acre-feet taken by water districts on the California side of the lower Colorado River (Parsons Corp. 1985). Imperial Irrigation District has a “present perfected right” (meaning it must be supplied first in case of shortage) to 2.6 million acre feet-yr<sup>-1</sup> of Colorado River water, but normally takes  $\sim 3$  to 3.5 million acre-feet-yr<sup>-1</sup> (Imperial Irrigation District Public Information Office 1991a). Of this amount,  $\sim 1.3$  million acre-feet-yr<sup>-1</sup> ( $>1/3$ ) wind up in the Salton Sea (Parsons Corp. 1985).

Much of the agricultural production of the Imperial Valley consists of low-value but high water-consuming crops such as alfalfa and cotton, rather than high-value and lower water-requiring crops such as salad vegetables, citrus, tomatoes, and grapes. Even so, Imperial County agriculture was valued at  $\sim \$1.04$  billion in 1997, based primarily on cattle, alfalfa, carrots, sugar beets, lettuce, hay, wheat, cantaloupes, and broccoli (Salton Sea Authority 2000). Conversion of crops to less thirsty ones would release water for other uses and would provide more agricultural jobs since high-value crops are labor-intensive. But farmers point out that raising low-value crops allows farms to stay profitable even when prices drop, and that if everyone grew only high-value crops, prices would drop. Alfalfa, a legume, is important as a rotation crop in the Imperial Valley (Anonymous 1999). Agriculture in the  $\sim 15,321$  ha cultivated in the Coachella Valley consists primarily of such high-value crops as grapefruit, lemons, cotton, dates, grapes, peppers, watermelons, carrots, and salad vegetables -- valued at  $\sim \$332$  million in 1997 (Nordland 1978; Salton Sea Authority 2000).

Major conflicts arise during droughts over the “wastage” of agricultural water in the Imperial Valley at the same time as residents of metropolitan and suburban Los Angeles are under domestic water use restrictions. An important feature of California

water law is that failure to use an adjudicated water right for beneficial use for 5 yr can result in its loss ("use it or lose it"). Thus, a water district or utility must use all of its legal allotment or forfeit the excess over what it actually uses (Engelbert and Scheuring 1982). Many have accused the Imperial Irrigation District and the Coachella Valley Water District of wasteful practices just to seem to be using all their legal allotments (Engelbert and Scheuring 1982). This legal issue informs the controversy over proposals to market "excess" water from the Imperial Valley to San Diego, using Metropolitan water District pipelines (*Los Angeles Times* 30 January 2000). There are also many serious international problems between the US and México over Colorado River water allocation and salinity issues. It was only as recently as 1972 that México was assured not only 1.5 million acre-feet·yr<sup>-1</sup>, but that this water be of low enough salinity as to be usable for agriculture (Holbert 1975; Fradkin 1981; Hundley 1986).

"Water in a transfer process is treated as a commodity, such as oil and gas, and sold to the highest bidder -- a process that often assumes that Nature has no need for water" (Cagle 1998). A 1988 agreement between Metropolitan Water District and Imperial Irrigation District provides Metropolitan with "excess" Imperial water if Metropolitan lines 322 km of the All-American and Coachella Canals to prevent water loss by seepage, along with a number of other Metropolitan-financed projects (*Los Angeles Times* 13 November 1988; Breuer 1990). When canal lining is complete, Whitefield Creek, Salt Creek, and a number of other desert oases, springs, and seeps will surely desiccate, with loss of important aquatic and riparian habitats and water for many desert mammals, birds, amphibians, fishes, invertebrates, and plants. In addition, as much as 80% of seepage water from the Coachella Canal may now enter the Salton Sea as low salinity groundwater; its loss would worsen the problem of the Sea's increasing salinity. Seventy-seven km of the Coachella Canal in the Coachella Valley itself have been concrete lined; the 61 km between Niland and North Shore along the east side of the Salton Sea are still not lined (Layton and Ermak 1976; Pryde 1999; Coachella Valley Water District

2000).

Recent proposals by some Imperial Valley farmers to sell “unneeded” irrigation water to Metropolitan Water District and San Diego County Water Authority have created a storm of controversy within the Valley. One proposal by Imperial Irrigation District calls for Metropolitan to compensate Imperial Valley farmers who voluntarily fallow a portion of their land, or do not water alfalfa for 75 d during the summer; this proposal might provide Metropolitan with as much as 100,000 acre-feet annually (*Los Angeles Times* 5 April 1999).

Coachella Valley Water District asserts that Imperial Irrigation District is taking more than its legal share of Colorado River water, which is complicating and delaying negotiations on the other issues (*Los Angeles Times* 6 September 1998, 5 April 1999).

A “truce” between the Metropolitan Water District, Imperial Irrigation District, and Coachella Valley Water District, mediated by California Governor Davis and the US Department of Interior, was announced in August 1999. The three water agencies agreed to accept less water than they contended they are legally allotted, pay more for infrastructure than they contended they should, and promised not to file legal complaints against their rivals (*Los Angeles Times* 16 October 1999). The agreement permits sale and export of up to 200,000 acre-feet of water-yr<sup>-1</sup> to San Diego County Water Authority, delivered through the Colorado River Aqueduct owned by Metropolitan (see *Los Angeles Times* 30 January 2000 for a critical analysis of this specific transfer). Salton Trough farmers will use the money to increase irrigation efficiency and install additional water conservation procedures.

If the six other Colorado River basin states agree, Department of Interior will seek to operate Hoover Dam to the increased benefit of California’s water agencies, to accommodate a predicted 37% increase in water demand over the next 20 yr. There is increasing opposition from several states, especially Nevada and Arizona, which do not want to draw down either Lake Powell (behind Glen Canyon Dam) or Lake Mead (behind

Hoover Dam) (*Los Angeles Times* November 1999) to help California. Under this agreement, California will gradually scale back its take of Colorado River water from its current 5.5 million acre-feet to its allotted 4.4 million acre-feet in 15 yr (*Los Angeles Times* 14 December 2000). Pomento (1998) wrote that this agreement would exempt the irrigation agencies as well as Metropolitan from liability for any damages to the Salton Sea that would arise from a reclamation plan or any other actions that would reduce inflow, including increased water conservation or export out of the Salton Trough to San Diego. With this agreement, it is unlikely that México will ever receive any “excess” water, thus degrading the delta’s remaining wetlands even further (*Los Angeles Times* 26 December 2000). Commented the *Los Angeles Times* (5 August 1999), “What makes water disputes so intractable is the tendency of all parties to believe that they have been aggrieved by history and generally misunderstood.”

At the same time, the International Boundary and Water Commission signed an agreement to authorize a \$3 million study of the feasibility of building a joint aqueduct to bring Colorado River water to San Diego in California and Tijuana and Rosarito in Baja California (*Los Angeles Times* 17 October 1999).

Any of these proposals would reduce the amount of water entering the Salton Sea (Parsons Corp. 1985), but rarely has anyone involved seemed to be concerned about the biology of the Salton Sea or maintaining its sport fishery. At the present time, ~1.3 million acre-feet are discharged into the Salton Sea annually, roughly matching annual evaporation. If all proposed water conservation and transfers are effected, this total will be reduced by as much as 775,000 acre-feet, reducing annual input to the Sea by well over one half (Horvitz 2000). Water conservation and transfers by Imperial Irrigation District would lead to several adverse effects on the Salton Sea, listed in a 1986 environmental impact report (California Regional Water Quality Control Board, Colorado River Basin 1991):

- Decrease in use by terrestrial biota of Salton Sea aquatic and riparian habitats.

- Accelerated loss of biota, including sports fish, in the Salton Sea.
- Accelerated loss in the recreational value of the Salton Sea.
- Accelerated loss in resort and property values near the Salton Sea.

A few important people have paid attention. On 6 October 1997, the late Rep. George Brown (D-Colton CA), long-time Chair of the House Committee on Science, worried in a *Los Angeles Times* op-ed piece that if the major competitors for lower Colorado River water developed an agreement coupling both water conservation and water transfer, they would surely destroy the biology of the Salton Sea. Brown wrote: "If MWD [Metropolitan Water District] carries the day, it would reinforce its monopoly over wholesale water use in the region, provide a disincentive for agricultural water conservation, and, most disastrously, drive the Salton Sea ecosystem into rapid, total collapse. The Salton Sea is a beautiful oasis that must be saved. San Diego is entitled to seek more secure sources of water than MWD provides. Imperial Valley farmers should be allowed to craft a deal that rewards them for water conservation. If MWD wins this struggle, it will be a regional disaster and a national disgrace." But has anyone actually paid attention to the late Rep. Brown? The summer 1999 agreement suggests no.

### **Possible Futures for the Salton Sea**

Since at least as far back as the early 1960s, there have been dire predictions that the Salton Sea sport fishery would fail "in the next five to ten years" because of too-high salinities: "but without such measures [an evaporation pond] the Sea would become so salty that the fishery would be seriously damaged with a few years, probably some time between 1970 and 1980" (Pomeroy and Cruse 1965). Such predictions are based on the fact that while water can leave this closed, terminal, below-sea level basin by evaporation, salts can only accumulate in the remaining lake water, increasing salinity and concentrating any pollutants. There have also been many predictions as to when the Salton Sea would come into water balance, based on the ~2 m evaporation rate (invariant) and inputs from



agricultural waste water. But because agricultural inputs are so variable, dependent as they are on climate, water politics, and export and conservation measures, these predictions of surface elevation and timing have always been futile. So far, none of these predictions has come to pass.

The twin and conflicting problems of stabilizing the elevation of the Salton Sea while maintaining its salinity at a concentration that will continue to support the sport fishery have often been discussed and studied over the years. The dilemma is real and difficult to solve: allow water elevation to rise to maintain a biologically viable salinity, and shoreline structures and agricultural fields will continue to be drowned; stabilize elevation to protect the shoreline, and salinity will rapidly rise to concentrations lethal to sport fish and then other biota.

Ecologists always have difficulty in predicting future states of ecosystems in response to major or minor changes, human-caused or natural. In one important attempt to assess the effects of a major rise in Salton Sea salinity, Hurlbert's group at San Diego State University published a series of papers on Salton Sea microcosm ecology (González et al. 1998; Hart et al. 1998; Simpson and Hurlbert 1998; Simpson et al. 1998).

Microcosms composed of Salton Sea water, shoreline sediment, and biota were set up in 380 l containers and monitored for 15 mo (1991 to 1992) in San Diego CA. Additional biota from Imperial Valley aquaculture ponds were also inoculated, to simulate possible new biota arriving when Salton Sea salinities become much higher than at present (43 to 47‰). Microcosm salinities ranged from 30 to 65‰, and were maintained at desired salinities through addition of freshwater. Temperatures were those experienced on a roof in San Diego, a city famous for its salubrious climate which varies little in temperature either diurnally or seasonally; nevertheless microcosm temperatures varied from 6 to 32°C, not much different in extremes from the Salton Sea. Juvenile tilapia (*Oreochromis mossambicus*) were added to some microcosms to simulate effects of fish predation, competition, feeding, excretion, and egestion.

Simpson et al. (1998) pointed out that while many biologists and limnologists believe that physical extremes of salinity, temperature, and oxygen control the distributions of biota in saline lakes, their laboratory microcosm studies demonstrated that biological interactions (competition and predation) are often important mechanisms in structuring saline lake communities. Loss of a dominant predator or competitor, perhaps because of salinity limitations, can lead to major changes in abundances of other species.

Taken as a group, these microcosm studies indicate there will be two critical salinities when the Salton Sea ecosystem will undergo major restructuring (González et al. 1998; Hart et al. 1998; Simpson et al. 1988):

- When the salinity rises high enough (~60‰) that all the major fish species are eliminated, with a resultant increase in absolute and relative planktonic and benthic invertebrate densities, now released from predation.
- When the salinity rises so much higher (>>100‰) that the present major planktonic and benthic invertebrates are eliminated through physiological intolerance. *Artemia franciscana* will likely become the dominant zooplankter and *Ephydra riparia*, the dominant benthic animal.

These predicted changes are congruent with the distributions of biota in many existing salt lakes. One can look at other terminal saline lakes in closed basins to seek models of what might occur as the Salton Sea becomes increasingly saline; a future Salton Sea is likely to track none of these:

- California's Mono Lake was 52‰ in 1940, before it was subject to water diversion and desiccation by Los Angeles Department of Water and Power, and increased to ~95‰ at its elevational low point in 1982, when its elevation had dropped by 19 m. Because of a sweeping 1994 legal decision, Water and Power must reduce diversions and allow Mono Lake to rise to an elevation where the salinity would drop to ~70‰. Saline and alkaline (pH ~10), Mono Lake has not supported fish in

historic times. Its macroinvertebrate fauna is dominated by the brine shrimp *Artemia monica* and the brine fly *Ephydra hians* (Winkler 1977; Gaines 1981; Mono Lake Ecosystem Study Committee 1987; Hart 1996). Mono Lake is oligotrophic, fed by low-nutrient precipitation, Sierra Nevada runoff, and groundwater, not by nutrient-rich agricultural waste waters.

- Utah's Great Salt Lake (pH 8) has a variable (depending on precipitation) elevation with a salinity of ~130‰ (south arm) to ~340‰ (north arm) (Hammer 1986). Despite major differences in water chemistry, its biology is generally similar to that of Mono Lake, being dominated by brine shrimp (*Artemia franciscana*) and brine flies (*Ephydra hians* and *E. gracilis*; Herbst 1999); there are no fish (Gaines 1981). Great Salt Lake is oligotrophic, fed primarily by low-nutrient precipitation and mountain runoff, and only to a small extent by nutrient-rich agricultural waste waters.
- The Dead Sea (Israel and Jordan) has a salinity >350‰, and not only has no fish, has no multicellular plants or animals. Its biology is dominated by photosynthetic and other prokaryotes and some eukaryotic algae and protozoa (B. W. Walker et al. 1961b; Hammer 1986). The Dead Sea is oligotrophic, fed only by the increasingly diverted Jordan River, only rarely by low-nutrient precipitation and mountain runoff, and even less by agricultural waste waters; its elevation has been dropping in the past 50 yr at the rate of  $0.7 \text{ m}\cdot\text{yr}^{-1}$  (Al-Weshah 2000), and its salinity has risen concomitantly.
- The shriveled Aral Sea (former Soviet Union, now Uzbekistan) is a tragic monument to the worst of Soviet agricultural policies and practices, beginning in the 1920s, aimed at growing cotton in Central Asia. The major rivers feeding the Sea were almost completely diverted for cotton irrigation. Formerly the world's fourth largest lake, the Aral Sea has now lost 80% of its volume and exposed 34.6 million ha of former Sea bed; the shoreline in places has retreated as much as 70 km.

The prediction is that the Aral Sea will break into three separate, small salt lakes by ~2010. The desiccated Aral Sea has created a number of major human health problems from air pollution (about five toxic dust storms·yr<sup>-1</sup>, reaching as far away as Pakistan and Arctic Russia), loss of all 24 native fish species, a destroyed fishing industry, salinized and water-logged soils, and continuing decline in cotton production. Costly proposals are being made to slow or even stop further degradation, to protect human health, and to maintain at least some wetlands for wildlife, including such expensive projects as importing water 2574 km from the Ob and Irtysh Rivers in Siberia (Micklin 1988; Cagle 1998; Cohen et al. 1999; Stone 1999).

None of these saline lakes serves as a good model for any future Salton Sea.

It must be emphasized that the successive desiccations of the many iterations of Lake Cahuilla in the Salton Trough do not offer a good model for what might happen to a desiccating Salton Sea. Lake Cahuilla was an oligotrophic freshwater lake, populated by a native freshwater biota derived both from drowned springs and streams and from the Colorado River. It was a flow-through freshwater system with an outlet (often the Río Hardy) to the Gulf of California. By contrast, the Salton Sea is a hypereutrophic hypersaline lake with no outlet other than evaporation, fed only by agricultural wastewater, populated by a species-poor but population-rich quasi-marine biota introduced from all over the world.

In January 2001, the US Supreme Court greatly restricted wetlands protection under the 1972 US Clean Water Act (Solid Waste Agency of Northern Cook County vs. Corps of Engineers). The court concluded that the Act covered only those waters that are navigable or connected to a navigable waterway, thus denying federal protection to any landlocked body of water, likely including the Salton Sea, Mono Lake, the Great Salt Lake, vernal pools in California, prairie potholes (vital puddle duck nesting sites), and other terminal lakes in closed basins, no matter how important to resident and migratory

wildlife -- perhaps 20% of remaining inland water bodies in the US. The decision overturned the migratory bird rule under which the US Army Corps of Engineers prevented landowners from filling or polluting wetlands (*Los Angeles Times* 10 January 2001).

### **“Restoration” of the Salton Sea**

Since at least the 1960s, proposals to “restore” or “save” the Salton Sea have been put forward. The most recent of these was presented in January 2000 by the Salton Sea Authority (see below), but it is only the latest of many. All such proposals, including the most recent, suffer from major, perhaps even fatal, defects, including lack of a vision as to what state the Salton Sea would be “restored” to (e.g., Friend 1999; Salton Sea Authority 2000), crucial gaps in scientific knowledge of how the Salton Sea ecosystem works, similarly crucial gaps in knowledge of which problems are most affecting the Salton Sea adversely, and a narrow focus on salinity *per se* rather than on other parameters that may currently be affecting the Salton Sea ecosystem adversely. Research and restoration agendas are driven more by politics and agriculture than by science. Four decades of proposals have foundered on their great cost and lack of funding, even though economic analyses of maintaining an ecologically viable Salton Sea show that there will major net benefits to communities of the Salton Trough. For example, Bazdarich (1998a,b), deliberately ignoring the economic benefits of the sport fishery, hunting, and birding, calculated a benefit of nearly \$5 billion for “improving” Salton Sea conditions to a “state conducive to widespread economic development,” and another \$3.3 to 5.7 billion in benefits from “preventing further pollution,” as he seemed to think the Sea is polluted (it isn’t: see above). Components of these “restoration” proposals fall into several general categories:

1. **Diked evaporation ponds within the Salton Sea (salt harvesting).**\_\_The most popular proposal is to remove salts from the Salton Sea by way of a diked

evaporation pond built within the Salton Sea, occupying as much as  $\frac{1}{2}$  the present area of the Sea (see Fig. 7 for one proposed version). This impoundment would evaporate Salton Sea water and collect salts, preventing them, plus any contaminants, from returning to the Sea. Any diked impoundment would reduce the area and volume of the Salton Sea. Since a pond would displace a portion of the Sea, the elevation of remainder of the Sea could be maintained closer to target elevation (Salton Sea Authority 2000). Three of the five alternatives presented by the Salton Sea Authority (2000) involved evaporation ponds, differing in their locations and numbers, and whether they also involved the Enhanced Evaporation System approach (see below). Proposed sizes of impoundments have ranged from 8% to 50% of the surface area of the Sea, and proposed locations have included all areas of the Sea. Some proposals involve building dikes as much as 20 m or more high (White and Hart 1996). Construction of dikes would greatly increase suspended sediments in the Sea, along with associated Se, trace elements, and  $H_2S$ , all probably adversely affecting the biota and perhaps public health (Salton Sea Authority 2000).

Most proposals for diked evaporation ponds place them in the gently-sloping shallow southern or northern parts of the Salton Sea, that is, in the most productive parts of the Salton Sea in terms of benthos, sport fishery, and water-related birds (Fig. 7). The Salton Sea Authority (2000) did not discuss these serious problems: “[T]he shallow water habitat that currently exists and is utilized by a number of species will change.” This is a totally inadequate analysis.

Large diked ponds in the Salton Sea could hinder water circulation and current velocities in the remaining Sea; interfere with water inflow from the rivers; cause scour or sediment deposition; change transport routes of nutrients, trace elements, and biota; and change horizontal and vertical temperature, oxygen, and salinity gradients. Models to predict such changes (Cook and Orlob 1997; Cook et al. 2000) are summarized by Salton Sea Authority (2000). In these models, the fundamental counterclockwise circulation in



the southern basin is not altered, but there are sometimes important local changes in all these parameters, including eddies at the mouths of the New and Alamo Rivers.

The problem of how to dispose of hypersaline wastes collected in evaporation ponds is major. Evaporation ponds would quickly become uninhabitable for any biota but prokaryotes. The Salton Sea Authority (2000) estimated that evaporation ponds would reach 200 to 244‰ in just 7 yr, at which point salts would begin to precipitate out. At best, these evaporation ponds might simulate natural saline playa lakes. The 1974 Feasibility Report (US Department of the Interior and The Resources Agency of California 1974a,b), recommended a 154 km<sup>2</sup> impoundment and suggested pumping evaporation pond brines outside the Salton Trough to Palen Dry Lake basin to the northeast, while pointing out that this approach would meet with public opposition.

Evaporation ponds would concentrate substances, such as Se, trace elements, and pesticides, that are known to affect bird reproduction adversely elsewhere, which did in fact happen at evaporation ponds at Kesterson, leading to abandonment and capping of the ponds. Any Salton Sea evaporation pond would have to be created in such a way that birds could not use it for feeding, nesting, or resting, to avoid developmental anomalies and reproductive failure. Ducks and other waterfowl become covered with crystalline salt and die from sodium toxicity when visiting saline playa lakes in New Mexico (Meteyer et al. 1997). Evaporation ponds in the Salton Trough might well case the same problems even if potential pollutants did not reach hazardous concentrations. Industrial brine evaporation ponds in Arizona showed elevated Se concentrations, though well below the concentration to cause acute toxicity (Tanner et al. 1999). These authors warned that zero-discharge evaporation ponds may be useful as an interim solution to brine disposal problems, but do not represent a safe, permanent solution.

If no water diversions are made, the Salton Sea Authority (2000) estimated from models that the remainder of the Salton Sea would continue to rise in elevation, overtopping dikes in ~25 yr. On the other hand, if the Sea were allowed to drop in

volume and elevation, existing inflows from agricultural wastes would lower the salinity, according to supporters of this approach. But allowing Sea elevation to drop would expose many km<sup>2</sup> of salt and mud flats as a “bathtub ring” around the Sea. There would be downcutting of unlined rivers, canals, drains, and washes in both the Imperial and Coachella Valleys, dewatering wetlands and riparian areas. Between the exposed salt flats and the stark dikes in the Salton Sea, any evaporation pond is likely to have a significantly adverse visual impact, as would the Displacement, Pupfish Pond, and North Wetland Habitat dikes (see below). The Salton Sea Authority (2000) proposed to paint the dikes beige to mitigate these adverse visual effects.

Discussions of the diked evaporation pond approach have not indicated whether it could be combined in any way with the diked solar pond proposal for electricity generation (WESTEC Services Inc. 1981).

Any diked evaporation pond would be susceptible to earthquake damage, breaching dikes and releasing hypersaline water into the remaining Salton Sea. It is hard to imagine any dike withstanding lateral or vertical offsets up to 5 to 6 m, as occurred during the 1941 Imperial and 1892 Laguna Salada earthquakes. Salton Sea Authority (2000) discussed the possibility of earthquake-breached dikes, but did not adequately address how to prevent or alleviate the nearly certain adverse consequences of brine spills through breached dikes. In addition, earthquakes might generate seiches in the ponds, causing water to overtop the dikes even if the dikes themselves did not fail.

The 1974 Feasibility Report’s (US Department of the Interior and The Resources Agency of California 1974a,b) overall conclusion was that only a diked evaporation pond approach was remotely feasible for stabilizing the Salton Sea at 35‰ while also stabilizing its elevation.

Estimates of \$300-500 million have recently been made to “preserve” the Salton Sea and its sport fishery using the diked evaporation pond approach, with \$1.25 to 2.5 million needed for yearly maintenance. Cohen et al. (1999) estimated that the total cost

of the diked evaporation pond approach might be as much as \$1 to 2 billion if protective measures against earthquake damage were included.

**2. Enhanced Evaporation System (salt harvesting).**—This proposal, based on showerline technology now used in Israel, involves pumping Salton Sea water out of the Sea to the adjacent desert, where the water would be misted and evaporated from high (~98 m) towers. About 150,000 acre-feet·yr<sup>-1</sup> would be removed from the Sea. Ideally, salts would precipitate in the air and be collected in catch basins below the towers and kept from returning to the Salton Sea. Catch basins would have to be large enough to collect wind-blown water and salts, an adverse effect which Salton Sea Authority (2000) discussed but did not propose adequate mitigations for. Its major mitigation would be to shut down the showerline when winds exceeded 22 to 26 km·hr<sup>-1</sup>. Furthermore, it is very likely that not all the water would be evaporated in the air, so that the catch basins would have to be constructed to catch and hold hypersaline water as well as salts. These basins must be lined to prevent brines from contaminating groundwater, canals, drains, or the Salton Sea. Problems with birds would have to be averted (see above). These hypersaline waters and desiccated salts will have to be disposed of (see above). It is estimated that ~66 km<sup>2</sup> of desert land would be needed, proposed for either the Navy's closed Salton Sea Test Base or east and north of Bombay Beach. Salton Sea Authority (2000) stated that the Bat Caves Buttes northeast of Bombay Beach and the barkhan (graceful crescent-shaped sand dunes) field just southwest of the Naval Test Base are both "expected" to be protected from construction and operation of the Enhanced Evaporation System. A showerline array in either location would have major visual impacts, due to the height of the towers and the gentle topography. The Authority (2000) proposed setting up radar surveillance to detect nocturnal bird migration and to shut down the showerlines to prevent mass mortality. Use of the Salton Sea Test Base site may increase the salinity of San Felipe Creek water through groundwater seepage; the Authority (2000) proposed lining the catchment ponds to avert this problem.

Four of the five alternatives proposed by the Salton Sea Authority (2000) involve the Enhanced Evaporation System, differing in location of the system (Salton Sea Test Base or Bombay Beach) and whether it is combined with evaporation ponds. The Authority (2000) concluded that a combined evaporation pond-Enhanced Evaporation System approach offers the greatest flexibility in managing both salinity and elevation.

A demonstration of this system was conducted in March 2000 on a very small scale, using a Turbo Mist machine towed by a tractor. One Turbo Mist can remove 22 metric tons salt·d<sup>-1</sup>, but to maintain the current salinity, 1.36 million tons of salt would have to be removed from the Sea each year (*Los Angeles Times* 2 March 2000). This showerline approach has been vigorously opposed by residents and others, and is no longer used in Israel because of problems with wind-driven saline mists on agricultural fields (San Jose CA *Mercury News* 15 February 2000; *San Diego Tribune* 6 August 2000).

**3. Pump-Out.**—Over the years, proposals have been made to pump hypersaline Salton Sea water out of the Salton Trough. Most proposals involve an exchange with lower-salinity water from another source, and so are discussed below. Pump-out options, absent any pump-in of water, can lead only to a decline in elevation of the Salton Sea. Exporting Salton Sea water to the ocean, no matter where, may lead to serious biological impacts, such as introduction to the ocean of alien species (tilapia is the one most written about) that may adversely affect coastal oceanic organisms and ecosystems. Export of hypersaline Salton Sea water to the former Colorado Delta may further degrade this already profoundly degraded wetland system, a United Nations International Biosphere Reserve. Mellink and Ferreira-Bartrina (2000) argue that the delta does not merit Biosphere Reserve status, as its biology is so very altered. The two Gulf alternative destinations (Salton Sea Authority 2000) are the Golfo de Santa Clara just downstream from the Ciénega de Santa Clara, and near San Felipe on the west side well south of the northern shoreline. The northern Gulf of California does not mix rapidly with the rest of the Gulf (Salton Sea Authority 2000). Pumping to the Pacific Ocean (either Gulf of

California or near San Diego) would require major energy expenditure, as Salton Sea water would have to be raised ~74 m just to reach ocean sea level, plus whatever pumping is needed to get over or through intervening mountains. Pumping to the Gulf will require the cooperation of México. The large aqueducts needed (diameter ~2.5 to 3 m) could be broken by earthquake ruptures, releasing Salton Sea water onto sensitive lands or waters.

Export to Palen Dry Lake basin northeast of the Salton Trough (lowest elevation 140 m above ocean sea level, ~214 m above current Salton Sea elevation) may lead to transmission of pathogens such as avian cholera and avian botulism, plus high concentrations of toxic substances, affecting bird reproduction just as at Kesterson. About 250,000 acre-feet-yr<sup>-1</sup> would be exported. At its maximum, the new Palen Lake would be ~328 km<sup>2</sup> in area, nearly 50% the size of the present Salton Sea. Because of its elevation, significant energy would be required to pump Salton Sea water to Palen Dry Lake, and a dam (~5 to 7 m high) would have to be built to prevent water from spilling over into adjacent desert basins. Earthquakes may cause dam failure or break aqueducts. In effect, pumping Salton Sea water to Palen Dry Lake would create a second, smaller Salton Sea, complete with all the problems that the present Salton Sea supposedly has.

Some have proposed pumping Salton Sea water into the Laguna Salada in México, an alternative that would involve much less energy, but which would create not only the same problems as pumping to Palen Dry Lake but would create the risk of overflowing into the Gulf of California since the Laguna Salada is supposedly occasionally filled by extremely high tides in the Gulf (Residencia General de Cerro Prieto 1998); it already receives Mexican irrigation wastewater. México would have to agree.

Screening any pipeline intake from the Salton Sea is proposed by Salton Sea Authority (2000) to guard against introductions into receiving waters, but since this approach is rarely adequate elsewhere (small fish and other biota readily get through most aqueduct screens), it is unlikely to work any better here.

#### 4. **Pump-In.**—Under most scenarios (evaporation ponds, Enhanced Evaporation

System, water conservation, water transfers), the elevation of the Salton Sea will decline over the next several decades, declining below target elevations. Simulations show that with reduced inflows it will be impossible to control both elevation and salinity without a new source of lower-salinity water (Salton Sea Authority 2000).

Since the Salton Sea, at ~43 to 47‰, is only ~23 to 34% saltier than the ocean (35‰), exchanging ocean seawater for Salton Sea water would dilute the Salton Sea only slowly. The Salton Sea Authority (2000) stated that to exchange sufficient water to bring the Sea's salinity back down to 40‰ would require moving 1.1 million acre-feet-yr<sup>-1</sup> of water each direction, and much more should water conservation in the Imperial Valley reduce the Sea's present 1.3 million acre-feet-yr<sup>-1</sup> inflow. Another alternative is to use reclaimed, treated domestic waste water from the secondary Point Loma Wastewater Treatment Plant in San Diego, with a salinity of ~1.75‰, and perhaps a capacity as high as 266,000 acre-feet-yr<sup>-1</sup>. An 85 km pipeline, ~3 m in diameter, would be used to reach the mountains of eastern San Diego County, where the water would enter a 34 km tunnel under the mountains, followed by a 53 km gravity pipeline to the Salton Sea. Further wastewater treatment would be required before this reclaimed water could be discharged into the Sea. A variation of this approach would be to use municipal wastewater generated by San Bernardino or other San Bernardino or Riverside County cities. The Salton Sea Authority (2000) rejected both these wastewater alternatives.

Several pump-out scenarios would result in Sea elevation declines of as much as 3 to 5 m, which might re-create a land connection to Mullet Island, which has been an island for ~50 yr and which is a major nesting site for colonial waterbirds such as California brown pelicans and double-crested cormorants. A land connection would permit access by such land-based predators as coyotes, kit foxes, striped skunks, raccoons, and feral dogs and cats. The Authority (2000) suggested surrounding Mullet Island with a dike, preventing land predator access. But a dike would not prevent access by land predators; surely the Authority meant a moat.



Aside from the concomitant increased salinity, any elevation drop will expose a “bathtub ring” of salt flats around the entire perimeter of the Sea, widest at the shallow southern and northern ends, leading to potentially serious air pollution (dust, other particulates, pesticides, Se, and trace metals). An elevation drop of 3 m would expose ~9142 ha, all susceptible to wind erosion and wind-mobilizing of sediments of potential harm to human health and crops downwind in the Imperial Valley. Federal and state standards for particulate air pollution are already frequently exceeded in the Salton Trough (Salton Sea Authority 2000). An increase of  $10 \mu\text{g}\cdot\text{m}^{-3}$  in daily coarse particulates ( $>10 \mu\text{m}$  diameter: PM10) -- now common in the Coachella Valley -- was associated with an increase of ~1% in human mortality (Ostro et al. 1999).

Particulate air pollution became a major problem afflicting the Owens Valley east of the Sierra Nevada after Los Angeles Department of Water and Power dewatered Owens Lake in the early 20th century. Water and Power has been legally required by the Clean Air Act, US Environmental Protection Agency, and Great Basin Unified Air Pollution Control District to alleviate particulate air pollution in the Owens Valley (273,000 metric tons $\cdot\text{yr}^{-1}$ : *Los Angeles Times* 18 August 1999; Cohen et al. 1999). Water and Power must assure that the Mono Lake basin to the north also meets particulate air quality criteria, in this case by allowing the lake elevation to rise through reduced water diversions to a level that submerges major alkali flats (Hart 1996). Mitigation measures for both lakes will be expensive (\$100 million for Owens Lake alone) and will involve use of considerable water (up to 40,000 acre-feet $\cdot\text{yr}^{-1}$  to rewater Owens Lake) that would otherwise go to Los Angeles, costing Los Angeles additional hundreds of millions of dollars in both lost water and hydroelectric energy (*Los Angeles Times* 18 August 1999).

The Salton Sea Authority (2000) regarded the potential for increased problems from degraded air quality and human health by wind-blown exposed sediments and precipitated salt deposits to be “less than significant,” due to rapid revegetation of these exposed lands, as happened between 1907 and 1925, but pointed out that Clean Air Act

criteria must be conformed to and permits must be obtained from both Imperial County Air Pollution Control District and South Coast Air Quality Management District.

The major way for any “harvesting salt” project to be successful would be to increase input of fresher water into the remainder of the Salton Sea, either from the Colorado River or from other sources. The Colorado River is famously over-allocated (Weatherford and Brown 1986a; Reisner 1993; deBuys 1999), and is not a viable source for additional water to assist the Salton Sea. General Manager Mulroy of the Southern Nevada Water Authority is paraphrased as saying, “any attempt to use Colorado River water to save the troubled Salton Sea will kill any chances for consensus” of the seven states of the Colorado River Users Association (*Los Angeles Times* 18 December 1999). Salton Sea Authority Director Kirk announced in August 2000 that the Authority had dropped any proposals to use additional Colorado River water to dilute the Salton Sea, “in response to political considerations” (*Los Angeles Times* 2 August 2000), that is, strong opposition from California and Arizona agricultural interests who want all Colorado River water for themselves and environmentalists who do not want any further degradation of the Colorado Delta in México (*San Francisco Chronicle* 6 August 2000). Director Kirk was quoted as being optimistic about finding other sources of water; however, alternative water sources have not been identified, let alone developed.

The as-yet unbuilt Central Arizona Salinity Interceptor would take  $\sim 304,800$  acre-feet-yr<sup>-1</sup> waste irrigation water ( $\sim 4.4$  to 5 ‰, seven times lower than the Sea’s target salinity) from the Phoenix and Tucson areas by gravity to Yuma, but which by treaty with México cannot be discharged into the Colorado River. It is still unknown how concentrated Central Arizona Salinity Interceptor water would be in potentially toxic substances such as pesticides, Se, and trace metals, as well as nutrient concentrations. Since the Interceptor and associated water treatment plant are now only being “considered” by Phoenix and Tucson, the ability to use Interceptor water to assist the Salton Sea would at best be 25 yr in the future. The water would arrive by canal at Yuma,

enter a new, lined canal constructed mostly parallel to the All-American Canal, and then use the Alamo River for conveyance to the Salton Sea, taking advantage of the wide upper river bed created by the 1905 to 1907 flood. The many critics say, among other things, that this proposal is “designed to feed the Bureau of Reclamation’s appetite for large-scale engineering projects.” Michael Cohen of the Pacific Institute was quoted, “The Bureau knows only how to build monuments to human engineering, not how to sustain an ecosystem” (San Jose CA *Mercury News* 15 February 2000).

Using either Central Arizona Salinity Interceptor or “excess” flood flows, thus diverting water that would have gone into the Colorado River, the remaining and degraded Colorado River Delta wetlands would be degraded even further, especially the Río Hardy wetlands and the Ciénega de Santa Clara. Existing treaty obligations do not require the US to release any “excess” flood flows to México (Salton Sea Authority 2000).

deBuys (1999), based on conversations with longtime director of the Imperial Irrigation District Cox, proposed a novel low-salinity water source for the Salton Sea. Pointing out that now  $\sim 1/3$  of the water used in irrigation in the Imperial Valley drains to the Salton Sea, Cox and deBuys suggested that  $1/4$  of any “excess” Colorado River water exported from the Salton Trough be retained and run into the Salton Sea, just as it is now. Thus, if San Diego County Water District were to obtain rights to 200,000 acre feet-yr<sup>-1</sup>, it would actually receive only 150,000 acre-feet, while 50,000 acre-feet would be directed to the Salton Sea. This proposal seems not to have yet been vetted in public fora, and would surely be opposed by any recipient water agency.

**5. Pump-In - Pump-Out.**\_\_Merely pumping low salinity water into or pumping hypersaline saline water out of the Salton Sea is unlikely to be adequate in maintaining both elevation and a viable ecosystem. Rather, most proposals combine Pump-In and Pump-Out -- an exchange of high for lower salinity water, for example, exchanging hypersaline Salton Sea water with ocean seawater from the Gulf of California or from the Pacific Ocean near San Diego. This approach would require the active participation of

México, huge volumes of water, immense aqueducts, a tremendous amount of energy to pump water both directions, and the severe risk of destroying the Salton Sea ecosystem and sport fishery through contamination by Gulf or ocean biota.

The 1974 Feasibility Report (US Department of the Interior and The Resources Agency of California 1974a,b) discussed three approaches to pumping hypersaline Salton Sea water out of the Trough combined with import of ocean seawater to stabilize elevation and salinity, concluding, "This plan was found to be infeasible," even without addressing any adverse biological impacts to the Salton Sea of ocean water exchange.

One variant of Pump -In Pump-Out is to dredge a deep water ocean seaport at Mexicali ("Port Mexicali") as part of the water exchange system: build a pipeline from the Gulf of California to pump ocean seawater into the Laguna Salada, from which water would flow by gravity to the Salton Sea, generating hydroelectricity. Using this power (and more), water would then be pumped from the Salton Sea ~30 m uphill to Mexicali, where a deep-water harbor would be dug; a sea level ship canal would lead from "Port Mexicali" back to the Gulf. A variation on this proposal puts the seaport in the Laguna Salada (White and Hart 1996). Quite aside from all the other probable problems (see above), how would the "Port Mexicali" proposal function with the 10-13 m tides in the northern Gulf, not mentioned by the proposers?

Exchanging water between the Salton Sea and the Gulf of California is an approach that has generated a number of impossible, even ludicrous, proposals. As one example, according to the Palm Springs *Desert Sun* (10 January 2000), Metcalf and Eddy, an engineering firm in Wakefield MA, proposed a \$3.3 billion project to build two parallel ocean sea level canals between Sea and Gulf to within 1.6 km of the Sea, ending in "a system of locks" to "drop the water -- and pleasure boats and small barges -- down to the Salton Sea, a [70 m] drop." If these canals were truly at ocean sea level in the Imperial Valley, they would have to be supported by something like a trestle, ultimately ~70 m high at the shoreline and strong enough to support both water and barge traffic. Metcalf

and Eddy apparently ignored the problem of those 10-13 m tides in the Gulf and presumptive catastrophic collapse of the strange but productive Salton Sea ecosystem from biotic contamination from the Gulf. The Pacific Institute's Michael Cohen was quoted, "I think that, once we stopped laughing, we'd oppose it" (*Desert Sun* 10 January 2000).

The Gulf alternative (including the "Port Mexicali" version) would initially cost more than the diked evaporation pond proposal, but supposedly would have greater long-term benefits. But unless difficult and expensive measures are taken to prevent colonization (contamination) of the unusual but highly productive Salton Sea ecosystem with Gulf biota -- unlikely to be successful -- major biological problems will occur, surely including the rapid collapse of the present sport fishery through inadvertent introductions of new species of marine fish and other marine biota. Mere screens over the intakes will not suffice.

**5. Desalinate Salton Sea water (salt harvesting)**\_\_At first glance, removing salt from the Salton Sea and returning the water to it as freshwater seems a promising alternative. The 1974 Feasibility Report (US Department of the Interior and The Resources Agency of California 1974) discussed utilization of a desalinization plant and concluded that it was "prohibitively costly." In 1974 they could not yet discuss using the federal desalinization plant south of Yuma (Fig. 6), finished in 1992, required as part of a 1973 compact between the US and México (Minute 242 of the International Boundary and Water Commission). After lying idle for several years, the Yuma Desalting Plant has now been put into operation, with no consideration of the effects of its effluents on downstream ecology in the Colorado Delta, particularly the Ciénega de Santa Clara (Glenn et al. 1992; Mellink and Ferreira-Bartrina 2000). An official of the Colorado River Commission was quoted, "We could have bought up the Wellton-Mohawk Project [in Arizona] and retired the whole thing for a lot less than [the desalinization plant] is going to cost, but politically, of course, it is not feasible" (Sheridan 1981). This proposal

would be by far the most expensive, both in terms of construction of the desalinization plants and the energy to remove salts from the water.

**6. The “Do Nothing” Alternative.**—Of course, one could do nothing at all, letting the future of the Salton Sea (volume, elevation, salinity, biota, ecology, sport fishery, birds) continue to be at the mercy of policies of irrigation districts. There is no question that waste agricultural inflows (now  $\sim 1.3$  million acre-feet $\cdot$ yr $^{-1}$ ) will decline significantly, perhaps to as low as  $\sim 800,000$  acre-feet $\cdot$ yr $^{-1}$ , both because of enforced water conservation and because of marketing water outside the basin. With a drop in elevation, there will be a rapid rise in the salinity of the Sea, and consequent loss of the sport fishery and then other current biota.

See Cohen et al. (1999) for a description of one scenario to turn the Salton Sea into a *Artemia-Ephydra*, fishless salt lake, a scenario that might well not be followed. Should the Sea become fishless, the sport fishery will of course have collapsed, and the Sea would be of only limited value to the present avifauna of the Salton Trough.

While models and simulations have been developed and used for small subsets of these approaches (Salton Sea Authority 2000) no comprehensive model has been developed or used to cover all the major water issues in the Colorado River basin as a whole. Such models exist (T. Hand per. comm.) and are being used for watershed analyses both in this country (Chesapeake Bay, Mississippi River) and abroad. Hand has developed a model for the Mekong River system in Asia, which involves seven countries, major dams, agricultural and other water diversions, and Tonlé Sap -- a seasonally variable salt lake in Cambodia with conflicting demands for fish production and agriculture not unlike the Salton Sea. Without such comprehensive models, planning for the Colorado River and the Salton Sea can only be deficient.

California's Water Quality Control Board made the first study of problems facing the Salton Sea and preliminary plans to control salinity rise (Pomeroy and Cruse 1965). The 1965 Pomeroy Report startled many by predicting that without salinity control



measures, the Salton Sea's popular sport fishery would soon collapse, "probably some time between 1970 and 1980." The 1965 Pomeroy Report urged early action and recommended further study (Pomeroy and Cruse 1965; US Department of the Interior and The Resources Agency of California 1969, 1974a,b).

As a direct result of Pomeroy Report recommendations, a late 1960s task force made the first diked evaporation pond proposal (Calhoun 1969; US Department of the Interior and The Resources Agency of California 1969). In 1971, a report was issued by The Aerospace Corporation on behalf of the US Air Force, presenting engineering studies of a wide range of possible solutions; this report recommended further study. The 1969 Reconnaissance Study was followed up in 1974 by a more detailed Feasibility Report and Environmental Impact Report by the same agencies (US Department of the Interior and The Resources Agency of California 1974a,b). Both reports concluded that a diked evaporation pond was the best way to stabilize both salinity (at concentrations to maintain the sport fishery) and elevation. The calculated benefit-cost ratio was 4:1, very favorable. In neither case was any action taken.

There was a flurry of political activity about the Salton Sea in the early 1970s because then-Rep. Veysey (R-Palm Springs CA) was concerned. A \$200,000 study of the salinity problem and possible solutions was authorized by Congress (*Los Angeles Times* 29 April 1973). But Rep. Veysey was gerrymandered out of the Coachella Valley by redistricting and then lost his next election bid to Congress. The 1970 study resulted in no action, despite the fact that it made a strong case for the biological viability of the Salton Sea and described relatively inexpensive solutions for maintaining the sport fishery.

A Salton Sea Task Force was formed in 1988, composed of representatives from federal, state, county, and local agencies, all appointed by the California Resources Agency. The Task Force concluded that the diked evaporation pond approach was the best. The Task Force was dissolved in 1993 in favor of the Salton Sea Authority, formed

under the Joint Powers Authority by the California legislature (Cohen et al. 1999). The Salton Sea Authority has the power to tax and spend funds and to enter into binding contracts. Its board includes members from Coachella Valley Water District, Imperial Water District, Riverside and Imperial Counties, and US Bureau of Reclamation (Salton Sea Authority 2000). No scientists or others knowledgeable about the ecology of the Salton Sea are on the Board, although there is a Science Subcommittee. No representatives from México are formally involved. The legal mandate for the Authority focuses on continued agriculture in the region and recreational and economic development, not ecological restoration, thus excluding a significant public interest and many possible alternatives (Cohen et al. 1999).

From its beginning, Salton Sea Authority discussed, evaluated, and rejected most of 68 proposals to “restore” the Salton Sea, eventually settling on several “salt harvesting” alternatives. Screening criteria included: (1) stabilize the Sea’s elevation at ~76.1 m; (2) reduce the Sea’s salinity to 40‰; and (3) use only proven technology (Cohen et al. 1999). These narrow criteria excluded wildlife and ecosystem values. Among the rejected proposals were those which would reduce nutrient loading and alleviate other potential water quality problems. Even though there have already been demonstration projects to reduce Se input and to improve agricultural drainwater quality prior to discharge to the Sea, these were not incorporated into Phase I of the Restoration Plan (Cohen et al. 1999; Salton Sea Authority 2000). The Authority and its discussions were not much noticed until the late 1990s.

Beginning in 1998 there was again some stirring of political interest at both state and national levels to protect the Salton Sea sport fishery by finding some feasible way both to control rising salinity and elevations. The 1996 bird and 1999 fish die-offs were headline news in major southern California newspapers and on television. In August 1997 a multi-agency workshop was held in Palm Springs to discuss ways to develop and evaluate programs to address problems with elevation, water quality, and salinity, with

the existing Salton Sea Authority as lead agency.

Then-Rep. Sonny Bono (R-Palm Springs CA) was taking a leadership role on this issue in Congress, the major source of potential funding. According to deBuys (1999), Rep. Bono wanted the Sea to become a “premier destination resort and residence opportunity” with floating island marinas, intense shoreline development, major economic opportunities for residents and Indian tribes, and a first-class resort.

Remarkably, Rep. Bono’s death in a skiing accident in January 1998 changed the political dynamic in Congress. A week after Rep. Bono’s funeral in January 1999, then-House Speaker Gingrich (R-GA) toured the Sea and announced a multiyear plan to reduce the Sea’s salinity and amount of inflowing pollutants. “Our goals should be to have the Salton Sea have the most fish, the most birds, and the most viable economy it can possibly have,” said Gingrich in announcing the Salton Sea-Sonny Bono Restoration Project. His three-part plan included (1) using money already allocated to build a New River treatment facility in cooperation with state and federal agencies; (2) developing a complex of marshes along the New River to filter and clean its water; and (3) committing Congress to decide which of two methods to use first to stabilize and then reduce the Sea’s salinity, either (3a) the diked evaporation pond approach, or (3b) making a direct connection to the Gulf of California to pump Salton Sea water into the Gulf in exchange for normal salinity Gulf water to refill the Sea; all these proposals are described above. Gingrich said that the economic impact of a “restored” Salton Sea would be from \$6 to 10 billion as a sports fishery and recreation area, with an annual benefit of \$270 to 360 million, so that the cost of saving and maintaining the Sea would be small compared to the benefits.

In October 1998 Congress passed the Salton Sea Restoration Act but appropriated only \$5 million for yet another study of the Salton Sea ecosystem, geochemistry, problems, and possible solutions, due on 1 January 2000; Congress appropriated another \$13.1 million to the Environmental Protection Agency to assist the

Authority (deBuys 1999; Kaiser 1999; Salton Sea Authority 2000). This act also renamed the federal wildlife refuge after Rep. Bono.

The Congressionally mandated goals of the Salton Sea Authority were:

1. Maintain the Sea as a repository for agricultural drainage. The Authority's Environmental Impact Report (2000) pointed out that the Salton Sea would not exist in the absence of agricultural drainage from the Coachella and Imperial Valleys and Valle de Mexicali.
2. Provide a safe, productive environment at the Sea for resident and migratory birds and endangered species.
3. Restore recreational uses at the Sea.
4. Maintain a viable sport fishery at the Sea.
5. Enhance the Sea to provide economic development opportunities.

These official goals significantly constrain possibilities for maintaining the unique ecosystem of the Salton Sea, since maintaining agricultural drainage is the most important goal. While preserving the ecological integrity of the Salton Sea may be implicit in Goals 2 and 4, it is not explicit. Goals 3 and 5 have nothing directly to do with the ecology of the Salton Sea. As a consequence of these narrow goals, proposals by the Authority do not address some of the most important issues concerning the Salton Sea. A summary of the Authority's plan is given by Cohn (2000), but with little critique. A much more balanced and analytical critique of the Authority's plan was published by Nijhuis in the *Paonia CO High Country News* (19 June 2000, <<http://www.hcn.org/>>).

In January 2000, the Authority unveiled its proposal for Phase I of the Salton Sea Restoration Project, presenting five alternatives combining just two methods to control Salton Sea salinity and elevation: diked evaporation ponds and enhanced evaporative systems (Salton Sea Authority 2000). The design life of all Phase I Alternatives was ~30 yr, with longer-term utility during Phase II. Costs were projected to be great: using "excess" Colorado River flood waters alone would cost \$10 million. Building diked

evaporation ponds would cost \$400-465 million. The showerline approach would cost \$300-425 million. A pipeline to the Gulf would cost \$470 million, and one to San Diego from \$1.2 to 2.8 billion, because of the cost of getting across the mountains (Cohn 2000). In a 28-page analysis of the Authority's Draft Environmental Impact Report, the US Environmental Protection Agency was harsh: the Draft was "inadequate" in a number of ways. The EPA believed "there is no assurance the project will meet its objectives, even after a significant expenditure of resources." The Authority's report failed to detail water-quality standards, did not evaluate how reaching certain goals would adversely affect other restoration plans, and handled data on inflows inconsistently. The Environmental Protection Agency wanted a much more broadly defined project to assure sustaining a viable ecosystem in the Sea (Palm Springs *Desert Sun* 17 May 2000).

Key findings of the Science Subcommittee, most "unexpected" (why?) were (Salton Sea Authority 2000):

1. The Salton Sea is alive and vibrant in terms of biological complexity rather than nearly dead.
2. Fish populations, thought to be seriously depressed, are actually abundant; in fact, the Salton Sea may be the most productive fishery in the world.
3. Pesticides, presumed to be a major problem, are not; most pesticide concentrations in the sediments and waters of the Sea were found to be at or below detection concentrations of the analytical methods used.
4. Though algal toxins have long been thought to be a major cause of fish and bird mortality at the Sea, investigation failed to reveal any evidence of toxins causing either fish or bird kills.

The Authority (2000) proposed a set of six "Common Actions" which could be conducted with any of its five alternatives:

1. Harvest "excess" tilapia to reduce phosphorous concentrations and thus reduce eutrophication. As discussed above, there is no valid evidence that such an approach

would either work or be beneficial; the proposal is based on unsupported assumptions and inadequate scientific information.

2. Improve recreational facilities by improving boat access.
3. Clean up the shoreline and the Sea surface of dying and dead fish, which would be incinerated, particularly from locations accessible to the recreational public.
4. Initiate an Integrated Wildlife Disease Program to minimize losses from fish and avian pathogens through early detection, diagnosis, and appropriate action. The proposed program would be operated by the National Wildlife Health Center of the US Geological Survey, US Fish and Wildlife Service, Salton Sea Authority, and California Department of Fish and Game.
5. Initiate a Long-Term Management Strategy, including long-term operation and maintenance, scientific investigations of the ecology of the Salton Sea ecosystem, and long-term monitoring.
6. Initiate a Strategic Science Plan, a comprehensive life-of-the-project effort of restoration managers to prepare solutions for future changes, based on on-site ecological studies, modeling, and simulations (see Appendix B in Salton Sea Authority 2000).

In addition the Authority proposed several additional features which would “enhance” any of the five alternatives:

1. Construct a Pupfish Pond, ~1 m deep. This pond was proposed for the shoreline along the southwestern Salton Sea, inshore from the southeastern evaporation pond, to permit in-Sea movement of desert pupfish between San Felipe creek and drains from the Imperial Valley. The Pupfish Pond would contain snag habitat for colonial-nesting tree birds such as cormorants, herons, and egrets, though there are few snags there now. Water would be pumped into the Pupfish Pond from the New River. It was not made clear by the Authority (2000) why the proposed Pupfish Pond is needed, or needs to have a lower salinity than the present or future Salton Sea, since desert pupfish are



strongly euryhaline. Desert pupfish are endangered not because of increasing salinity, but because of competition and predation by such introduced animals as tilapia, sailfin mollies, mosquitofish, and bullfrogs. To enhance desert pupfish populations, control and removal of these aliens will be required. Dunham and Minckley 1998) wrote, "The fish needs little more than water to survive as long as non-native species are excluded." The Authority (2000) was not concerned about alien animals and their effects on desert pupfish. The Authority (2000) lists a number of ecological drawbacks -- some of them severe -- to the Pupfish Pond, but does not discuss any mitigations.

2. Develop a North Wetland Habitat, ~1 m deep. Justification, design, and concerns for this managed North Wetland Habitat are about the same as for the Pupfish Pond, though the North Wetland Habitat would not be managed specifically for desert pupfish, and water conditions might differ considerably from those in the Pupfish Pond, as water quality would be dominated by inflow from the Whitewater River. The North Wetland Habitat would protect snags for cormorant and heron nesting and maintain several islets to be used by ground nesting colonial waterbirds such as terns and skimmers. The Authority (2000) listed a few ecological drawbacks to a managed, diked North Wetland Habitat, but did not address any mitigations. The Authority wrote that the North Wetland Habitat should be used for trials of new technology.
3. Construct a Displacement Dike between the mouths of the New and Alamo Rivers, seawards of the Sonny Bono National Wildlife Refuge to reduce area, volume, and salinity while maintaining the elevation of the Salton Sea (Salton Sea Authority 2000). Simulations showed that the Displacement Dike would change circulation in the southern Sea basin, causing eddies at the mouths of the New and Alamo Rivers. Salinity would be lower at the mouths of the two rivers than in the Sea itself, which may have reflections on the distribution, abundance, and diversity of the biota. When there is standing water within the Displacement Dike, it is likely to be of poor quality. Being adjacent to the federal wildlife refuge, the Displacement Pond will attract birds,

which are unlikely to thrive in it. The Authority (2000) did not address these issues at all.

4. Augment present inflows to the Salton Sea by using a portion of the total “excess” flood flows available from the Colorado River, defined as the quantity of water that is delivered to México above the amount the US is obligated to deliver under the 1944 treaty ( $1.5 \text{ million acre-feet-yr}^{-1}$ ). This water represents “excess” water that is released from, or passed through, storage and conveyance facilities (dams and reservoirs) in the US. As defined, “excess” water, proposed to be made available to the Salton Sea, has been delivered to México in 14 yr since 1950. The amount of flood flows available in the future can only be speculative, but the Authority (2000) presented predictions based on probability models. Not surprisingly, models showed that there may a number of years in a row with no available flood flows, and that flood flow years may be clustered together -- overall averaging one flood every 3 to 5 yr. The Colorado River is a very variable river, even with its many dams, reservoirs, and diversions.

These flood flows would be delivered to the Salton Sea by the Alamo River, Salt Creek, and Detention Channel #1 (also known as Coachella Evacuation Channel and Cleveland Street Spillway) at the north end of the Sea. The capacity of the Alamo River channel might be exceeded by these flood flows, but the Authority (2000) does not discuss how to prevent or alleviate this problem. The Authority commented that scouring of the river bed might occur, with concomitant removal of plant and animal communities. Salt Creek might lose its wild population of desert pupfish, a possibility not mentioned by the Authority (2000), as well as becoming both colder and siltier. The Authority (2000) erroneously stated “Detention Channel #1 is dry the majority of the time and does not support aquatic resources;” the Authority therefore did not discuss any adverse effects of using this channel for flood flows. In fact, the lower part of the Cleveland Street Spillway has a constant flow of agricultural wastewater from just

above the highway 86 and transcontinental railroad bridges; it supports a diverse population of plants, invertebrates, and fish, including desert pupfish (see many Tables; Oglesby pers. obs.). The Authority does not address the undoubted deleterious impacts on Delta wetlands of diverting even more water away from the Colorado River.

Phase II of the Salton Sea Restoration Project would involve one or more of the following: (1) expand the Enhanced Evaporation System; (2) export Salton Sea water out of the Salton Trough to the Gulf of California, to the Pacific Ocean near San Diego, or to Palen Dry Lake bed, and (3) import Central Arizona Salinity Interceptor water from Arizona through Yuma to the Salton Sea. The design life of all Phase II Alternatives would be ~100 yr (Salton Sea Authority 2000).

Because any Phase II actions would not take place for some 30 yr after Phase I is completed, they were not analyzed in detail in the Authority's 2000 Environmental Impact Report. Many potential impacts on the Salton Sea ecosystem and on the ecosystems of receiving waters were ignored.

At the third Salton Sea Symposium in January 2000, the Authority unveiled its final report together with a draft Environmental Impact Report. There was a refreshing change in attitude about the Sea's condition: "contrary to its putrid smell and off-putting look, the sea is not hopelessly polluted and is actually robustly healthy in many ways." Milton Friend, lead federal scientist on the project was quoted: "What in some instances has been accepted dogma is now being revealed to be largely myth. Innuendo is now being challenged by data. The fish population is actually booming, pesticide concentrations in the water and sediment are minimal, and there is no evidence of bacteria in the sea that can harm humans." As discussed above, all these positive conclusions were well documented prior to the Authority's 2000 report.

The Authority's five alternatives have been actively opposed by many residents of the Salton Trough, San Diego, and elsewhere. Many worry that restoring the Salton

Sea will require additional freshwater that is needed elsewhere; using any additional Colorado River is now impossible. Residents especially oppose the Enhanced Evaporation System because of its visual impacts and are concerned that none of the alternatives would maintain the sport fishery or provide opportunities for enhanced recreation and economic growth. Many objections are based on lack of knowledge of the ecosystem of the Salton Sea and of lack of understanding of the Authority's proposals -- some of the criticism and alternative proposals are remarkable for their lack of any factual foundation; several are totally infeasible on just engineering grounds. Some people are opposed to spending any additional money on the Salton Sea. These concerns are vetted especially through several World Wide Web sites devoted to the Salton Sea.

As discussions continue about the January 2000 report of the Salton Sea Authority, virtually all attention has been paid only to dealing with the twin problems of maintaining an ecologically viable salinity and preventing further rise of the Salton Sea. A few others, rarely listened to, pointed out that other problems may, at least in the short run, be more important. Superintendent Horvitz of the Salton Sea State Recreation Area believes that excessive nutrient input must be controlled immediately to reduce eutrophication and hypoxia, though he believes that increasing salinity is also very important (Horvitz 2000).

A highly critical study was published by the Pacific Institute for Studies in Development, Environment, and Security, before the Authority issued its January 2000 report. The Pacific Institute strongly criticized the direction the Authority was taking (Cohen et al. 1999). Its major conclusion was that the current approach is seriously flawed for the following four interconnected reasons:

1. The current strategy of the Authority's Restoration Project neither reflects nor satisfies the public interest. The public interest is the preservation and restoration of the Salton Sea ecosystem, but there is no evidence that the Restoration Project, focused only on salinity and elevation stabilization, will improve the ecosystem.

2. Decisions are being driven by arbitrary and unrealistic political timelines, not by scientific evidence. The Salton Sea Restoration Act of 1998 and the Authority's January 2000 proposals do not draw upon scientific evidence and information. Detailed research on the current ecology of the Salton Sea has only recently been begun, *after* the Authority chose its five alternatives. Much of the research discussed in the present review was not mentioned by the Authority.
3. The major problems may not be directly related to salinity, which is the focus of the current plan. The major crisis facing the Salton Sea at present, if there is a crisis, is the increased number of fish and bird die-offs, which most scientists do not see as being directly related to salinity. Rather, they see extreme eutrophication, high nutrient concentrations, and perhaps contaminants as proximal problems.
4. The focus on salinity distracts from other anthropogenic factors in the basin that are more directly linked to the ecological problems of the Salton Sea. The Authority's narrow focus excludes recognition and evaluation of the Sea's complex agricultural-ecological system, where natural factors (climate, elevation) and anthropogenic factors (land use) impact the Sea.

Cohen et al. (1999) presented the following principles for sustainability and equity:

1. The primary goal of any restoration plan must be to provide for a healthy ecological system and protect human health.
2. Any restoration plan should be firmly grounded in a scientific understanding of the ecology of the Salton Sea and related systems.
3. Any restoration plan should address all the water quality factors responsible for the current problems at the Salton Sea.
4. Parties responsible for the current problems facing the Salton Sea and beneficiaries of its restoration should bear an equitable share of the costs.
5. Any restoration plan must be compatible with region-wide water conservation and

voluntary reallocation programs.

6. Any restoration plan for the Salton Sea must be compatible with protection and restoration of the Colorado River delta, northern Gulf of California, and other related ecosystems in the region.
7. The Restoration Project must be transparent, inclusive, and fully integrated with other actions impacting the Salton Sea.

Cohen et al. (1999) made a number of recommendations to improve the “restoration” process. Few of these were even hinted at in the January 2000 documents released by the Authority (2000), which thus remain seriously flawed in its approach and conclusions.

### **Conclusions**

The future of the Salton Sea as a viable, if strange, ecosystem with a splendid sport fishery and vital importance to migratory birds of the Pacific Flyway remains problematical. Current proposals may do little to protect this ecosystem.

The last word belongs to Jim Matthews of the Ontario *CA Inland Valley Daily Bulletin* 8 July 1999): “Rumors of the Salton Sea’s death are greatly exaggerated. This fishery is thriving and healthy. It ranks as perhaps the single most productive fishery in California.”

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