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The Future of the Salton Sea as a Stable Salt Lake
Draft Position Statement, October, 1998

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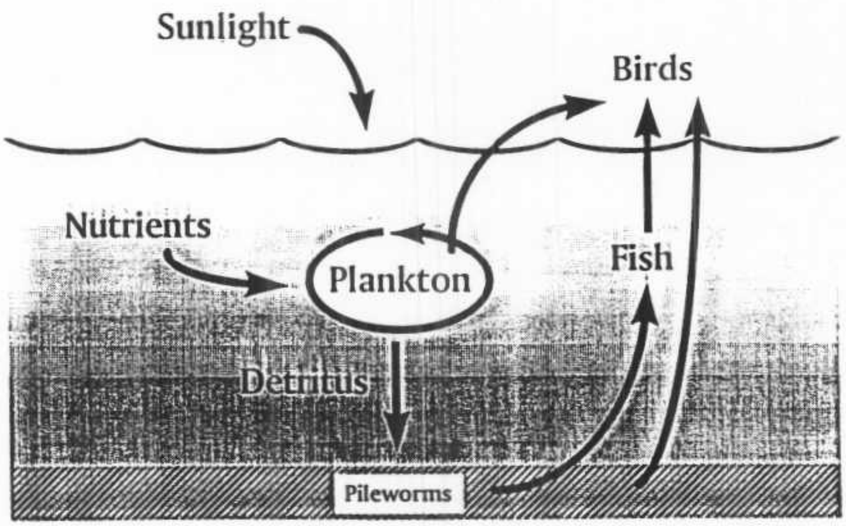
The Salton Sea is a southern extension of the Great Basin system of inland salt lakes, which includes the Great Salt Lake, Mono Lake, and dozens of smaller water bodies and playas. These are remnants of larger fresh water lakes that covered much of the southwestern United States 15 million years ago. Lacking outlets to the sea, they became saline or alkaline as they evaporated over time. They can fluctuate widely in volume and salinity due to variations in rates of precipitation and evaporation in their watersheds, yet they tend to be biologically stable. Many are colonized by a few native, salt-tolerant organisms that can withstand the swings in salinity, temperature and other stress factors that characterize a shallow, terminal lake in a desert environment. The Great Salt Lake and Mono Lake have high primary productivity due to blooms of single-celled algae and photosynthetic bacteria which support brine shrimp (*Atremia spp.*) and brine flies (*Ephydra spp.*), upon which millions of waterfowl and shorebirds feed (Figure 1). The key to their ability to support large numbers of birds is their lack of fish, which would consume the invertebrates that are now harvested directly by the birds.

By contrast to natural salt lakes, the Salton Sea, since filling, has developed an unstable biology, dominated by a few introduced invertebrate and fish species that are increasingly challenged by the rising salinity, extremes of heat and cold, and anoxic bottom conditions in this manmade ecosystem. An initiative to "save the Salton Sea" is now underway, in which it is proposed to halt the salinity increase by pumping in ocean water or diking the lake. We argue instead that the best way to develop a sustainable ecosystem (one capable of receiving agricultural drain water indefinitely) might be to allow the Salton Sea to evolve in the direction of the natural salt lakes in the region. As salinity increases, we believe that the biological hazards associated with the present ecosystem will diminish, as exotic species are replaced by better adapted, halotolerant species forming more stable food chains. This scenario is compatible with the goal of achieving more efficient use of Colorado River water; as water use efficiency increases in the watershed, the amount of drainage into the Sea will decrease and the salinity increase will inevitably accelerate.

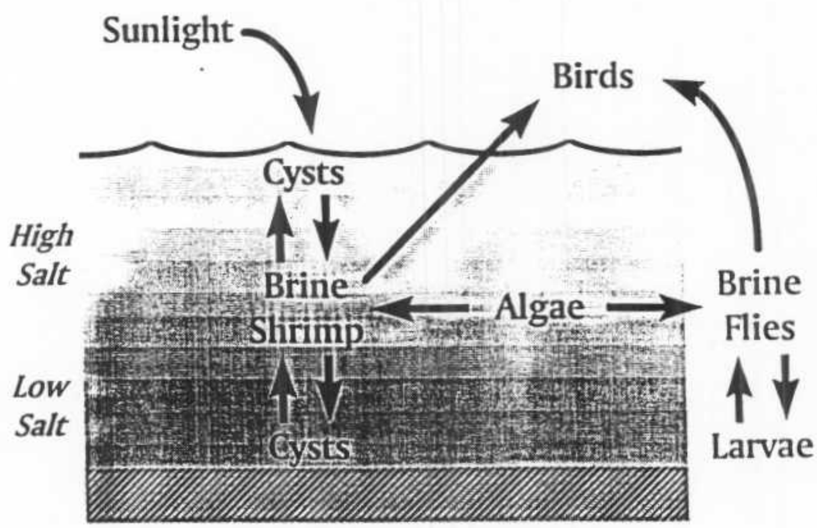
The following sections outline the biological hazards of the Salton Sea in its present state, describe how a less hazardous biology may develop as salinity increases, and discuss some of the management needs for the Salton Sea in its transition to a hypersaline water body.

The Food Chain in the Salton Sea. In less than 100 years the Salton Sea has



Salton Sea Food Chain

Figure 1. Simplified food chain relations at the Salton Sea (from Setmire et al., 1993). Sunlight and nutrients drive the planktonic food chain. Due to lack of planktivorous fish, most primary productivity is recycled in the detrital food chain. Pileworms, amphipods and bacteria decompose the detritus. Pileworms, which accumulate selenium from the sediments, are at the base of the food chain leading to fish and birds in which selenium undergoes biomagnification.



Salt Lake Food Chain

Figure 2. Simplified food chain relationships for the Great Salt Lake, Mono Lake or other salt lakes. Planktivorous algae and cyanobacteria are grazed by brine shrimp and brine flies which are food for birds. Brine shrimp cysts float in water >60 ppt and sink in less saline water. Brine fly larvae are bottom feeders but most primary productivity is recycled in the planktonic food chain where selenium accumulation is not a problem.

changed from a fresh water lake to a pseudo-marine ecosystem dominated by a handful of deliberately introduced species. The ecology of the Sea has been described in several reports and publications and the following account is simplified to illustrate the problematic aspects (Figure 2). Just two diatoms (*Nitzchia* and *Cyclotella spp.*) account for most of the primary productivity in the lake. Their activity is augmented by near-shore, winter blooms of two dinoflagellates (*Glenodinium* and *Exuviaella*), and by the growth of a narrow fringe of attached, filamentous and tubular green algae (e.g. *Enteromorpha*) along the shoreline. This low algal diversity contrasts with the hundreds of algal species in the nearest true marine ecosystem, the upper Gulf of California. The diatom blooms are intense due to enrichment from agricultural runoff and sewage effluent entering the lake. Most of the year the photic zone is only 1 meter deep; below this not enough light penetrates to support photosynthesis and the water column becomes seasonally anoxic.

Within the photic zone, diatoms are consumed mainly by two zooplankton, a rotifer (*Brachionus plicatilis*) and a copepod (*Apocyclops dengizicus*) which are most active in summer, augmented by the larvae of pile worms and barnacles which are released in spring and autumn. There are no planktivorous fish to harvest the plankton, so as they die most of them sink to the bottom of the lake and enter the detrital food chain. Pileworms (*Nereis succinea*) in the bottom sediments, along with bacteria and amphipods, recycle the detritus. Pileworms were introduced into the Salton Sea in 1930 and, with their high fat and protein contents, are at the base of the food chain leading to fish and fish-eating birds. They are eaten by four species of forage fish in the lake: bairdiella or croaker (*Bairdiella icistia*), tilapia (*Tilapia mossambica*), longjaw mudsucker (*Gillichthys mirabilis*) and sargo (*Anisotremus davidsoni*), which are eaten in turn by orangemouth corvina (*Cynoscion xanthulus*), introduced in the 1950's as a sport fish. *T. mossambica* is now by far the most numerous fish in the Salton Sea. Tilapia and the other species are prey for a large number of fish-eating birds including black terns, herring gulls, snowy egrets, great blue herons, brown pelicans, white pelicans, osprey and double-crested coromonts. Other birds feed directly on copepods, rotifers and algae in the planktonic community or on attached algae along the shore. These include black necked stilts, ruddy ducks, lesser scaups, eared grebes, marbled godwits, American avocets and western sandpipers.

Wildlife Hazards Posed by the Existing Food Chain. Two biological hazards have been linked to the pileworm-fish-bird food chain. The first is potential selenium toxicity. Water in the Salton Sea contains low levels of selenium which can biomagnify in the food chain to levels hazardous to wildlife. A detailed study concluded that the most hazardous selenium food-chain pathway in the Salton Sea begins with accumulation of selenium by pileworms followed by uptake by fish feeding on pileworms and then by fish-eating birds. In a 1988-1990 study, pileworms were the only invertebrates that exceeded the critical concentration of 5 ug/g for food chain organisms. Their high selenium content was attributed to the high levels of selenium in the sediments in which they live, over 3,000 times higher than in the water column. Fish feeding on pileworms had whole-body selenium contents that exceeded the critical level of 12 ug/g for reproduction of sensitive species. It would be expected that birds feeding on the fish would have even higher levels. In fact, it was found that 40% of the bird species evaluated in the Imperial Valley surrounding the Salton Sea exceeded the 30 ug/g threshold associated with high biological risk, with the highest levels found in species utilizing the Salton Sea as a feeding station.

The second hazard related to the pileworm-fish-bird food chain is bird kills due to infectious diseases spread by fish or bottom sediments. One type of bird kill that affects fish-eating birds in the Salton Sea is avian botulism (which is rare among fish-eating birds elsewhere). The botulism virus is present in bottom sediments and is picked up by Tilapia feeding on bottom organisms. Tilapia are also susceptible to infection by *Vibrio* bacteria, a common disease organism in marine fish. *Vibrio* infection weakens and eventually kills Tilapia and it also creates anaerobic conditions in their guts, which allows the avian botulism virus to multiply. Starting in 1996, late summer Tilapia die-offs numbering over 100,000 fish attracted thousands of bird-eating fish which then contracted avian botulism. The fish die-offs are caused by a combination of stress conditions including *Vibrio* infection and low oxygen content due to high water temperatures and summer winds which mixes anoxic bottom water into the water column. The bird kills have affected over 8,500 white pelicans, 1,200 brown pelicans and 4,000 other fish-eating birds.

Not all the biological hazards of the Salton Sea are related to the pileworm-fish-bird food chain. Organopesticides are accumulating mainly in birds feeding in freshwater ecosystems (drains and canals) leading into the lake, whereas boron accumulates in birds such as ducks that feed directly on benthic invertebrates. In 1997 most of the lake's population of double-crested coromonts died from Newcastle Disease (an infectious virus). Another type of bird die-off has occurred in non-fish-eating birds, starting in 1992 when 150,000 eared grebes died mysteriously in the Salton Sea. Although the cause of death remains unknown, similar but smaller grebe die-offs have occurred elsewhere on the Pacific flyway, so these deaths may not be related directly to conditions in the Salton Sea. Nevertheless, the high annual bird mortality since 1992 is responsible for the perception that the Salton Sea has become dangerous to wildlife and that something must be done to repair its aquatic ecosystem.

<u>Increasing salinity will diminish pileworm and fish populations</u>. The proposals to save the Salton Sea call for stabilizing or reducing the lake's salinity, based on the supposition that the biological hazards will worsen if salinity increases. The salinity is now in the range of 43-45 ppt (the northern Gulf of California is 36 ppt), and it is increasing at a rate of about 0.5 ppt per year. However, there is no evidence that the current problems are directly related to salinity. To the contrary, we believe that rising salinity may actually reduce the biological hazards in the Salton Sea by reducing the reproductive fitness of pileworms, amphipods and fish that accumulate selenium and attract fish-eating birds.

Adult pileworms, for example, survive well up to 68 ppt, but eggs and larvae are sensitive to 45-50 ppt. *T. mossambica* adults also survives well beyond 60 ppt, but reproduction is optimal at 10 ppt, slows above 30 ppt, and may not be effective above 49 ppt. The other fish species in the Salton Sea have difficulty reproducing above 40 ppt and are already in decline. Adults of Salton Sea copepods survived above 90 ppt, but their reproduction was seriously impaired at 68 ppt. The amphipod, *Gammarus mucronatus*, had reduced reproduction above 39 ppt. Thus, the Salton Sea is approaching salinity levels at which the population size of the main faunal species will be reduced by impaired reproduction. On the other hand, there is no evidence that increasing salinities are contributing directly to the mass die-offs of fish, since *Tilapia* adults are resistant to salinities well above the present Salton Sea salinity (*T. mossambica* and its hybrids are commercially cultivated on seawater).

Loss of fish from the Salton Sea does not necessarily mean there will be a net loss of fish-eating birds from the lower Colorado River ecosystem. The fish-eating birds that presently use the Salton Sea can be expected to move into the nearby Colorado River delta habitats in Mexico as the fish populations in the Salton Sea decline. The delta habitats have been partially reestablished by flood releases and agricultural drainage from the United States over the last two decades. Corvina stocks are presently at record levels.

As pileworms disappear from the Salton Sea, the link between selenium in the detritus and biomagnification to higher trophic levels will be broken. Therefore, the loss of pileworm-fish food chain from the Salton Sea can be viewed as the elimination of an attractive nuisance which has been responsible for killing tens of thousands of birds in the last decade, rather than as a loss of valuable habitat.

<u>Likely Changes in the Salton Sea Ecosystem with Increasing Salinity</u>. If agricultural inputs diminish and are not replaced by ocean water, the water level in the Salton Sea will decrease. One consequence is likely to be an increase in the areas of marsh habitat where the Alamo River, New River and Whitewater River enter the lake. When the Salton Sea National Wildlife Refuge was established in 1930, it contained over 10,000 ha of marshes, formed at the points of entry of agricultural drain water into the Salton Sea. Currently only 800 ha of marshes remain due to rising lake levels. However, a contraction in lake volume will also expose many square kilometers of bare shoreline that may need to be artificially vegetated to prevent blowing dust. Plantings of native halophytes or halophyte agricultural plantings irrigated with drain water, are possible methods for introducing shoreline vegetation. Although salinity will continue to increase indefinitely, the volume of the Salton Sea will stabilize at a new size at which evaporation from the exposed surface area matches inputs. As long as agricultural drainage flows, the Salton Sea will remain an aquatic habitat.

The present food chain organisms will most likely be replaced by the algae-brine shrimp-brine fly community, or a variation of this food chain. These organisms are not just found in Mono Lake and the Great Salt Lake, they occur in natural and manmade salt lakes around the world. They are stable over a very wide range of salinities and salt mixtures. For example, the salinity of Mono Lake ranged from 42-99 ppt from 1913-1998, and it is composed of a highly alkaline mix of sulfate, carbonate and chloride salts, yet the basic diatom-brine shrimp-brine fly food chain has been preserved in the lake. Productivity of the food chain decreased at higher salinities, and water inputs are now regulated so that a salinity no higher than 69.3 ppt will be achieved within 20 years (the present salinity is 80.8 ppt). Salinity in the Great Salt Lake, composed mainly of sodium chloride, has varied even more widely, from 55 ppt in the south part of the lake during record floods in 1983-1987, to over 180 ppt in the north part due to construction of a railroad causeway across the lake in 1957 that reduced water exchange between north and south. The basic food chain has persisted, although the commercial brine shrimp harvest was negatively affected at the lowest and highest salinities.

The present diatom species, particularly *Nitzchia*, are likely to remain dominant in the Salton Sea well beyond 60 ppt. At higher salinities, single celled cyanobacteria and the single-celled halotolerant algae, *Dunaliella*, can be expected to become prominent. When fish disappear, brine shrimp (*Artemia* spp.) can be expected to thrive and the detrital food chain will diminish in importance. A small, commercial brine shrimp industry based on pond culture has already been established using Salton Sea water near Salton City. Brine shrimp are slow-swimming, filter-feeding crustaceans which graze planktonic algae from the water column. Brine shrimp in turn are easily harvested from the water column by waterfowl and aquatic insects such as water boatmen (*Corixidae*). Hence, most of the primary production is recycled within the planktonic food chain or removed by birds. The planktonic food chain is not reported to accumulate selenium or other elements to harmful levels, hence unlike the Salton Sea, the Great Salt Lake and Mono Lake are not regarded as selenium hazards at present, even though vast quantities of selenium and other elements accumulate in their bottom sediments. The benthic habitat in these lakes is occupied by larval stages of brine flies which graze on algae and detritus and by the cysts of brine shrimp which may sink to the bottom of the lakes when salinities are below approximately 60 ppt. Brine flies are harvested by birds when they hatch out along the shoreline.

Both Mono Lake and the Great Salt Lake are highly productive and valuable lakes for birds. Mono Lake provides critical habitat for nesting California gulls and snowy plovers, and migrating Wilson's phalaropes, red-necked phalaropes and eared grebes (which number up to a million). The Great Salt Lake supports millions of breeding and migrating shorebirds and waterfowl, including 17,000 breeding adult white pelicans. Though the lakes are fishless, fish are found in their tributaries and adjacent marshlands. In addition to supporting birds, brine shrimp in the Great Salt Lake produce vast quantities of floating cysts which are harvested for the aquaculture industry around the world; this industry is worth as much as $200 million per year, depending on the size of the harvest. The basic, ecological similarity among salt lakes despite differences in salt composition and climate, argues that the Salton Sea will also develop into a stable salt lake.

The speed of ecosystem turnover will be determined by the rate of water input, which is within human control. The natural evaporation loss of water from the Salton Sea is 1.5 m/yr, or 18% of the average depth. Without water inputs, the lake would go dry in under 10 years. However, present water inputs roughly match evaporation so salinity only increases by the amount of salts present in the incoming water, or 1%/yr. If these inputs are maintained, the Salton Sea will reach 50 ppt within 10 years, at which salinity reproduction of fish and pileworms should be impaired and the ecosystem should be in transition. The point at which brine shrimp will become important in lake is unknown, and requires study. Certainly they will not thrive as long as forage fish are present. If a more rapid conversion to a fishless ecosystem is desired due to continued bird kills, a portion of the drain water that now enters the Salton Sea could be diverted to the Colorado River delta, where it could be managed to enrich bird habitat in marine zone. If the volume of input water was reduced by 25% (Mexico's contribution to the Salton Sea), the salinity could reach 60 ppt within ten years. Just as at the Great Salt Lake and Mono Lake, the brackish ecosystems will persist as refugia at points where water enters the lake.

Management, Monitoring and Research Needs. Allowing the Salton Sea to become hypersaline has been labelled the "do nothing" scenario, but this is a mischaracterization. As mentioned, a reduction in agricultural drain inputs will reduce lake size and expose areas of shoreline which will need immediate management attention. Further, the rate of salinity increase can be managed by controlling the volume of drain water entering the lake, and research is required to determine whether a fast or slow transition is best. In either case, intensive monitoring of the aquatic ecosystem will be needed during the transition period to a fishless water body. If fish kills continue, methods to reduce their hazard to wildlife and humans will be needed.

The fate of fish-eating birds using the Salton Sea will need to be determined. Replacement habitat may be needed in the upper Gulf of California, which will require binational cooperation. Co-management and monitoring of bird populations between U.S. agencies and the management team of the Biosphere Reserve of the Upper Gulf of California and Delta of the Colorado River may be desirable. Intensive water quality monitoring in both the Colorado River delta and the Salton Sea will be required to determine safety of the altered habitats for wildlife.

As the Salton Sea evolves into a true salt lake, new economic opportunities such as the harvest of brine shrimp cysts or the development of a chemical extraction industry may become feasible. This will require cleanup and monitoring of polluted input sources, such as sewage effluent from Mexicali. The Great Salt Lake, Mono Lake and even the seasonally-flooded Owens Lake all have on-going management issues and the Salton Sea will be no exception. However, we believe it will be much easier to manage the Salton Sea as an ecologically-stable salt lake than as an artificial, quasi-marine ecosystem which is not sustainable without a massive human intervention to import and export ocean water or create an elaborate dike system with unknown ecological effects.

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