Eutrophic Conditions at the Salton Sea

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EUTROPHIC CONDITIONS AT THE SALTON SEA

BACKGROUND:

LOCATION AND HISTORY OF SALTON SEA

The Salton Sea is located in the southeastern desert of California. It occupies the northern part of the Salton Trough that includes the Coachella and Imperial Valleys of California and the Mexicali Valley of Mexico. The current Salton Sea was formed during the 17 months from October 1905 to February 1907 following summer flooding and the failure of a temporary diversion of the Colorado River. During the 17 months, most of discharge of the Colorado River flowed into the Salton Trough. At the closure of the break, the Salton Sea's elevation was -195 ft Mean Sea Level (MSL) and the surface area was 520 square miles. Evaporation and lack of significant tributary inflow caused the Sea's elevation to gradually recede to a low of -250 ft MSL by 1925. From 1925 to the mid 1980's, the elevation of the Salton Sea gradually increased to its current level at about -227 ft MSL as a result of increased agricultural discharge. The current Sea occupies about 365 mi^2.

Climate is an important factor controlling many of the physical, chemical and biological processes affecting the Salton Sea. The Imperial Valley, one of the most arid areas in the United States, has an average annual rainfall of 3 in. The maximum temperature exceeds 100 ^{0}F more than 110 days per year. The average annual temperature is 74 ^{0}F. Evaporation in the Salton Sea is estimated at 5.78 ft/yr (Hely and others, 1966). At its current elevation, about 1.34 million acre-ft of water annually is lost from the Salton Sea by evaporation. This loss is balanced by tributary inflow.

Agriculture in the Coachella and Imperial Valleys is sustained by Colorado River water diverted at the Imperial Dam and delivered via the All-American and the Coachella Canals. There are 481,000 acres (1995) of irrigated farmland in the Imperial Valley where agriculture and livestock grossed one billion dollars in 1995. The New and Alamo Rivers carry agricultural discharge from the Imperial Valley to the Salton Sea. The New River also carries agricultural discharge and municipal and industrial effluent from Mexicali, Mexico. The Whitewater River carries agricultural discharges, municipal and industrial effluent, and stormwater runoff from the Coachella Valley. Agricultural discharges from the Imperial, Coachella, and Mexicali Valleys along with municipal and industrial effluent maintain the elevation of the Salton Sea.

SALTON SEA HISTORY

Visitor use at the Salton Sea was at its peak levels during the 1950's and 1960's when the number of visitor days at the Salton Sea exceeded visitor use at Yosemite National Park. The boom period at the Sea saw development of marinas, a golf course, major recreational use, and the beginnings of home construction with the paving and naming of roads. Fishing and boating were at their peak, with record numbers of corvina caught. However, as a result of the continual loading of agricultural and municipal discharges, the very high evaporation rates, and no outlet for the Sea, the salinity continued to increase and the elevation to rise. The rising water level inundated many of the new structures and the salinity threatened the fishery. As the 1960's ended, the next decade seemed to bring forebodings of the demise of the Sea. Visitor use began to taper off, the stability of the Sea's elevation was uncertain, and the effects of eutrophication became more pronounced. Each succeeding decade seemed to heighten the previous decades problems, especially as the tilapia found their way into the Sea. The 1990's brought major bird die-offs, fish kills in the millions and concern for the health of the Sea's ecosystem. With no control over the increasing salinity, the uncertainty of the elevation, massive fish and bird kills, odor problems, shores lined with the skeletons of dead fish, and incredible algal blooms, the economic future of the area was bleak and the ability of the ecosystem to support a healthy fishery for the many fish-eating birds questionable.

SALTON SEA RESTORATION

The Salton Sea Restoration Project authorized under the Salton Sea Reclamation act of 1998 (Public Law 105-372) directs the Secretary of the Interior to: "complete all studies, including, but not limited to environmental and other reviews, of the feasibility and cost-benefit of various options that permit the continued use of the Salton Sea as a reservoir for irrigation drainage and: (i) reduce and stabilize the overall salinity of the Salton Sea, (ii) stabilize the surface elevation of the Salton Sea, (iii) reclaim, in the long term, healthy fish and wildlife resources and their habitats, and (iv) enhance the potential for recreational uses and economic development of the Salton Sea."

The current project builds upon decades of previous efforts to develop a means to address the increasing salinity of the Salton Sea and stabilization of its elevation. This focus has been driven by the impacts of these factors on recreational use of the Sea and on shoreline development. Other factors such as eutrophication, which impact the current Restoration Project, have not benefited from previous focused attention. As a result there has been no foundation to build upon. Solutions to the eutrophication of the Salton Sea have been comparatively intractable and/or costly. However, to meet the goals of the restoration project, a means to decrease the eutrophic character of the Salton Sea is needed. To these ends a workshop was convened as an initial evaluation of whether or not eutrophication was a problem meriting action, and if so, could it be addressed.

MEETING

On September 7-8, 2000, a panel of ten scientists, convened at the University of California at Riverside, concluded that eutrophication adversely affects the beneficial uses of the Salton Sea. Panel members were from both academic and federal institutions, some involved in past or active research in the Salton Sea, while the remainder had backgrounds in limnology and research experience in other eutrophic systems. The first day of the meeting was an open discussion session attended by about 50 individuals with varied interests in the Salton Sea. A brief introduction to the concepts of eutrophication was followed by presentations of case studies of eutrophic systems and nutrient cycling studies at the Salton Sea. The second day was a closed session at which panel members discussed the extent of eutrophication of the Sea and examined possible solutions to improve the problem. **This paper presents the results of the discussions, and as such, is not a complete analysis of nutrient cycling in the Salton Sea. It is intended to provide a glimpse of the complex dynamics of the Sea and possible actions to reduce its eutrophication.**

EUTROPHICATION – GENERAL CONCEPTS

Eutrophication is defined as "the loading of inorganic and organic dissolved and particulate matter to lakes and reservoirs at rates sufficient to increase the potential for high biological production and to lead to a decrease in basin volume" (Cooke and others, 1993). Eutrophication is a natural process that leads to the evolution of a lake through succession of different stages, from oligotrophic (least productive) to mesotrophic (intermediate state) to eutrophic (most productive). Usually this process takes thousands of years, but in recent decades, it has been rapidly accelerated in a number of systems around the world through the effects of human activities. This accelerated eutrophication process is often termed "cultural eutrophication."

Oligotrophic
Oligotrophic lakes generally are clear with low inputs of nutrients. The aquatic community of oligotrophic lakes is characterized by low biomass and low productivity. Because of the low productivity in the system, only small population densities of rooted vegetation (macrophytes), zooplankton, benthic invertebrates, and fish are supported.

Mesotrophic
Mesotrophic lakes show increased biological productivity, supported by higher inflows of nutrients. Although occasional algal blooms can occur, losses of dissolved oxygen in the deeper water are generally not severe or of an extended duration. Fisheries in many of these systems are excellent, with relatively high abundance of several desirable species. Moderate populations of rooted macrophytes, zooplankton, and benthic invertebrates are supported.

Eutrophic
Eutrophic systems, like the Salton Sea, typically are highly turbid. Productivity and biomass are very high which can become a problem if the biomass exceeds the capacity of the system to support it. One of the most common manifestations of this excess is the development of extensive oxygen depletion (anoxic conditions), caused by decay of accumulated senescent biological material. These conditions stress the aquatic life and may cause extensive fish kills, leading to even further oxygen depletion along with unpleasant odors.

Because of the high biological and chemical oxygen demand, anoxia can develop at almost any time in the hypolimnion. The lack of oxygen is not only a major biological stressor; it also has the important chemical effect of creating reducing conditions. The reducing environment leads to many chemical changes, including the transformation of sulfates to sulfides (including hydrogen sulfide gas that has a strong odor of rotten eggs) and reduction of nitrate to ammonia, which, at high concentrations, can be toxic to fish and other biota.

Algal communities in eutrophic systems commonly include populations of blue-green algae, some species of which are likely to produce extensive nuisance blooms. Fish species are generally limited to those with a tolerance for low dissolved oxygen, and other stresses; those species may indeed thrive under these conditions, finding plenty of food to support rapid metabolism and growth. Although they are subject to population crashes when the conditions become too stressful, they usually are able to recover quickly. Systems with very high turbidity that experience frequent algal blooms and fish kills are considered hypereutrophic.

Eutrophication is principally a function of nutrient inflow, but is often associated with sediment inflow; sediments flowing into a lake carry nutrients with them and, once they become part of the bottom material, they act as a nutrient reservoir in the lake, from which nutrients can be released to the water column.

A common misconception about eutrophication is that it correlates to toxicological problems in the same water body. In fact, eutrophication is *not necessarily* associated with toxic substances in the system. In some watersheds, where the nutrient sources are also toxicant sources, increases in nutrients and toxic substances might happen simultaneously, but in others, there is no relationship whatsoever. Eutrophic systems may or may not have elevated concentrations of toxic substances, and toxic-contaminated systems may or may not be eutrophic.

Limiting nutrients
Nitrogen and phosphorus are nearly always the chemical elements that act as the primary nutrients capable of stimulating primary productivity in aquatic systems. The ratio of their concentrations (the "N:P ratio") provides an indication of when a system changes from a potential imitation by one nutrient to a potential limitation by the other. This threshold ratio is determined by the needs of the primary producers, the algae and the macrophytes. Their needs are a function of the N:P ratio within their tissues. The "Redfield ratio" (Redfield et al. 1963) – often cited as a reference value by which to judge nutrient limitation – gives a ratio of 7.2:1 as the relative abundance of nitrogen and phosphorus (by weight) in marine phytoplankton. For freshwater systems, and for other organisms, this number can fluctuate considerably, but a reasonable estimate for most systems is 10:1. If the N:P ratio in the water is much higher than 20:1, P is nearly always the potential limiting nutrient; if it is lower than 10:1, N would likely be the limiting nutrient. Between these values, either nitrogen or phosphorus can become deficient, either in fresh water or salt water (Guildford and Hecky 2000). Light also could be locally limiting, especially during periods of intense algal blooms.

SALTON SEA AND EUTROPHICATION

CHARACTERISTICS

The Salton Sea is a eutrophic to hypereutrophic water body characterized by high nutrient concentrations, high algal biomass as demonstrated by high chlorophyll *a* concentrations, high fish productivity, low clarity, frequent very low dissolved oxygen concentrations, massive fish kills, and noxious odors. Water quality of the Salton Sea is summarized in the following tables, which were constructed from data collected from July 1968 to May 1969 (U.S. Department of the Interior Federal Water Quality Administration, 1970) and during 1999 from the Salton Sea Restoration Project (C. Holdren, USBR, 2000, written communication).

Salton Sea – Nutrient concentrations at the center of the Salton Sea

* Average mean concentration of three sites (4 depths sampled during summer)

Depth	Season	Ortho-P mg/L	Total P mg/L	NH3-N mg/L	NO3/NO2-N mg/L	TKN mg/L	Total N mg/L	N:P Ratio
				1968-69				
Surface	Summer	0.04	0.06	0.22	0.11	3.0	3.1	52:1
	Fall	0.02	0.05	0.36	0.22	3.3	3.5	70:1
	Winter	0.03	0.07	0.25	0.16	1.5	1.6	23:1
	Spring	0.06	0.20	0.27	0.49	4.5	5.0	25:1
				1999				
Surface	Annual mean*	0.024	0.087	1.3	0.1	3.6	5.0	104:1
	Summer	0.013	0.067	1.6	0.1	4.1	5.8	192:1
	Fall	0.032	0.043	1.2	0.1	4.2	5.5	137:1
	Winter	0.040	0.120	1.5	0.2	2.5	4.2	24:1
	Spring	0.012	0.116	0.9	0.2	3.7	4.8	64:1
Bottom	Annual mean	0.016	0.061	1.6	0.1	3.7	5.4	213:1
	Summer	0.003	0.056	2.5	0.1	5.3	7.9	430:1
	Fall	0.015	0.027	1.4	0	4.0	5.4	288:1
	Winter	0.037	0.079	1.5	0.1	1.8	3.4	25:1
	Spring	0.011	0.083	0.9	0.1	3.7	4.7	108:1

In 1968-9, average seasonal total phosphorus concentrations near the surface in the Sea range between about 0.04 and 0.12 mg/L. For samples collected during 1999 from three sites in the Salton Sea, total phosphorus concentrations in water ranged from a low of <0.005 mg/L to a high of 0.222 mg/L with a median of 0.071 mg/L in the surface waters and a median of 0.059 mg/L in the bottom water. Concentrations are generally highest in the winter and spring and lowest in the summer and fall. Ortho phosphorus is quite variable representing 10 percent (spring) to 75 percent (fall) of the total phosphorus. Phosphorus concentrations slightly decrease with increasing depth in the Sea, indicating little net release of phosphorus from the sediments (discussed later). Phosphorus concentrations in water, although high, appear to be unchanged from the 1969 to 1999.

Total nitrogen concentrations in the Salton Sea range from about 4 to 6 mg/L (see table). Concentrations are slightly higher during the summer and fall than in the winter and spring. Organic nitrogen is the main form (about 75 percent) of nitrogen in the water column possibly reflecting the algal population and algal breakdown. Ammonia (NH_3) generally represents about 25 percent of the total nitrogen; very little nitrate was measured. By comparison, nitrate is by far the dominant form of nitrogen in the tributaries, followed by organic nitrogen. Although ammonia is present in the tributaries, especially in the New River, ammonia is the dominant redox-indicating form of nitrogen in the Sea. In the 1960's, ammonia concentrations, averaging 0.2-0.3 mg/L, were significantly lower than in 1999. This increase in ammonia (greater than one order of magnitude) is one of the most obvious changes in nutrient concentrations that have occurred in the Salton Sea. Ammonia concentrations in 1999 are higher in the bottom water, especially in summer months with seasonal averages as high as 2.8 mg/L. The presence of ammonia clearly indicates that reducing conditions are often present in the Salton Sea. It is unclear what effect these levels of ammonia have on the fish. Overall, total nitrogen concentrations appear to have increased by about 50 percent since the 1960's, primarily as a result of increasing ammonia concentrations.

Limiting nutrient

Water samples collected from the surface and bottom of the water column at three sites in the Salton Sea during 1999 had an overall mean N:P mass ratio of 185:1. Data were summarized seasonally. There was significant seasonal variation in the N:P ratio with the highest ratios (from about 200:1 to over 400:1) occurring during summer when total phosphorus was limiting, especially in the bottom water. The overall ratios show that phosphorus is by far the potential limiting nutrient in the Salton Sea. Even though the lowest nitrogen to total phosphorus ratios (23:1 to 28.7:1) during winter approach the threshold above which phosphorus would become limiting (about 25:1), the SRP:TIN ratio of 154:1 still strongly indicates potential phosphorus limitation. Winter has the greatest variability in total phosphorus concentrations, having both the maximum and minimum concentrations. Any efforts to reduce eutrophication in the Salton Sea needs to focus on phosphorus removal, especially the SRP (soluble reactive phosphorus) portion of total phosphorus.

High algal populations result in high chlorophyll *a* concentrations, a parameter often used to estimate phytoplankton biomass (Cooke and others, 1993; Wetzel, 1983). Chlorophyll *a* concentrations in the Sea are usually over 25 µg/L. Water clarity is generally fairly poor as measured by Secchi depths, which were usually less than 5 feet.

Salton Sea nutrient concentrations, chlorophyll a, and transparency

Constituent/year	**Summer**	**Autumn**	**Winter**	**Spring**
Total N (mg/L)				
1968-9	3.13	3.48	1.61	4.96
1999	4.2	4.2	2.5	3.5
Total P (mg/L)				
1968-9	0.06	0.05	0.07	0.2
1999	0.053	0.026	0.107	0.087
Chlorophyll *a* , µg/L				
1968-9	-	50.4	35.7	48.2
1999		27		
Transparency (ft)				
1968-9	3.6	4.1	3.4	3.5
1999	3.0	2.4	2.9	2.5

One method of classifying the water quality or productivity of water bodies is by computing water-quality indices (Trophic State Indices, or TSI's). These indices, based on near-surface concentrations of total phosphorus, chlorophyll *a*, and on Secchi depths, were developed by Carlson (1977). TSI's place each water-quality characteristic on the same scale. TSI's less than 40 are considered oligotrophic water bodies, between 40 and 50 are mesotrophic systems, and greater than 50 are considered eutrophic systems. Water bodies with TSI's greater than 60 are usually considered hypereutrophic.

All three indices indicate that the Salton Sea is generally eutrophic and often hypereutrophic. Chlorophyll *a* concentrations in 1968-9 give a TSI of between 60 and 70. A single sample collected during 2000 had a chlorophyll *a* concentration of 27 µg/L also would classify the Salton Sea as eutrophic. The Secchi depth in the Salton Sea for both 1968-69 and 1999 translates to a TSI of 60-70). The total phosphorus concentrations in 1968-9 translate to a TSI of between 50 in the autumn to over 80 in the spring placing the Salton Sea in the eutrophic to hypereutrophic category. In 1999, total phosphorus concentrations were variable. Calculated TSI's averaged between 50 and 70.

Nitrogen concentrations also can provide an indication of the trophic state of a water body. If the system is phosphorus limited, however, increases in nitrogen concentration will not be reflected by increases in productivity as indicated by Secchi depth or chlorophyll *a* concentration. Total nitrogen concentrations also place the Salton Sea in the eutrophic category.

Throughout much of the year, dissolved oxygen (DO) in the surface waters (epilimnion) is supersaturated during daylight hours. Dissolved oxygen, however, is nearly absent in the deep water (hypolimnion) when the water is stratified (C. Holdren, USBR, 2000, written communication). Occasionally the DO within certain areas of the Sea is absent from the top of the water column to the bottom. These episodes are usually associated with or follow algal blooms (described by others as green water) and often result in massive fish kills. The presumption is that algae in the bloom die and the subsequent aerobic bacterial breakdown depletes the available DO in the water column.

Much of the Salton Sea is a wind driven system (Cook and others, 1998), and fish kills also occur associated with wind shifts. The prevailing wind direction is from the west-northwest (Cook and others, 1998). Because the Sea is 35 miles long, wind direction and velocity at the southern end are different than those at the north or center (Cook and others, 1998). Major shifts in the direction and velocity in the southern end appear to be associated with fish kills. Strong winds from the south agitate the anaerobic sediments creating an immediate oxygen demand in an area that already has DO depleted water in the lower part of the water column. As this water is turned over and mixed with the upper water column, the entire water column of these shallow water areas is depleted of DO, killing the fish. As prevailing winds reestablish, windrows of dead fish often are found off of the New and Alamo River deltas. Although fish kills have been common at the Salton Sea for a long time, during the past decade die-offs are more numerous and many of the die-offs number several million fish. Tilapia, the most abundant fish in the Salton Sea, also is the species most often involved in kills. Other fish such as sargo and croakers also have experienced large die-offs, but none of the magnitude of those involving tilapia. The following table presents fish kills during the past year.

Date	Total Dead	Tilapia Dead	Croaker Dead	Corvina Dead
16-Jan-00	50,000	50,000	0	0
21-Jan-00	100,000	100,000	0	0
10-Feb-00	2,600,000	2,600,000	0	0
04-May-00	40,000	40,000	0	0
18-May-00	83,000	83,000	0	0
29-May-00	50,000	0	50,000	0
30-May-00	5,000	0	5,000	0
01-Jun-00	1,000	0	0	1,000
06-Jun-00	120,000	100,000	17,000	1,200
16-Jun-00	5,800	1,200	4,600	0
27-Jun-00	55,000	25,000	30,000	0
30-Jun-00	10,000	10,000	0	0
10-Jul-00	100,000	100,000	0	0
13-Jul-00	55,000	49,500	5,500	0

03-Aug-00	120,000	120,000	0	0
03-Aug-00	25,000	0	25,000	0
15-Aug-00	2,500,000	2,500,000	0	0
18-Aug-00	5,200,000	5,200,000	0	0
25-Aug-00	115,000	25,000	90,000	0
26-Sep-00	3,090,000	3,000,000	90,000	0

Source: Tahni Johnson, Salton Sea Authority; Compiled byJacquie Lesch, Digital Library Administrator, University of Redlands

The eutrophic state of the Salton Sea with its high biomass translates to high fish production, especially for forage fish such as tilapia. If the Salton Sea were less eutrophic, there likely would be fewer tilapia, fewer and different algal blooms, and fewer occasions of fish kills associated with anoxic conditions.

Another problem associated with eutrophication in the Salton Sea is the objectionable odor that is so pervasive. This odor, that directly impacts recreational use, likely results from a unique combination of factors. The massive numbers of dead and decaying fish in the water and on the shores, algal decay, hydrogen sulfide from anoxic areas within the Sea, the Sea being saltier than the ocean, geothermal plants and agriculture all contribute to the smell near the Salton Sea. A significant reduction in the eutrophic state of the Sea likely would cause a reduction in the odor and a change in its character. There would be fewer dead fish, fewer algal blooms and hopefully less anoxic sediments. The Salton Sea would still have a unique smell, but hopefully not the noxious odor of decay that currently is so unpleasant.

SOURCES OF NUTRIENT LOADING

The eutrophic condition of the Salton Sea is controlled or limited by phosphorus; therefore, we need to examine where the phosphorus in the Sea is coming from. Possible sources of phosphorus to the Sea include external loading from inflowing tributaries, ground water, precipitation, and from internal loading from the sediments.

Tributary loading

The major tributaries to the Salton Sea are the New, Alamo, and Whitewater Rivers. These rivers currently account for about 46, 32, and 6 percent of the inflow to the Salton Sea (J. Agajanian, USGS, 1998, written communication). Imperial Valley drains discharging directly to the Sea account for an 8 percent of the inflow. Tributary loading supplies the majority of nutrients to the Sea. The following table presents average historical and current phosphorus and nitrogen concentrations and loading to the Salton Sea in 1968-69 and 1999. Trends in annual loading and changes in nutrient sources can be evaluated by comparing data from 1968-9 with data from 1999.

Comparison of nutrient concentrations and loads to the Salton Sea

Site	Org.-N	NH3-N	NO2-N	NO3-N	O-P	T-P	T-N	Q, in acre-ft
Alamo River,								
1968-69, in mg/L	1.23	0.58	0.32	6.00	0.20	0.33	8.13	
load, in kgX10^6	0.966	0.454	0.249	4.72	0.176	0.258	6.39	637,700
1999, in mg/L	1.5	1.26	NM	6.42	0.408	0.719	9.2	617,130
load, in kgX10^6	1.14	0.959		4.89	0.310	0.574	7.08	
New River,								
1968-69, in mg/L	0.97	0.47	0.22	4.48	0.29	0.60	6.14	
load, in kgX10^6	0.50	0.240	0.113	2.28	0.15	0.304	3.13	413,000
1999, in mg/L	1.0	3.72	NM	3.55	0.697	1.11	8.2	488,080
load, in kgX10^6	0.482	2.24		2.14	0.50	0.660	4.96	
Whitewater River,								
1968-69, mg/L	0.83	0.16	0.06	6.28	0.26	0.58	7.33	
load, in kgX10^6	0.077	0.014	0.0045	0.59	0.024	0.054	0.686	76,300
1999, in mg/L	1.2	0.729	NM	14.3	0.710	0.865	16.3	52,983
load, in kgX10^6	0.078	0.048		0.935	0.046	0.053	1.03	

1999 loads in this table were based on mean concentrations and total annual discharge from C.Holdren, USBR, 2000 (Written Communication). 1968-69 data were from U.S. Department of the Interior Federal Water Quality Administration, 1970.
org-N = organic nitrogen, NH3-N = ammonia nitrogen, NO2-N = nitrite nitrogen, NO3-N = nitrate nitrogen, O-P = ortho phosphate, T-P= total phosphorus, Q = discharge, and NM = not measured

In the Alamo River, total phosphorus concentrations and loads increased by about 120% from 1968-9 to 1999 and ortho phosphate increased about 85%. In the New River, total phosphorus loads increased by about 80% and ortho phosphorus loads increased by 230%. The total annual phosphorus load discharged to the Salton Sea in 1968-69 by tributaries was estimated to be 0.660 $X10^6$ kg, one-half of the current load.

In the New River, ortho phosphorus comprised 75% of the total phosphorus load in 1999 compared to 50% in 1968-9. Municipal and industrial waste discharges to the New and Alamo Rivers contributed 0.179 $X10^6$ kg of ortho-phosphate to the Salton Sea in 1964 (Regional Board,1964, written communication). Mexicali's contribution was estimated to be 48 percent of this load. Insufficient data are available for the year 2000 to evaluate changes in total phosphorus and ortho phosphorus loading from municipal and industrial effluent. Advances in sewage treatment technology make comparisons between the 1960's and today less indicative of basin wide changes. Elimination of phosphorus containing detergents also has impacted phosphorus loading from treatment plants. Similar changes were observed in the Whitewater River; however, ortho phosphate has become less important in the Alamo River.

Nitrogen concentrations and loads are presented in the above table for comparison and perspective, but will not be discussed. Because the Salton Sea is phosphorus limited, control of nitrogen, given the tremendous loading, cannot possibly be reduced to a level where eutrophication of the Sea can be reversed.

Agricultural drains

Agricultural drains that discharge directly to the Sea account for about 8 percent of the inflow. If it is assumed that the total phosphorus concentration in these drains is similar to the Alamo River (0.712 mg/L; it is expected that this is a high estimate), direct drains would then supply about 91,000 kg/yr to the Sea.

Ground water and precipitation

Ground water accounts for less than 5 percent of the inflow to the Salton Sea, the majority of which comes from the Coachella Valley. Concentrations of total phosphorus in ground water are usually very low and, therefore, phosphorus loading to the Sea is expected to be insignificant. Only about 4 inches of precipitation falls on the Sea per year. Phosphorus concentrations in precipitation are also usually very low and, therefore, phosphorus loading from precipitation is also thought to be insignificant.

Internal sediment release

Chemical compounds that reach the sediments do not necessarily remain there permanently. In many lake systems, sediments function as a reservoir or temporary resting place for certain elements such as phosphorus, which can be released back into the water column with changing environmental conditions. Depletion of dissolved oxygen in the overlying water of these lakes produces a reducing environment that can result in remobilization of phosphorus from the bottom sediments. This process termed “internal loading” is calculated in mg/m^2/day. Estimates of the net internal phosphorus loading from column studies using sediments from the Salton Sea range from –5 mg/m^2/day for deep-water sediments to –10 mg/m^2/day for shallow-water sediment (C. Amrhein, UCR, 2000, written communication). These internal loading estimates indicate the potential for a tremendous negative flux, or a sink for phosphorus in the sediments at certain times of the year rather than a source of phosphorus. These, however, are instantaneous values from chambers where the input of external phosphorus is stopped and the sediment interface is oxygenated. The continuous high phosphorus loading, diffusive fluxes, and the lack of increased near-bottom phosphorus concentrations indicate that there is a significant phosphorus loss to the sediments.

Total phosphorus loading

Therefore the current total phosphorus loading to the Salton Sea is about 1.385 million kg/yr:

Alamo River*	574,000 kg/yr
New River*	660,000 kg/yr
Whitewater River*	52,000 kg/yr

Direct drains	99,000 kg/yr
Internal sediment release	*A*
Ground water precipitation	insignificant
Total	1,385,000 kg/yr

* Loads computed from monthly sampling (bimonthly during summer) using instantaneous concentrations and discharges, which were then averaged to compute annual loading (C. Holdren, USBR, 2000, written communication)
*A N*o current level available although current research indicates that it likely is a negative number

Apportioning this load over the 365 square mile surface area of the Salton Sea gives an areal loading of 4.02 mg/m^2/day.

Clearly, no matter what trophic index is applied, the Salton Sea is a eutrophic water body. What is interesting is that the eutrophic state of the Salton Sea is virtually unchanged over the past 30 plus years. Although nutrient loading has increased, it has not significantly increased the eutrophic state of the Sea. The algal species composition, salinity, and fish type and abundance all have changed since the 1960’s, but the overall eutrophic character is the same as indicated by the above characteristics.

MODELING PHOSPHORUS CONCENTRATIONS IN THE SALTON SEA

To understand the role of phosphorus in the eutrophication of the Salton Sea, it is important to determine if the present phosphorus concentrations (and resulting eutrophic conditions) in the Salton Sea is expected given the loading of phosphorus from the watershed. One way to answer this question is to compare the phosphorus loading rate and measured phosphorus concentrations in the Sea with those predicted by models developed from similar measurements made in lakes and reservoirs from around the world. Twelve of these empirical models that relate hydrologic and phosphorus loading to in-lake phosphorus concentrations are contained within the Wisconsin Lakes Modeling Suite (WiLMS; J. Panuska, Wisconsin Department of Natural Resources, written communication, 1999). When these models are applied to the current hydrologic and phosphorus loading of the Salton Sea, all but one of these models predict the phosphorus concentrations in the Sea should be much higher than that measured (the other model predicts a concentration of 0.095 mg/L, slightly higher than that measured).

Model	Predicted P (mg/L)
Walker, 1987 Reservoir	0.598
Canfield-Bachmann, 1981 Natural Lake	0.181
Canfield-Bachmann, 1981 Artificial Lake	**0.095**
Rechow, 1979 General	0.120
Rechow, 1977 Anoxic	1.133
Rechow, 1977 water load<50m/year	0.188
Walker, 1977 General	3.491
Vollenweider, 1982 Combined OECD	0.905
Dillon-Rigler-Kirchner	7.323
Vollenweider, 1982 Shallow Lake/Res.	0.950
Larsen-Mercier, 1976	2.365
Nurnberg, 1984 Oxic	5.474

PROCESSES CONTROLLING PHOSPHORUS DYNAMICS

Since modeling results indicate that phosphorus concentrations in the Sea should be higher than observed concentrations, there appears to be processes controlling phosphorus concentrations in the water column of the Salton Sea. Typically following this modeling exercise one can determine what type of loading reduction is required to result in a specified change in P concentrations in a lake (Sea). In this case, it is obvious that the Sea responds much differently than most other systems and has other factors controlling the phosphorus concentrations in the Sea.

Geochemical Precipitation

Initial geochemical modeling (C. Holdren, 2000, U.S. Bureau of Reclamation, written communication) indicates that Salton Sea water is supersaturated with respect to hydroxyapatite when phosphorus concentrations are greater than 0.005 mg/L. While formation of this mineral is kinetically hindered, it often forms on calcite nuclei and is likely to be forming in the Salton Sea. As such, precipitation of hydroxyapatite could also represent one possible sink for phosphorus. To quantify phosphorus cycling from the bottom sediments, water samples were collected from "peepers" placed at multiple depths in bottom sediments (C. Amrhein, UC Riverside, 2000, written communication). The phosphorus concentrations in pore water were about 10 times higher than that in the overlying water; therefore, a concentration gradient exists and phosphorus should diffuse into the water column whenever anoxic conditions are present at the interface. However, monitoring data does not show accumulation of phosphorus in the hypolimnion even during anoxic periods. Bottom sediments from cores collected during the summer of 2000 (C. Amrhein, UCR, 2000, written communication) are high in organic carbon in the deepest parts of the Salton Sea. In these areas of fine grain sediments, Calcite ($CaCO_3$) is 35% of the material composition, which also includes barnacles and other precipitates. There also are areas of high phosphorus in coarse material in the northern end of the Sea, which may be attributed to the accumulation of $Ca_5(PO_4)_3OH$. The median total phosphorus concentration in sediments is 672 mg/kg, which is typical of calcareous lake sediments.

In 1910, three years after the Salton Sea was formed, the composition of the water was clearly dominated by dissolution of sodium chloride salts in the Salton Trough. The ionic composition was significantly different from the Colorado River water that formed it. The ionic composition of the Salton Sea and its sources of water are shown in the table below (In the table, ion ratios are calculated on an atomic basis rather than a mass ratios because mass ratios are strongly affected by heavier ions such as sulfate and carbonate). The percent of sodium has decreased as magnesium increased, and the percent chloride has decreased as sulfate increased from 1948 to 1989. The solubility and equilibrium chemistry of sulfate, sodium, calcium and magnesium likely have controlled their concentrations as the salinity increased. Based on the solubility of sulfate, gypsum should be found in the bottom sediments (Hely and others, 1966). X-ray diffraction analysis and dissolution studies of bottom sediment samples collected in 2000 indicate the presence of an amorphous precipitate containing Na, Ca, SO_4, and possibly CO_3. The formation of this precipitate in the sediments of the

Salton Sea could account for the apparent loss of the compound's constituents from the water column. At this time, it is unknown whether or not there is any phosphate associated with this compound.

Source	**Ca**	**Mg**	**Na**	**K**	**Alk**	**SO_4**	**Cl**	**TDS**
Colorado River 1989 [1]								
mg/L	76	31	10	4.1	152	290	100	737
%	17	12	4	1	14	27	25	
Salton Sea 1910 [2]								
mg/L	137	98	1,893	35	64	764	2,809	5,600
%	2	2	46	0.5	0.5	4	44	
Salton Sea 1948 [2]								
mg/L	804	992	11,824	192	192	7,550	16,990	38,550
%	2	4	45	0.4	0.3	7	42	
Salton Sea 1955 [2]								
mg/L	764	951	9,938	224	180	6,806	14,422	33,290
%	2	4	44	0.6	0.3	7	42	
Salton Sea 1988 [1]								
mg/L	950	1,300	11,000	220	185	10,000	17,000	43,700
%	2	5	42	0.4	0.2	9	42	
Salton Sea 1999 *								
mg/L	942	1,400	12,340	259	249	10,520	17,470	43,920
%	2	6	44	0.5	0.2	9	40	
Ocean 1989 [3]								
mg/L	403	1,260	10,500	390	120	2,650	18,900	34,200
%	1	5	42	1	0.1	2.5	49	
Alamo at Outlet[1]								
mg/L	180	100	430	12	212	910	580	2,500
%	8	7	34	0.6	4	17	29	
1999 mg/L*	166	83	389	8.2	259	762	443	2,020
%								
New at Outlet[1]								
mg/L	180	90	600	15	227	800	880	2,850
%	6	5	37	0.5	3	12	35	
1999 mg/L*	177	82.8	566	12.6	300	716	724	2,440
%	10	8.4	24.4	0.5	6.4	19.5	30.6	
Whitewater at Outlet*								
1999 mg/L	122	32	303	9	245	527	235	1,553
%	9	4	41	0.7	7.6	17	20.5	

Schroeder, Rivera, and others, 1993

2 Walker, 1961

3. Scripps Pier, published in Schroeder, Rivera, and others, 1993: Ca = calcium, Mg =magnesium, Na = sodium, K = potassium, Alk = alkalinity as calcium carbonate, SO_4 = sulfate, Cl = chloride, and TDS = total dissolved solids.

* C. Holdren, USBR, 2000

Phosphorus Release from the Sediments

In many lakes, phosphorus released from the sediments is transported to the surface water during lake overturn as the anoxic bottom water from a stratified lake is mixed with upper oxygenated water. Bacterial processes in the hypolimnion remove oxygen from bottom water gradually producing anoxic conditions that release phosphorus from the sediments and settling particles. In the Salton Sea, this process is not likely important due to the high sulfide concentrations.

Biological Processes

It appears, however, that algae and tilapia may play a significant role in cycling phosphorus in the Salton Sea. In order to determine the relative importance of algae and tilapia, it is important to compare their potential contributions with the overall content of phosphorus in the water column.

The average mass of phosphorus in the Salton Sea is 6.3×10^5 kg using a weighted average total phosphorus concentration of 68 µg/L and a weighted average volume of 7.48×10^6 acre-ft for 1999 (C. Holdren, USBR, written communication). Overall net phosphorus in the water column remains about the same from year to year although major spikes and drops occur within a year. These changes likely occur following major algal blooms when most of the total phosphorus incorporated in the algae settles to the bottom. As the algae die, bacteria use the available oxygen to breakdown the settling biomass, leaving behind a very low total phosphorus concentration in the water column. This phosphorus is likely stored as organic compounds in the bacteria. Much of this phosphorus may become available as the wind driven system stirs up the sediments and causes additional algal blooms.

The number of tilapia in the Salton Sea, which appears to have increased dramatically since the 1980's, further complicate the cycling of phosphorus. Recent studies show there are about 90 million tilapia present in the Salton Sea (B. Costa-Pierce, Mississippi-Alabama Sea Grant Consortium, written communication). Tilapia tie up a portion of the phosphorus in their tissues that is eventually released as the tilapia die and decompose. The average tilapia is about 0.5 kg, comprised of about 76 percent water and 2.9 percent phosphorus (Tan, 1971 and Costa-Pierce, 2000). Therefore, the mass of phosphorus tied up in tilapia is

$$9.0 \text{ X } 10^{7} \text{ tilapia X 0.5 kg/tilapia X 24 \% dry weight X 2.9 \% P in tilapia} = 3.13 \text{ X } 10^{5} \text{ kg},$$

representing about 25 percent of the annual external phosphorus loading to the Salton Sea. Therefore, harvesting of tilapia may be an option and has been discussed as a means of removing phosphorus from the Sea.

When fish in the Salton Sea die, phosphorus in their bones may be lost from the system and not remineralize because of the high salinity of the water. With a life span in the Salton Sea of approximately two years, about 45 million tilapia die each year. If we assume that 75 percent of the dry weight of tilapia is bone, about 1.2 X 10^{5} kg of phosphorus is deposited in the bones of dead fish each year and removed from the system. This amount is 10 percent of the total phosphorus loading to the Salton Sea. Tilapia, therefore, not only tie-up a significant mass of phosphorus in the Salton Sea, but in their death, may permanently remove a small portion of the external phosphorus load. In addition, the large number of tilapia and their bottom feeding habits coupled with the increasing salinity also could affect the species type and abundance of the plankton population and in turn affect the water clarity of the Sea.

This discussion shows that tilapia appear to play an important role in phosphorus cycling in the Salton Sea. If the salinity of the Salton Sea is allowed to increase to a point where the tilapia no-longer can survive, the effect on the eutrophication of the Sea could be significant.

A similar calculation for the Salton Sea in 1968-9 (elevation –232 ft. MSL) using a maximum total phosphorus concentration in the spring of 0.2 mg/L gives a total phosphorus mass in the Sea of 1.6 X 10^{6} kg. This mass, resulting from an external loading of 6.241 X 10^{5} kg, is about the same as current mass. In other words, at twice the total phosphorus loading today, the total phosphorus in the Sea is about the same as it was in 1968-69. This similarity in total phosphorus mass indicates that a phosphorus removal mechanism in the bottom sediments or incorporation into the fish and other macro organisms has accommodated the additional phosphorus. The implication is that to reduce the eutrophic state of the Salton Sea, a reduction in phosphorus loading of greater than 50 percent is necessary.

REDUCING EUTROPHICATION

Based on the above discussion that phosphorus is the limiting nutrient in the Salton Sea, and external loading is significantly larger than internal loading, it appears that reducing the external phosphorus loading may reduce eutrophication problems in the Salton Sea. The major limitation is that because some unknown process seems to be controlling phosphorus in the Sea, phosphorus concentrations are about the same now as they were in the 1960's in spite of a doubling of the phosphorus loading. Therefore it is difficult to quantify the exact response of the Sea to various loading reduction scenarios. Because there has been no apparent change in the eutrophic character of the Sea since the 1960's (based on this limited evaluation), it is very likely that a greater than 50 percent reduction in external loading will be necessary to achieve a marked reduction in eutrophication. A reduction of at least 80 percent probably will be required.

POSSIBLE SOLUTIONS

Alum, aluminum sulfate, $Al_2(SO_4)_3$, has been added to lakes and reservoirs since the 1950's to control algal blooms by reducing internal phosphorus loading (Cooke, 1986). When added to water, the aluminum forms aluminum hydroxide which is a colloidal, amorphous flocculent with high phosphorus adsorption properties (Cooke, 1986). Typically, alum is added directly to lakes to adsorb the phosphorus and form a barrier on the sediments, limiting internal phosphorus loading. The sheer size of the Salton Sea makes such alum treatment impractical. However, alum may be able to be added to the tributaries to tie-up phosphorus before the water enters the Salton Sea. A significant amount of phosphorus is associated with fine suspended particles in the tributaries to the Salton Sea. These fine particles likely have a high percent of the phosphorus adsorbed to their surfaces. Various polymers have been added to river water to increase the settling rate of fine particles. Another way to reduce the phosphorus loading to the Sea may be to increase the settling rate of the fine particles by the addition of a specific polymer and increasing the settling rate of the fine particles in the tributaries.

The panel recommends:

1. Alum and/or polymer addition to the New and Alamo Rivers at or near their outlets to the Salton Sea could remove significant loads of phosphorus and decrease the eutrophication of the Salton Sea.
2. Experiments should be initiated to investigate the ratio of aluminum to phosphorus and the possible addition of polymers needed to remove at least 80 percent of incoming phosphorus and to determine the effects of the flocculent when it mixes with the saline water of the Salton Sea. Available information indicates that the high sediment concentrations in the Alamo River (>300 mg/L) interfere with alum removal of phosphorus. Experiments to test multiple upstream injection sites to maximize the effectiveness of sediment and phosphorus removal and minimize the volume of alum and/or polymers need to be performed. A proposal, “Reducing Eutrophic Conditions of the Salton Sea,” to test and evaluate the efficiency of sediment and phosphorus removal from tributaries to the Salton Sea has been approved for Proposition 13 funding by the State Water Resources Control Board’s Nonpoint Source Pollution Control Program.

OTHER POSSIBLE SOLUTIONS

Other possible solutions may eventually reduce the amount of alum and/or polymers needed to treat the tributaries to the Salton Sea. However, in the absence of direct phosphorus removal from the tributaries these solutions are not expected to cause major improvements in the eutrophic nature of the Sea. These possible solutions include:

1. Reduction in loading to tributaries

Nutrient loading to tributaries is from three major components: 1) treatment plant effluent; 2) agricultural discharge; and 3) municipal and industrial effluent from Mexicali. Municipal effluent from both the United States and Mexicali will continue to contribute an ever-increasing load of ortho phosphorus as populations in the area continue to grow. Controlling these sources, however, is expensive. Agricultural phosphorus inputs need to be further evaluated to determine: 1) what component of the total phosphorus contributed by tailwater runoff is bio-available after reaching the Salton Sea; and 2) how much of the phosphorus applied in fertilizers washes off during irrigation. To be effective in reducing eutrophication in the Sea, 50 to 75 percent (rough estimate) of the farmers in the Imperial Valley would have to participate in phosphorus reduction efforts.

Total maximum daily loads (TMDL's) currently are being implemented in the Salton Sea area. The sediment TMDL may remove some of the phosphorus associated with the sediment, but whether or not this phosphorus is biologically available is unknown.

2. Wetland treatment

Wetland treatment to remove various contaminants from water is gaining in popularity worldwide. The consensus of the panel was that wetlands constructed along tributaries or in deltas of the rivers would not significantly change the eutrophication of the Salton Sea. Wetlands are effective at removing nitrogen, but not effective at removing phosphorus. Wetlands primarily affect a small portion of the total flow, and if present in substantial acreage, will reduce the water inflow to the Sea because of increased evaporation. The wetlands do promote other benefits such as creating habitat and possibly removing some nitrogen, selenium, and sediment.

3. Fish Harvesting

Fish harvesting has been proposed as a means to remove phosphorus from the Salton Sea. From the previous discussion, it is clear that tilapia may play a significant role in tying up and removing phosphorus. Even if about 50 percent of the fish are harvested each year, it has been calculated that harvesting could remove only 10 percent of the external loading of phosphorus from the Sea. If this were the only solution, it would have minimal impact on eutrophication. However, coupled with other possible solutions, it could prove to be helpful. Fish harvesting also might be feasible for economic reasons, but it is possible that it may increase the productivity of the Sea by reducing grazing by tilapia on phytoplankton.

CONDITIONAL RECOMMENDATIONS

Eutrophication of the Salton Sea has severely impacted its beneficial uses, including recreation and fish and wildlife resources. Some of the effects of eutrophication include high algal biomass, high fish productivity, low clarity, frequent very low dissolved oxygen concentrations, massive fish kills, and noxious odors. Salinity increase also is threatening the survival of corvina, the major sport fish, and eventually the other fish in the Sea. External loading of nutrients, particularly phosphorus, to the Salton Sea from agricultural discharges and from municipal and industrial effluent is responsible for the eutrophication of the Salton Sea. Because internal phosphorus loading in the Salton Sea appears to be very low and external phosphorus loading to the Sea is high, reduction of tributary phosphorus loading to the Salton Sea may reduce eutrophication. The reduction in tributary loading is not expected to have an immediate effect on the state of eutrophication but may have an effect within 5 years.

To reduce phosphorus loading to the Salton Sea, the workshop panel thinks the best solution is to evaluate and test the addition of alum to the tributaries, forming an aluminum-phosphate flocculent. The flocculent should settle as river water mixes with water in the Sea, thereby removing phosphorus from the biological cycle. Also, addition of polymers to the tributaries may increase the settling of fine particles with adsorbed phosphorus.

Other solutions that we think may help to reduce phosphorus loading to the Salton Sea are to:

1. Require tertiary treatment of all municipal effluent in the basin.
2. Initiate Best Management Practices to reduce phosphorus originating from agricultural fields, feed lots, and fish farms.
3. Harvest fish in the Salton Sea to remove their phosphorus

Additional solutions to reduce phosphorus loading to the Salton Sea that we considered, but felt to be minimally promising are to:

1. Control golf course phosphorus applications, septic systems, and lawn fertilizers.
2. Evaporation ponds for salinity control and removal of phosphorus.
3. Wetlands intercepting tributary inflow to remove phosphorus.

Finally, to better understand eutrophication of the Salton Sea and prior to trying to correct the eutrophication process, we suggest that the following information be collected:

1. A detailed phosphorus budget for the Salton Sea needs to be developed which includes the complete physical and biogeochemical cycling of phosphorus.

2. Temporal trends in phosphorus loading to the Salton Sea should be evaluated to better understand its relation to eutrophication in the Sea (chlorophyll *a* concentrations).
3. Temporal trends of phosphorus in the Salton Sea should be evaluated to determine how chlorophyll *a* concentrations are related to the observed changes in eutrophication.
4. Develop a one-dimensional vertical model of the Salton Sea to determine how changes in hydrologic management will affect water levels and stratification of the Salton Sea.
5. Explore the geochemistry of the alum and polymer complexes to determine the fate of the aluminum-phosphate and other complexes as they enter the saline environment of the Sea.
6. Develop a monitoring program to evaluate the success of the eutrophication reduction program to include measurement of Secchi depth, chlorophyll *a*, total phosphorus and C^{14} based primary productivity rates.

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