Eutrophic Conditions at the Salton Sea

A topical paper from the Eutrophication Workshop convened at the University of California at Riverside, September 7-8, 2000

Edited by

Jim Setmire[1]

Contributions from:

Chris Holdren[2]
Dale Robertson[3]
Chris Amrhein[4]
John Elder[3]
Roy Schroeder[5]
Geoff Schladow[6]
Hank McKellar[7]
Rick Gersberg[8]

Workshop sponsored by the Salton Sea Authority, the Salton Sea Science Office, and the U.S. Bureau of Reclamation

1. Jim Setmire – Hydrologist, U.S. Geological Survey on detail to the U.S. Bureau of Reclamation, Temecula, CA.
2. Chris Holdren – Limnologist, U.S. Bureau of Reclamation, Denver, CO.
3. Dale Robertson – Research Hydrologist, U.S. Geological Survey, Middleton, WI.
3. John Elder, Research Hydrologist, U.S. Geological Survey, Middleton, WI.
4. Chris Amrhein, Professor, University of California, Riverside
5. Roy Schroeder, Research Hydrologist, U.S. Geological Survey, San Diego, CA.
6. Geoff Schladow, xxxxxxxxx, University of California, Davis
7. Hank McKellar, xxxxxx,xxxxx
8. Rick Gersberg, Professor, San Diego State University, San Diego, CA

EUTROPHIC CONDITIONS AT THE SALTON SEA

Draft

BACKGROUND:

MEETING

On September 7-8, 2000, a panel of scientists, convened at the University of California at Riverside, concluded that eutrophication of the Salton Sea adversely affects its beneficial uses. 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. Agencies reviewing the Salton Sea Restoration Project's EIS/EIR have indicated that current alternatives do not adequately address eutrophication as an integral part of meeting the project's goals. The first day 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 eutrophication of the Salton Sea to identify limiting nutrients, nutrient cycling, and possible solutions. This paper is not a complete analysis of nutrient cycling in the Salton Sea, but provides a glimpse of the complex dynamics of the Sea and possible actions to reverse its eutrophication.

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 1billion 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 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 proposed solutions to date address increasing salinity and stabilizing the elevation of the Salton Sea but do little to address the effects of eutrophication. The effects of eutrophication are closely tied to several of the restoration goals, however, solutions to the eutrophication of the Salton Sea are comparatively intractable and/or costly. To meet the goals of the restoration project, a means to improve the eutrophic character of the Salton Sea is needed. To these ends, the workshop was convened.

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 hundreds or 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 and cold 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 – a quite common occurrence in eutrophic systems. 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 which 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.

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 limitation by one nutrient to 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 25:1, P is nearly always the potential limiting nutrient; if it is lower than 10:1, N would likely be the limiting nutrient. In between these values, either nitrogen or phosphorus can become deficient, either in fresh water or salt water (Guildford and Hecky 2000).

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, 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 as part of the Salton Sea Restoration Project (Holdren, 2000, written communication).

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

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
Surface				**1968-69**				
	Summer	0.04	0.06	0.22	0.11	3.0	3.13	52:1
	Fall	0.02	0.05	0.36	0.22	3.3	3.48	70:1
	Winter	0.03	0.07	0.25	0.16	1.5	1.61	23:1
	Spring	0.06	0.20	0.27	0.49	4.5	4.96	25:1
				1999				
Surface	Annual mean*	0.024	0.087	1.275	0.1	3.6	4.98	104:1
	Summer	0.013	0.067	1.575	0.1	4.1	5.78	192:1
	Fall	0.032	0.043	1.182	0.1	4.2	5.48	137:1
	Winter	0.04	0.12	1.47	0.2	2.5	4.17	24:1
	Spring	0.012	0.116	0.876	0.2	3.7	4.78	64:1
Bottom	Annual mean	0.016	0.061	1.579	0.1	3.7	5.38	213:1
	Summer	0.003	0.056	2.52	0.1	5.3	7.92	430:1
	Fall	0.015	0.027	1.354	0	4	5.35	288:1
	Winter	0.037	0.079	1.51	0.1	1.8	3.41	25:1
	Spring	0.011	0.083	0.931	0.1	3.7	4.73	108:1

Average seasonal near surface total phosphorus concentrations in the Sea range between about 0.04 and 0.12 mg/L (see table below). For individual samples 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 (spring) to 75 (fall) percent of the total phosphorus. Phosphorus concentrations slightly decrease with increasing depth in the Sea, indicating a sink for phosphorus released from the sediment (discussed later). Phosphorus concentrations in water, although high, appear to be unchanged from the 1969 to 1999.

Salton Sea – Nutrient concentrations

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

Total nitrogen concentrations 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 generally represents about 25 percent of the total nitrogen; very little nitrate was measured. In the tributaries, nitrate is by far the dominant form of nitrogen, followed by organic nitrogen. Although ammonia is present in the tributaries, especially in the New River, ammonia (NH_3) is the dominant redox indicating form of nitrogen in the Sea. In the 1960's, ammonia concentrations are significantly lower than in 1999, averaging 0.2-0.3 mg/L. This ammonia increase (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 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 was summarized seasonally with Summer - Jun, Jul, Aug; Fall - Sep, Oct, Nov.; Winter - Dec, Jan, Feb; and Spring - Mar, Apr, May. 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 is extremely limiting, especially in the bottom water. The lowest N:P ratios (23:1 to 28.7:1) occurred during winter. Clearly, the overall ratios show that phosphorus is by far the limiting nutrient in the Salton Sea. During winter, however, total phosphorus ratios approach the threshold of 25:1 below which phosphorus may no longer be limiting. Winter has the greatest changes 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 the total phosphorus.

High algal populations result in high chlorophyll *a* concentrations, 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 are usually less than 5 feet.

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 and chlorophyll *a* and on Secchi depths, were developed by Carlson (1977). TSI's of oligotrophic water bodies are less than 40, between 40 and 50 for mesotrophic systems, and greater than 50 for 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. Data collected during 1998 for the Salton Sea Restoration Project are unavailable. A single sample collected during 2000 having 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.) In other classification schemes, these Secchi depths also rank the Sea as eutrophic (Wetzel, 1983).

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 category. In 1999, total phosphorus concentrations were variable. Calculated TSI's averaged between 50 and 70, significantly less than in 1968-9, but still eutrophic.

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 (Carlson TSI does not use total nitrogen). Clearly, nitrogen concentrations in the Salton Sea are similar for 1968-69 and 1999 during the summer, autumn, and winter months, except for increased concentrations of ammonia (discussed earlier).

Clearly, no matter what 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 input loads have increased, they have not significantly impacted the eutrophic state. 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.

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 (Holdren, 2000, written communication). Occasionally the DO within the Sea is zero from the top of the water column to the bottom. These episodes are usually associated 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. 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 often are associated with fish kills as the anaerobic sediments are agitated, creating an immediate oxygen demand. As a result, DO in the shallow water areas is depleted, 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 always been common at the Salton Sea, during the past decade 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. For example, 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	82,500	82,500	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	120,990	102,850	16,940	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	117,434	117,434	0	0
03-Aug-00	25,000	0	25,000	0
15-Aug-00	2,398,721	2,398,721	0	0
18-Aug-00	5,200,000	5,200,000	0	0
25-Aug-00	112,338	24,964	87,374	0
26-Sep-00	3,100,770	3,007,750	93,023	0

Compiled: Jacquie Lesch, Digital Library Administrator, University of Redlands

The high biomass of the Sea 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.

The objectionable odor that is so pervasive at the Salton Sea likely results from a unique combination of factors. The massive numbers of dead and decaying fish on the shores, algal decay, hydrogen sulfide from anoxic areas within the Sea, the saltier than ocean water, geothermal plants and agriculture all contribute to the smell that is 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

As stated earlier 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, and 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 (USGS, 1998, written communication). Drains discharging directly to the Sea from the Imperial Valley account for 8 percent of the inflow. Other minor sources of inflow include San Felipe Creek and Salt Creek. Ground water accounts for less than 5 percent of the inflow with the majority coming from the Coachella Valley. Since 1980, the annual flow in the New River entering the United States from Mexico has averaged about 182,000 acre-feet, which represents between 30 and 35 percent of the flow at its outlet to the Salton Sea, some 60 miles downstream. The total annual discharge to the Salton Sea is about 1.3 million acre-feet.

The major supply of nutrients to the Sea is from tributary loading. The following table presents average current and historical phosphorus and nitrogen concentrations and loading to the Salton Sea in 1968-69 and 1999.

Comparison of nutrient concentrations

Site	Org.-N	NH3-N	NO2-N	NO3-N	O-P	T-P	T-N	Q, in acre-ft
Alamo River,								
1968-9, 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		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,								
1968-9, 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		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,								
1968-9, 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		14.3	0.710	0.865	16.3	52983
load, in kgX10^6	0.078	0.048		0.935	0.046	0.053	1.03	

1999 loads in this table are based on mean concentrations and total annual discharge
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

Data from the 1960's provides a historical perspective of nutrient loading to the Salton Sea. Trends in annual loading and changes in nutrient sources can be evaluated by comparing data from 1968-9 with data from 1999.

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 percent and ortho phosphorus loads increased by 230%. Ortho phosphorus in the New River made up a larger percentage of the total phosphorus load, 75% in 1998 compared to 50% in 1968-9. Total phosphorus in the tributaries has doubled since 1968-9.

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.

In 1964, municipal and industrial waste discharges to the New and Alamo Rivers contributed 0.179 X10^6 kg of ortho-phosphate to the Salton Sea (Regional Board,1964, written communication). Mexicali's contribution was estimated to be 48 percent. Loading of ortho phosphorus to the Whitewater River from municipal and industrial sources was not included. The total phosphorus load discharged to the Salton Sea was estimated to be 0.624 X10^6 kg (includes Whitewater River but excludes direct drain discharge from the Coachella Valley).

Of this amount, ortho phosphorus was 54 percent of the total phosphorus loading. Municipal and industrial sources from the Imperial Valley and Mexicali represent 30 percent of the total phosphorus load. Insufficient data are available in 2000 to evaluate changes in total phosphorus and ortho phosphorus loading from municipal and industrial effluent. Advances in sewage treatment technology also 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.

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 with the majority coming 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.

Therefore the total external phosphorus loading to the Salton Sea is 1.34 million kg/yr:

Alamo River*	536,000 kg/yr
New River*	658,000 kg/yr
Whitewater River*	54,000 kg/yr

Direct drains		91,000 kg/yr
	Total	1,339,000 kg/yr

* Loads computed monthly (bimonthly during summer) using instantaneous and monthly discharges (Holdren, 2000, written communication)

The total external loading to the Salton Sea is $1.33X10^6$kg per year. Apportioning this load over the 365 square mile surface area of the Salton Sea gives a loading value of 3.87 $mg/m^2/day$. Internal loading is the second component to be considered. This load will either be added to or subtracted from the external loading to obtain the total phosphorus loading to the Salton Sea

Internal sediment release

Chemical compounds that reach the sediments do not necessarily remain there permanently. Sediments can 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, which typically occurs in the Sea, produces a reducing environment that can result in remobilization of phosphorus from the bottom sediments. This process is termed “internal loading”. Internal loading or the phosphorus flux from bottom sediment is calculated in $mg/m^2/day$.

No estimates of internal loading are currently available for the Salton Sea. Estimates of total phosphorus internal loading in other lakes and reservoirs are, however, available and enable internal loading to be approximated. Internal loading estimates range from about 0.5 $mg/m^2/day$ to 0.8 $mg/m^2/day$ (Schroeder and Holdren, 2000, written communication). If these loadings are projected as overall averages over the Sea's bottom sediments, the potential phosphorus contribution from internal loading would be 0.2 to 0.3 million kg/yr, excluding direct precipitation on the lake surface and groundwater inputs. Based on these estimates, internal loading is only about 16 percent of the total loading.

PHOSPHORUS CYCLING IN THE SALTON SEA

To better understand the eutrophication of the Salton Sea, it is necessary to look at the cycling of phosphorus in the Sea and its relation to external and internal loading. One question that arises is "Are the present phosphorus concentrations (and resulting eutrophic conditions) in the Salton Sea expected given the loading of phosphorus from the watershed?" One way to answer this question is to compare its phosphorus loading rate and measured phosphorus concentrations 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).

CONTROLLING PROCESSES

Since modeling results indicate that phosphorus concentrations in the Sea should be higher than observed concentrations, the processes removing phosphorus from the water column in the Salton Sea need to be determined. Initial geochemical modeling (Holdren, 2000, written communication) indicates that Salton sea water is supersaturated with respect to hydroxyapatite during periods when phosphorus levels are high. 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, it 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. 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. 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 (Amrhein, 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. 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 and diffusive fluxes, and the lack of increased near-bottom phosphorus concentrations indicate that there is a significant phoshorus loss to the sediments. Bottom sediments from cores collected during the summer of 2000 (Amrhein, 2000, written communcation) 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 $Ca_5(PO_4)_3OH$. Calcium phosphate minerals in fish bones may represent a sink for phosphorus. The median total phosphorus concentration in sediments is 672 mg/kg, which is typical of calcareous lake sediments.

Phosphorus mineralization

In 1910, three years after the Salton Sea was formed, the composition of the water is clearly dominated by dissolution of sodium chloride salts in the Salton Trough. The ionic composition is 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. Ion ratios are calculated on an atomic basis. Mass ratios were not used because they 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 along with that of sodium, calcium and magnesium likely have controlled their concentrations as the salinity increased. Sulfate solubility predicts that 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 constituents in the compound from the water column. At this time, it is unknown whether or not there is any phosphate associated with this compound. Tostrud (1999, written communication) found that the water column of the Salton Sea has less Na, Ca, and SO_4 than it should have based on a historical review of mineral inputs to the Sea from its tributaries. This loss began about 1980. Mineral formation in the highly saline Salton Sea is and will continue to be a significant factor in controlling ionic composition and possibly even eutrophication as the salinity continues to increase.

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, SO4 = sulfate, Cl = chloride, and TDS = total dissolved solids

* Holdren, 2000

PHOSPHORUS FLUX

In many lakes, phosphorus cycling is related to lake overturn as the anoxic bottom water from a stratified lake is replaced by oxygenated water. Bacterial processes in the hypolimnion remove oxygen from bottom water gradually producing anoxic conditions releasing phosphorus. In the Salton Sea, this process is not likely important due to the high sulfide concentrations. It does appear, however, that algae and tilapia play a significant role in cycling phosphorus in the Salton Sea.

The total phosphorus in the Salton Sea can be estimated from data collected at the surface and bottom of the water column at three sites (Holdren, 2000, written communication). Using the maximum whole-lake average concentration of 0.149 mg/L, the maximum total phosphorus in the Salton Sea is 1.38 X 10^6 kg. This total phosphorus represents an instantaneous maximum mass in the Salton Sea (water and plankton, excluding fish), produced by both internal and external loading minus the settling rate of the phosphorus. The average mass of phosphorus in the Salton Sea is 6.28 X 10^5 kg using a weighted average total phosphorus conc. of 0.068 mg/L and the weighted average volume of 7.48 X 10^6 acre-ft for 1999. Overall, the net phosphorus in the water column remains about the same from year to year. Major spikes and drops in phosphorus concentrations and mass occur within a year to account for the large fluctuations in total phosphorus shown in the table. Seasonal averages as shown in the table indicate changes in lake processes that typically occur during the annual cycle. They can, however, mask some of the intra-seasonal changes that occur. For the low concentrations of 5 µg/L total phosphorus, the mass of phosphorus in the Sea is only 4.8 X 10^4 kg. To go from the maximum mass to the minimum, the water column has to lose 1.33 X 10^6 kg of phosphorus to the sediment or incorporation into tissues of fish or other macro organisms. This process likely occurs after a major algal bloom where most of the total phosphorus is incorporated in the algae. As the algae die and bacteria use the available oxygen to breakdown the biomass, the mass settles leaving behind a very low total phosphorus in the water column. A major portion of the phosphorus from the breakdown is likely in the organic form in the bacteria. Much of this phosphorus is still available as the wind driven system stirs up the sediments and causes spring blooms. Again, the overall net stays about the same which means effectively that all of the incoming total phosphorus (1.33 X 10^6kg) must be taken up by the sediments via a yet to be determined mechanism.

Using a similar calculation for the Salton Sea in 1968-9 (elevation –232 ft. MSL) when the maximum total phosphorus concentration in the spring was 0.2 mg/L, gives a total phosphorus mass in the Sea of 1.6 X 10^6 kg, about the same as current values, with an external loading of 6.241 X 10^5 kg, about half of current

— Phosphorus is likely tied up in algae, then in bacteria (both of which strip phosphorus from water column) phosphorus suppressed from going back into water column by high sulfide content of water.

total phosphorus loading. At twice the total phosphorus loading today, the total phosphorus in the Sea is the same meaning that the phosphorus removal mechanism in the bottom sediments or incorporation into the fish and other macro organisms has accommodated the tremendous increase in 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.

The number of tilapia in the Salton Sea, which have increased dramatically since the 1980's, further complicate the cycling of phosphorus. Recent studies show there are about 90 million tilapia in the Salton Sea (Costa-Pierce, written communication). This is an estimate based on the number of fish per catch per habitat area and the area of the near-shore and pelagic habitats. The high number of tilapia and their feeding habits coupled with the increasing salinity also could affect the species type and abundance of the plankton population. Tilapia live approximately two years, meaning that 45 million tilapia die each year. Tilapia tie up a portion of the phosphorus in the organic form that is eventually released to the system as the tilapia die and decompose. Harvesting of tilapia has been discussed as a means of reducing the phosphorus load in the Sea. Tilapia are about 76 percent water and 2.9 percent phosphorus (Tan, 1971 and Costa-Pierce, 2000) The phosphorus mass tied up in the tilapia is:

$$9.0 \times 10^7 \text{ tilapia} \times 0.5 \text{ kg/tilapia} \times 24 \text{ \% dry weight} \times 2.9 \text{ \% P in tilapia} = 2.09 \times 10^5 \text{ kg}$$

which equals about 16 percent of the external phosphorus loading to the Salton Sea. Since half of the tilapia die annually, about 1×10^5 kg of phosphorus is cycled back into water column. Assuming that 75 percent of the dry weight is bone, about 7.5×10^4 kg of phosphorus is locked up in bones and removed from the system. This amount is 6 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, permanently remove a small portion of the external phosphorus load. This discussion shows that tilapia appear to play a considerable 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.

REDUCING EUTROPHICATION

Based on the above discussion showing that phosphorus is the limiting nutrient in the Salton Sea, that external loading is significantly larger than internal loading, and that some unknown process is removing phosphorus, it appears that reducing the external phosphorus loading to the Sea will reduce eutrophication. The major limitation is that phosphorus concentrations in the Sea are about the same now as they were in the 1960's in spite of a doubling of the phosphorus loading. Since there has been no apparent change in the eutrophic character of the Sea since the 1960's, 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 80 percent probably will be required.

POSSIBLE SOLUTIONS

Alum, aluminum sulfate, $Al_2(SO_4)_3$, has been added to water since the 1950's to control algal blooms (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 is unpractical. However, alum can be added to the tributaries to tie-up the phosphorus before the water enters the Salton Sea.

The panel recommends:

1. Alum addition to the New and Alamo Rivers at 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 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.

The consensus of several individuals experienced in alum treatment of lakes was that in-stream treatment should not pose any major problems and that desorption of the phosphorus should not occur upon mixing with the Salton Sea water. Although dosing studies need to be completed to verify these assumptions, some preliminary estimates are included.

Alum can be shipped to the Salton Sea in either rail cars or 4,400 gallon tanker trucks. Rail costs would be cheaper if the sidings were located near the application points on the New and Alamo Rivers. If it is assumed that a 1:1 aluminum to phosphorus treatment is needed, that alum is 4.2 percent aluminum, one tanker truck can deliver 2.2 X 10^4 kg of alum, and the cost per tanker of alum is $1,870, then the estimated costs associated with alum treatment of the New and Alamo Rivers is as follows:

Annual loading of phosphorus from tributaries (New and Alamo Rivers) =
    1.234 X 10^6 kg
Annual aluminum needed = 1.234 X 10^6kg
One tanker truck = 2.2 X 10^4 kg alum X 4.2% aluminum = 9.24 X 10^2 kg
1.234 X 10^6 kg Aluminum / 9.24 X 10^2 kg aluminum/truck = 1.34 X 10^3 trucks
1.34 X 10^3 trucks @$1,870/truck
    = $2.5 million/year

An existing rail line is located immediately east of the Salton Sea. Spur lines from this line to the outlets on the New and Alamo Rivers could easily be constructed, lowering the cost of the alum. It also is important to determine the fate of the alum flocculent one it enters the Sea. Where will it likely settle and what, if any will be the bioavailability of the phosphorus in the flocculent.

OTHER POSSIBLE SOLUTIONS

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 U.S. 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. The effects of agricultural phosphorus inputs need to be further evaluated to determine: 1) what component of the total phosphorus attached to sediments contributed by tailwater runoff is bio-available when it reaches 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 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 first TMDL is for sediment, however, there is a lack of data to aid in setting the level that is protective to the warm water fishery of the drains, rivers and the Salton Sea. The sediment TMDL may remove some of the phosphorus associated with the sediment, but whether or not this phosphorus is biologically available is not known.

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 not effective at removing phosphorus. Wetlands only affect a small portion of the total flow, and if present in substantial acreage, will reduce the water inflow to the Sea. 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 phosphorus flux discussion, it is clear that tilapia play a significant role in tying up and removing phosphorus. It has been calculated that harvesting could remove 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

Assumption: External loading comes from the New, Alamo, and Whitewater Rivers plus drains discharging directly to the Sea. Internal phosphorus loading in the Salton Sea is low while external phosphorus loading to the Sea is high. Recommendations: Reduction of tributary phosphorus loading to the Salton Sea may reduce eutrophication. The reduction in loading is not expected to have an immediate effect on the state of eutrophication but may have an effect within 5 years.

THE BEST SOLUTION is to reduce phosphorus loading to the Salton Sea is to:

Treat the tributaries with alum thereby forming an aluminum-phosphate complex that flocculates. The flocculent should settle out as the river water mixes with water in the Sea, removing the phosphorus from the biological cycle.

OTHER MODERATELY PROMISING SOLUTIONS 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

MINIMALLY PROMISING SOLUTIONS to reduce phosphorus loading to the Salton Sea are to:

1. Control golf course phosphorus applications, septic systems, and lawn fertilizers.
2. Evaporation ponds for salinity control and removal of phosphorus3. Wetlands intercepting tributary inflow to remove phosphorus.

MISSION INFORMATION:

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 determine any correlation to eutrophication in the Sea (chlorophyll *a* concentrations).
3. Temporal trends of phosphorus in the Salton Sea should be evaluated to determine if there is any correlation to chlorophyll *a* concentrations and/or any observed changes in eutrophication.

4. Develop a one-dimensional vertical model of the Salton Sea to determine how changes in hydrologic management will effect water levels and stratification of the Salton Sea.

5. Explore the geochemistry of the alum complexes to determine the fate of the aluminum-phosphate complex as it enters 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.

SELECTED REFERENCES

Cook, C.B., Huston, D.W., Orlob, G.T., King, I.P., and Schladow, S.G., 1998, Salton Sea Project Phase II Final Report – Data collection and analysis for calibration and verification of a three-dimensional hydrodynamic model: Water Resources and Environmental Modeling Group, Department of Civil and Environmental Engineering, and the Center for Environmental and Water Resources Engineering of the University of California, Davis. Report 98-2, 109p.

Cooke, D.G., Welch, E.B., Peterson, S.A., Newroth, P.R., 1993, Restoration and management of lakes and reservoirs: Lewis Publishers, New York, 533 p.

Guildford, S.J. and R.E. Hecky, 2000, Total nitroten, total phosphorus, and nutrient limitation in lakes and oceans; Is there a common relationship? Limnology and Oceanography, 45 (6): 1213-1223.

Hely, A.G., Hughes, G.H., and Irelan, Burdge, 1966, Hydrologic regimen of Salton Sea: U.S. Geological Survey Professional Paper 486-C, 32p.

Redfield, A.C., Ketchum, B.H., and Richards, F.A., 1963, The influence of organisms on the composition of sea water. *In*: N.Hill (ed.), *The Sea*, vol. 2, Interscience, pp. 26-77

Schroeder, R.A., Rivera, Mick, and others, 1993, Physical, chemical, and biological data for detailed study of irrigation drainage in the Salton Sea area, California, 1988-90: U.S. Geological Survey Open-File Report 93-83, 179 p.

U.S. Department of the Interior, Federal Water Quality Administration, Pacific Southwest Region, 1970, Salton Sea, California – Water quality and ecological management considerations: 54 p

Walker, B.W., 1961, The ecology of the Salton Sea, California, in relation to the sportfishery; Fish Bulletin no. 113, State of California , Department of Fish and Game, 204 p.

Welch, E.B., 1992, Ecological Effects of Wastewater; Applied limnology and pollutant effects, 2nd edition, Chapman and Hall, London, 425p.

Wetzel, R.G., 1983, Limnology: Saunders College Publishing, 767 p.