Physical and Chemical Limnology of the Salton Sea

A. Physical and chemical limnology is essentially the water quality of the Salton Sea, and the limnology includes the following characteristics:
   1. Historical change in the salinity of the Sea, as indicated by its conductance values.
   2. Turbidity and Secchi depth, the latter of which is indicative of the clarity of the water.
   3. Currents or circulation of the Sea.
   4. Sediment content, including grain size and composition.
   5. Microorganisms and their impact on the chemical and physical processes of the Sea.
   6. Nutrient loading, including ammonia, nitrate, and phosphate.
   7. Contaminants, such as sulfides, selenium, and others.
   8. Other factors, such as chlorinity, dissolved oxygen and pH.
   9. Given this context, selenium will be handled as part of the sediment story or a selenium sidebar, salinity will have its own story, and the nitrogen-phosphorus cycle will be treated as part of the eutrophication story.

B. Sampling location comments regarding the latest results from Holdren and Montano (2000).
   1. If the sampling locations are accurate, the New and Whitewater sites are located farther inshore than the Alamo sampling location, which could have an effect on the values obtained in water quality sampling.
   2. The suspended load is more likely to be deposited as inflow velocity is reduced, and reactivation of the bedload is more likely wherever the kinetic energy of the hydrologic system increases. Multiple sampling points along the rivers would be helpful in monitoring changes in the water quality, and in determining the depositional/erosional nature of the localized environment.
   3. The three main river monitoring sites, in other words, are suspect in terms of where the site is placed in relation to the layout of the stream and distance from the shore.

C. General nutrient comments for the Salton Sea.
   1. Nutrient concentrations are distributed such that mid-Sea stations show lower concentrations, and sites close to Mullet Island display the highest concentrations, perhaps due to the influence of the Alamo River (H&M, 2000).
   2. Bottom waters (hypolimnion) of the Sea displayed higher concentrations of ammonia-N and phosphate than surface waters (epilimnion), which indicate a high internal nutrient loading in the Sea, meaning that nutrients are being reactivated from the Sea floor and reentering the water column (H&M, 2000).
   3. The lake is considered "objectionably eutrophic", in which high algal growth leads to super-saturation of dissolved oxygen, especially in surface waters, and oxygen depletion in bottom waters (H&M, 2000).

4. The lake generally shows few nutrient limits to algal growth; only one study (FWQA) to date has shown that phosphorus content has actually limited growth (H&M, 2000).
5. Irwin (1971) reported nitrogen and phosphorus concentrations were high for both the New and Alamo Rivers, but low in the canals.
6. Nutrient concentrations were much higher in the rivers than in the Sea, and these high concentrations originate from agricultural activity, although the New River also derives a significant amount of its nutrients from municipal wastewater.
7. Seasonal variations were encountered.
    a. There was more variability in the concentration of nitrogen apparent in the rivers, and more variability in phosphorus content in the Sea.
    b. The Alamo had the lowest nutrient concentrations of the three rivers, but the greatest seasonal variation; the New and Whitewater Rivers had higher nutrient concentrations and lower seasonal variability.
    c. This is probably due to the Alamo retaining primarily agricultural runoff, and the New and Whitewater Rivers also containing wastewater effluents.
    d. Soluble orthophosphate is lowest in the summer, and the biggest drop is in the Alamo. Total phosphorus was highest in the winter and spring in the Alamo and New Rivers, and in the fall for the Whitewater River.
8. Total phosphorus was approximately 10 times greater in the rivers than in the Sea. In the rivers, the phosphorus was found in the form of soluble orthophosphate, and was inversely related to the total suspended solids.
9. In the Salton Sea, soluble orthophosphate was lowest in spring and summer, and highest in winter when biological activity was at its lowest. Total phosphorus was highest in the winter, and lowest in the fall.

D. <u>Nitrogen and ammonia results</u> (H&M, 2001).
1. Total nitrogen concentration in the rivers was 2-4 times than those of the Sea, but seasonal trends in nitrogen were not as pronounced as seasonal phosphorus variations.
2. Nitrate-nitrite, or oxidized nitrogen, was the major form of nitrogen in the Alamo and Whitewater Rivers (70 and 88%, respectively), but less than half in the New River (43%), where ammonia content was greater than nitrate-nitrite, possibly from municipal wastewater.
3. In the Sea, oxidized nitrogen was much lower than in the rivers, usually less than 1%, and yet, ammonia is one-third of the content.
4. Ammonia concentration varied with depth, with bottom concentrations greater than 50% higher than surface concentrations. This higher concentration near the bottom of the Sea may be an indication of internal nitrogen loading.

5. Since nitrate levels were lower in the Sea than in the rivers, but ammonia remained unchanged, the nitrogen loss may come from denitrification of the water. Algal uptake is a secondary possibility, although unlikely.
6. Ammonia levels in the Sea exceed water quality standards. The whole lake mean value is double the 6-month median value, and the daily maximum was exceeded at two of the three stations. Thus, the ammonia level at the Sea is considered toxic for some freshwater aquatic life.
7. Although the toxicological effects of ammonia on marine life are not known, the high level of ammonia at the Sea may contribute to fish toxicity.
8. EPA has indicated that toxicity of un-ionized ammonia increases with salinity (H&M, 2001). Hence, relatively high concentrations of ammonia are another source of stress to the fish population of the Salton Sea, and combined with the high temperature and low dissolved oxygen that accompanies algal blooms, may be contributing to fish die-offs.
9. Hurlbert (1999) indicates that mean total ammonia has increased by a factor of three since 1968.

E. <u>Nutrient results</u>, as shown by the "N:P" Ratio.

1. Nitrogen and phosphorus are the nutrients that usually limit algal growth under natural conditions, and the relative concentration of nitrogen versus phosphorus is actually more important than the absolute concentrations in structuring phytoplankton communities.
2. The Sea and inflowing streams both display high nitrogen-phosphorus ratios.
3. The average "N:P" ratio for healthy, growing cells is 7:1 by weight, 15+:1 by atomic ratio, which is known as the Redfield ratio. It is assumed that the 7:1 ratio is the actual amount of nitrogen versus phosphorus that is needed by healthy algae.
4. A large N:P ratio (>7) indicates that growth will likely be limited by amount of phosphorus present, and a small low N:P ratio (<7) means that growth will probably be limited by nitrogen availability.
5. The ratio of inorganic nitrogen (nitrate-N, nitrite-N and ammonia-N) to soluble orthophosphate is probably more effective than total nitrogen versus total phosphorus since inorganic nutrients are easier to obtain and use by aquatic organisms.
6. New River shows the lowest nitrogen-phosphorus ratio, while the Alamo and Whitewater Rivers have higher ratios. The Alamo and Whitewater Rivers are composed primarily of agricultural runoff, which naturally results in a higher nutrient content. The highest ratios occurred during the summer, with phosphorus being the obvious limiting factor (H&M, 2001).
7. The New River had considerably lower N:P ratios, but the peak ratios were once again achieved during the summer, but limiting nutrient was not clearly indicated by the lower values.
8. Within the Sea itself, there is a much higher nitrogen component on the central berm than in either basin, with the south basin being considerably lower, probably due to greater inflows into the south basin. Regardless,

the N:P ratios were very high in the Sea, strongly indicating phosphorus was the limiting nutrient (H&M, 2001). The highest ratios were observed during the summer when algal growth should be at its maximum.

9. Nutrient ratios are 20 to 40 times greater in the Sea than in the inflowing streams, indicating a much greater quantity of phosphorus in inflow waters than in the Sea. This is probably due to a currently unknown biological or chemical process that results in a loss of phosphorus within the waters of the Sea itself.

F. <u>Ammonia results</u>. This is based entirely from Hurlbert, 1999.

1. Ammonia occurs as one of two species, ammonia, a dissolved gas, and ammonium ion. The dissolved ammonia is toxic to many organisms, including fish and invertebrates, but the precise level at which it is toxic varies with temperature, dissolved oxygen, et al.
2. Ammonia levels at the Sea vary widely, but the highest values occur in bottom waters during stratification events.
3. Which species occurs depends on pH and temperature, with ammonium ion being the dominant form. As pH increase, ammonium ion increases.
4. Total ammonia appears to have increased threefold since the late 1960's, but lack of spatial information on older data makes this result suspect. Assuming the total ammonia content increase is valid, ammonia level could become toxic.
5. Abundant salts in the Sea provide strong buffering to pH increases that could have been stimulated by other factors, such as photosynthesis. Ammonia is likely not a contributor to fish die-offs at present.

1. → G. <u>Temperature results</u>.

1. Holdren and Montano (2000) focused on three sampling stations in the Sea itself, mapping temperature versus depth and time of year.
   a. All stations showed a warming of the waters of the Sea from late May to October, but the temperature increase was deeper on the berm between the two basins in the Sea. This probably assists in separating the north and south circulation gyres.
   b. The berm and south basin also showed short-term temperature fluctuations in the spring prior to the general summertime warm up of the waters of the Sea. These springtime fluctuations are probably the result of the vast majority of freshwater inflows coming into the Sea via the New and Alamo Rivers, and the relatively low level of inflow draining into the north basin.
2. Minimum and maximum temperatures were achieved for each of the three stations on the same day. August produced the maximum surface temperature of 36.5 C, and December produced the minimum surface temperature of 14.2 C, both of which were recorded in the south basin.
3. Hurlbert (1999) reports that the minimum mean temperature was recorded in early January (13-15 C), and maximum sometime from July to September (31-34 C), depending on the year.
4. The Sea is directly responsive to ambient weather conditions, and warming versus cooling regime can change anytime from July to

September. Watts (2000) states the monthly mean air temperature low is 13.5 C in January, and 33.5 C in June or August, correlating directly to surface water temperatures reported for the Sea. Solar radiation maximum actually occurs one month sooner, but otherwise, matches the surface water and air temperatures.

5. Hurlbert (1999) observed that temperature showed surprising variation between the stations, and these spatial differences are likely caused by the Salton Sea's size, bathymetry, circulation patterns, and possibly salinity gradients, especially in the southern basin. Some days little temperature variation is observed, and other days, either north or south basin can be significantly hotter or cooler than rest of lake.
6. During the cooling period, daytime warming affects the top 2 or 3 meters of the lake, but other than surface heating, thermal stratification is infrequent (Hurlbert, 1999). The water column mixes nearly daily due to convectional circulation driven by conduction and evaporative cooling of surface water, as well as windy conditions (Watts, et al., 2000).
7. Temperature varied 1 to 3 degrees C during the cooler months, and 3 to 9 degrees C during the summer. River temperatures were generally slightly lower than Sea surface samples, with a collective maximum of 30.5 C and a minimum of 11.4 C (Holdren and Montano, 2001).

3.?? H. <u>Lake stratification commentary</u> (Hurlbert, 1999).

1. Lake warming occurs from January until July to September (about 2/3 of the year), and lake cooling the rest of the year (about 1/3 of the year). Lake warming occurs through solar insolation and conduction, and cooling through evaporation, conduction and back radiation.
2. Lake heating is characterized by wind-driven vertical mixing events and rapid thermal stratification during calm (low or no wind) periods, whereas lake cooling is characterized by almost daily mixing due to convection and perpetually windy conditions, generating surface turbulence.
3. Wind-driven lake turnover occurs more in the spring, less often in the summer. Measurable quantities of hydrogen sulfide are found in bottom water during anoxic events, and have been observed to range up to the surface of the lake (Swan, et al., 1999).
4. Winds are strongest in the spring, and weakest in the summer and fall. Convectional circulation driven by evaporative and conductive cooling causes virtually daily mixing in the Sea during its cooling period (Hurlbert, 1999). Mixing is evidenced by an increase in the temperature of the bottom water throughout the warming period (Watts, et al., 2000).
5. Hurlbert (1999) states that the mixing and stratification regime of the lake is complex. The Sea is polymictic, which is to say the lake is prone to turnover and vertical mixing from surface to the bottom of the water column three or more times per year.
6. Wind events are the primary mechanism influencing the mixing of the Salton Sea. The frequency, strength and duration of such events influence the currents, temperature, dissolved oxygen, sulfide, nutrient cycling, and

distribution and abundance of biota. Seasonal variations in wind patterns can cause significant variations in lake dynamics (Watts, et al., 2000).

7. The action of wind on lake stratification is mentioned in the circulation section of this atlas. By mixing heated surface waters downward into the water column, wind-generated turbulence reduces heat loss through back radiation, and increases heat gain via conduction. Hence, the Sea heats more rapidly during a windy spring than a calm one (Watts, et al., 2000).
8. Frequent mixing in the lake causes the entire water column to increase in temperature throughout the warming period. Strong winds during thermal stratification events tend to push the warmed surface water layer southward (Watts, et al., 2000).
9. Stratification in the Sea seems to respond directly to variations in frequency and intensity of wind events in the region. A less windy season appears to result in fewer strong mixing events, greater thermal stratification, more irregular heating of bottom water, a slower rate of temperature increase for the lake, and a lower maximum temperature for the lake in a given season.
10. Shallow lakes with large surface areas relative to depth can have their stratification broken down even by low wind speeds (Watts, et al., 2000).

2. → I. Salinity gradients (Watts, et al., 2000).

1. There is often a salinity gradient in the southeast part of the lake, upcurrent from the New and Alamo Rivers (Swan, et al., 1999). This vertical salinity gradient can be observed extending towards Mullet Island and the Wister Unit north-northeast of the Alamo River delta.
2. In the south basin, freshwater inflows tend to form a "wedge" and extend out into the Sea, the rate of mixing with saline lake water being a function of wind conditions and current strength. Saline stratification is more effective at inhibiting water column mixing than thermal stratification, making this part of the lake more resistant to mixing during periods with calmer winds (Watts, et al., 2000).
3. Under windy conditions, the gyre pushes the freshwater from the mouths of the New and Alamo Rivers northeastward along the southeast shoreline and thence northwest along the eastern shoreline of the south basin. The vertical salinity gradient is often 2-8 km wide along these shorelines. Stronger winds would induce more mixing, reducing the spatial extent of surface water with lowered salinity. Current strength tends to be at its minimum during low wind periods when a strong vertical salinity gradient would extend well away from the deltas of the New and Alamo Rivers.
4. Salinity gradients inhibit the flow of oxygen and heat from the surface to bottom waters. This may counter the tendency in the southern basin to mix more readily at lower wind speeds than does the deeper northern basin. The impact of each river is probably further enhanced by their relatively close proximity, about 12.5 km, when the remainder of the shoreline of the lake is a total of approximately 150 km.
5. This also affects the distribution of biota and nutrients in the Sea. The majority of nutrients enter the Sea via the New and Alamo Rivers, leaving

the nutrients on the south or southeast part of the Sea. Phytoplankton density is higher and light penetration values are lower throughout the year in this area with fresher water. In addition, these currents are likely responsible for transporting the larvae of macroinvertebrates into the deeper parts of the Sea, assisting in the recolonization process of mid-lake sediments (Watts, et al., 2000).

J. Dissolved oxygen results.

1. The solubility of oxygen is a function of pressure, temperature, and salinity. DO enters the water via photosynthesis and diffusion, and is removed via respiration and reactions with reducing substances, such as hydrogen sulfide (Hurlbert, 1999). Decomposition removes dissolved oxygen from the water, while photosynthesis removes carbon dioxide.
2. Directly reflective of the temperature dependence of oxygen solubility, the oxygen level in the lake was observed to decrease as the temperature of the water increased, and conversely, the oxygen level of the lake increased during the general period of lake cooling, in which the water temperature declined (Hurlbert, 1999).
3. When thermal stratification exists, an oxygen gradient is formed with low DO at the base, and higher concentrations in the upper part of the water column. The presence or absence of oxygen affects the distribution of organisms and the chemistry of the lake (Hurlbert, 1999).
4. During its warming periods, the DO content of the lake varies greatly, due to limited mixing of the water column, and the removal of oxygen at the base of the column due to respiration. DO in surface water increases due to biotic photosynthesis and diffusion of atmospheric oxygen, the latter depending on the degree of wind turbulence (Hurlbert, 1999).
5. During cooling periods, DO is more uniformly distributed due to a low thermal gradient in the water column, convection, and frequent wind-driven mixing events which transfer oxygen-rich water downward into the column. Photosynthesis can cause occasional peaks of DO in surface waters any time of year (Hurlbert, 1999).
6. Severe wind-induced mixing events can also produce major fluctuations in the level of dissolved oxygen. In some cases, the entire water column can become anoxic or nearly so, due to dilution with anoxic bottom water and possibly from delivery of reducing agents (like hydrogen sulfide), organic matter and microbial heterotrophs into surface waters (Hurlbert, 1999).
7. Dissolved oxygen generally mimics temperature patterns, although not exclusively so. In general, during the summer, 60-100% of the lake bottom had low DO most of the time, but in winter when water temperature was lower and the Sea mixed frequently, most of the water column usually has an adequate supply of DO (Hurlbert, 1999).
8. One scenario for the Sea is that high water temperature and high organic matter in the sediments would cause anoxia to develop over much of the lake floor during the first extended period of thermal stratification, usually in early spring. Macroinvertebrates would vacate much of the lake bottom via mortality or migration, and a reactivation of phosphorus from bottom

Phosphorus flux

Phosphorus flux

sediments would ensue. After the last anoxic event of the year, usually in the fall, macroinvertebrates would then recolonize deep sediment areas, and the phosphorus flux would cease (Hurlbert, 1999).

9. Oxygen levels in the Salton Sea are typical for a highly eutrophic system. Surface oxygen content is often at greater than 200 percent saturation, while some level of oxygen depletion in the bottom waters was observed virtually throughout the year.
10. Bottom waters typically display severe oxygen depletion, especially from April through November. This zone of depletion ranged throughout the water column up to the surface in both August and September. Fish die-offs accompanied these surface oxygen-depletion events (H&M, 2001).
11. The Alamo River has the highest dissolved oxygen level from October through March, Whitewater from late spring to early fall, and the New River only briefly in early May and in September (H&M, 2001).
12. H&M (2000) also mapped dissolved oxygen in the Salton Sea proper, contrasting DO content throughout the water column against depth and time of year.
    a. Dissolved oxygen shows greater than 100% saturation for all stations in mid-Feb, variable but still good DO from early May to mid-July, another high in mid-August, and reoxygenation from October through December.
    b. However, DO is depleted at 10 meters or greater depth from July to early October for all three stations, and greater loss in August and September starting from 5 meters or greater depth. Complete loss of oxygen throughout the water column of the north basin was noted in September; how far towards shore this extended is undocumented.
    c. Best oxygen level is present in only the top 5 meters at virtually any time of year for all three stations.
13. Hurlbert (1999) reports that dissolved oxygen is driven by the mixing regime and by high rates of photosynthesis and respiration. During periods of mixing, the Salton Sea usually contains sufficient DO to sustain fish and invertebrates, but once stratification occurs, bottom water often becomes anoxic, and anoxic conditions can dominate throughout the water column in periods of extended stratification.
14. Oxygen depletion in the water column usually occurs during or just after a wind-driven mixing event following a period of stratification; this event is most likely facilitated by reduced stability and increased convectional circulation following cooling of surface water of the lake. Continued photosynthesis and shallow mixing replenish DO in the epilimnion waters, but any DO injected into bottom water is rapidly consumed. Hypoxia in the bottom waters apparently can last from March to early October, although windier conditions in the spring can delay the onset of anoxic conditions (Watts, et al., 2000).

Effect of pressure & salinity

15. Thickening of oxic stratum nearshore (Watts, et al., 2000).

a. The oxygenated layer is usually thicker in the nearshore environment, probably due to wind-driven turbulence and wave action, friction at the water-sediment interface generated by wind-driven surface currents, convection induced by greater cooling of shallow water at night, and possibly to less frequent and intensive mixing of hypoxic or anoxic bottom water with surface water nearshore.
b. Throughout the warming period for the lake, low wind speed days prevail between major wind events, which fail to mix the water column in mid-lake, but can generate wave action, surface currents, and nocturnal cooling.
c. Nearshore areas (<8m depth) are much less likely to exhibit a hypoxic zone, or to allow a buildup of sulfide concentrations.
d. Strong wind events reduce oxygen content in surface water by mixing with oxygen-poor sulfide-rich bottom water. In mid-lake, reoxygenation proceeds slowly, but in shallow nearshore areas, lower quality bottom water is either absent or involves a much smaller portion of the water column. Hence, mixing events eliminating DO in mid-lake may not affect the nearshore area, although under the right conditions, currents can carry mid-lake water to shore.
e. Most extreme example was the oxygenated layer extended only 3.5 meters deep >7.5 km from shore, and greater than 9 meters deep <4.5 km from shore.
f. This region acts as a refuge for fish and benthic invertebrates from hypoxic or anoxic conditions during deoxygenation events.

16. Historic DO variations (Watts, et al., 2000).
a. Since the mid-1950's, salinity has increased from 33 to 42 g/l, lowering oxygen solubility. Fish biomass has increased, increasing respiration and presumably, decomposition rates in the Sea. Temperature affects DO, but regime has not changed in that time frame, and surprisingly, neither has DO.
b. DO concentrations also did not vary much seasonally or daily, and surface waters were generally well-oxygenated. Today, there is a great variability in DO both daily and seasonally, and surface waters are often super-saturated in winter and spring, but hypoxic or anoxic in late summer.
c. In the 1950's, bottom waters were usually oxic, but hypoxic or anoxic only in August or September and only for a few days. Today, hypoxic or anoxic conditions can occur as early as February, and persist much longer.

bantam spectra for Ivan ~~[illegible]~~/EOG

d. These changes are likely caused by increased in primary biomass production, fish population, decomposition, and sulfide generation. More phytoplankton lead to greater photosynthetic production, which yields more DO in surface waters, particularly in warming period when the Sea is stratified.

e. Increased primary production supports larger populations of other organisms in the Sea, and therefore, more decomposition and sulfide concentrations in bottom waters throughout the year.
f. Sulfide production is enhanced by a 34% increase in sulfate concentrations, allowing more reduction of DO during mixing events.
g. During its cooling period when the Sea is well-mixed, processes favoring super-saturation and deoxygenation are inhibited, yielding DO concentrations comparable to historical values.

K. Consequences for Biota (Watts, et al., 2000).

1. Sulfide and DO regimes are driven by temperature and wind regimes, and have a great influence on the size and distribution of biota in the lake, including plankton, benthos and fish.
2. The major effect is an abandonment of the lake center by fish and benthonic life from May to September, and plankton and fish die-offs in August and September.
3. Fish exit the mid-lake area, except for the top 6m of the water column, in spring, probably in response to first encounters with hypoxic water and high sulfide water, which affects mid-lake plankton populations.
4. Tilapia move inshore to breed, making small nests which can be found at up to 12 meters depth. These could only be created prior to stratification events, after which they would move to shallow (<6m) areas. The reduced breeding area may affect their growth and reproduction rates.
5. In April and May, benthic macroinvertebrates vacate all lake bottom area (>4m deep) via either mortality or migration, probably due to anoxia or sulfide build up. They are usually resistant to hypoxic conditions, but sulfide levels can be lethal to aquatic organisms. Their numbers, however, are quite low, further reducing food available to fish.
6. Convectional circulation, usually in September, signals the recolonization of deeper water sediments by benthic macroinvertebrates.
7. Deoxygenation can cause population crashes for fish and plankton, accompanied by crashes of zooplankters, reductions in phytoplankton numbers (diatoms, dinoflagellates and a raphidophyte), and increases in anoxia-tolerant ciliates. Fish die-offs can involve massive numbers of fish; one event in August 1999 is estimated to include 7.6 million tilapia.
8. Not all fish die-offs are caused by deoxygenation; winter die-offs have been attributed to low water temperatures.
9. Large spring and summer population crashes are often associated with "green tides" that were originally thought to be phytoplankton blooms, but actually phytoplankton abundance declines during such events. The green color is probably gypsum crystals precipitating as sulfide is oxidized to sulfate, which is already at saturation with calcium. Green tides occur only in spring or summer, and are associated with strong wind events following prolonged stratification periods, sulfide odors in the air during such tids, and massive fish kills. "Green Tides" has also been applied to unrelated phytoplankton blooms.

L. Total Dissolved Solids and Conductivity. Conductivity is considered a direct measure of total dissolved solids, and hence, of salinity.

1. Total Dissolved Solids (Salinity).
    a. The New River has the highest concentration of dissolved solids (15 of 17 samples), with the Alamo River being second (17 of 17), and the Whitewater last, except for two samples where it was first. The New and Alamo Rivers are consistent year-round in terms of salt load delivered to the Sea. The Whitewater River showed peaks in both early September and early July, which probably corresponded to some notable upstream weather event, like a thunderstorm.
    b. TDS in the Sea was 20 to 30 times greater than the TDS in the inflow streams.
    c. Seasonal variations between the Sea and the streams totaled less than 10%, except for the New River, which exhibited 40% increase in TDS from winter to summer.
    d. Historical TDS values may have come in a little high due (4%?) due to a lower temperature for drying of sediments, which allows occluded water to remain in the sample. This occlusion happens in water high in sulfate content, as is the water of the Salton Sea.
2. Conductivity.
    a. The conductivity pattern is remarkably uniform for the deeper water stations in the Sea, with low conductivity extending up to the surface in April, being present at greater than 8 meters depth in July and early August, and a general reduction in conductivity visible from October to December.
    b. Changes in conductivity with depth are small and inconsistent, possibly from instrument inaccuracy, but may be valid due to geothermal activity at the south end of the Sea. Conductivity in the rivers is more variable than in the Sea, and are 3 to 7 percent of the values encountered at the Sea (H&M, 2001).
3. Watts (2000), however, states that the relation of salinity to specific conductance is well defined for salt water, but "that relation is a poor fit for the Salton Sea."
4. Salinity and lake elevation both vary seasonally, and are inversely related. Salinity ranged from 41.0 to 44.7 g/l, with maximum values occurring in late autumn or early winter, which correlates closely to when the lake is generally at its lowest elevation (late fall). The highest lake elevation occurs in early summer when evaporation is highest, but this occurs because agricultural runoff is highest during the spring (Watts, et al., 2000).

M. Total Suspended Solids (TSS).

1. TSS is very high in all the river samples, with the Alamo River retaining the highest TSS values, and the Whitewater River the lowest. The Alamo and New Rivers were always turbid during the study period (H&M, 2001)

2. Little seasonal variation was visible in the Alamo and New Rivers during spring, summer and winter. Fall showed the only seasonal variation for those two rivers as TSS content fell 15-25%. The Whitewater River, however, showed a comparable loss of TSS in the fall, but since the Whitewater is considerably less turbid, the seasonal variation looms larger. Seasonal variations in TSS may be related to agricultural practices, in which less irrigation is performed during the fall and winter months.
3. TSS in the Sea is much lower than the values encountered in the rivers, as expected, when the suspended sediment load rapidly settles out of suspension. TSS content varies widely in the Sea, and unlike the river samples, algal cells are an important component of TSS in the Salton Sea.
4. TSS in the Sea showed some seasonal and depth variation. TSS levels were highest in the Sea during the winter, next highest in the spring, and the lowest values in the summer. TSS values at the surface were considerably greater than at the bottom of the water column, which may reflect the quantity of algal cells. However, algal growth should be highest in the summer, when the TSS values were at their low ebb.
5. This conflicting information demonstrates the complexity of the Salton Sea ecosystem.

N. pH. This is a measurement of hydrogen ion concentration, which expresses both the alkalinity and acidity of a solution. Values of pH range from 0 to 14, with 7 being neutral, and numbers descending from 7 indicating increasing acidity, and those greater designating increasing alkalinity.

1. The pH values are also remarkably consistent in pattern, and reflect in broad outline what was shown in the conductivity parameter.
2. This pattern is higher values from January through April for all stations, then low pH values appear at depth (greater than 10 meters) in June, going to peak low values in July and August, and lower pH values dominate from September to December (progressively more alkaline).
3. In their final results, H&M (2001) state that there is little variation in pH in the river samples, and small temporal and spatial variations within the Sea itself. River pH values are generally 7.5 to 7.65, and surface pH on the Sea itself is about 8.2. Surface pH is typically 1 pH unit higher than at the bottom of the water column, which is typical of eutrophic systems.
4. Hurlbert (1999) reveals that waters of the Salton Sea ranged from 7.3 to 8.8 with a normal range of 8.0 to 8.8 in pH. When thermally stratified, the pH in bottom waters was at the low end of this range, and occasionally lower. Values in pH varied only 0.5 pH unit among stations, with difference rarely exceeding 0.3 pH unit. Main variables driving pH variation are thermal stratification, photosynthesis and respiration, which also affected dissolved oxygen. The importance of pH is that it affects the conversion of ammonia ion to ammonia gas (denitrification?).
5. Values of pH are lower in bottom waters during thermal stratification events, and during periods of mixing, pH for bottom and surface waters are similar (Hurlbert, 1999).

O. Oxidation-Reduction Potential.

1. Oxidation-reduction potential (ORP) closely parallels dissolved oxygen concentrations, and its pattern is remarkably consistent between the three sampling stations, although the south basin values remain higher longer than the north basin, perhaps indicative of more freshwater input in the south.
2. The very low mV values appear at depth (greater than 10 meters) in March, move up to 5 meters depth by July, ascending to 2 meters depth in August before subsiding in October.
3. The north basin shows the lower potential values sooner, with greater depth than the south basin or berm areas.

P. Secchi Depth and Light Penetration. Secchi depth is a direct measurement of the clarity of water, determined by actual depth at which you can still identify features (H&M, 2001). Water transparency is a function of the amount of dissolved and suspended organic matter, both organic and inorganic, that is present in a body of water (Hurlbert, 1999).

1. In the Salton Sea, transparency of the water at a distance from inflow sources, transparency is a function of plankton density, and quantity of dissolved organic matter produced by decomposition or algal secretions (Hurlbert, 1999).
2. The Salton Sea actually has fairly low Secchi depth values, ranging from 0.4 to 1.4 meters, presumably due to the high algal content. Actual Secchi depth figures varied widely from station to station, but showed no seasonal patterns (H&M, 2001). Hurlbert (1999) reports Secchi values of 0.10 to 0.45 meters.
3. Actual light penetration is greater than anticipated within the Salton Sea, but the ratio of 1% light penetration to Secchi depth was 4.2:1, and was consistent at all stations throughout the year (H&M, 2001).
4. Hurlbert (1999) states that light penetration was low, leaving a thin photic zone in the Salton Sea. Light penetration is greatest in the fall, when phytoplankton are at their lowest ebb, and lowest in the spring, when they are at their peak. Intensity at a depth of 1m never exceeded 30% of incident light. Depth of 1% light penetration extended between 2-4.5 m.
5. Secchi disk readings were typically 50-150 cm. Both measures, of course, correlate strongly with phytoplankton abundance, especially as measured by "chlorophyll a" concentration. (Hurlbert, 1999).
6. The nutrient-rich inflows of the New and Alamo River are pushed along the southeast shoreline of the Salton Sea by the counter-clockwise current or gyre of the south basin, resulting in a gradient of water with lower Secchi depth readings due presumably to a higher phytoplankton density in that part of the lake.

Q. Dissolved Organic Carbon (DOC).

1. The New River has the highest DOC content, the Whitewater is second, and Alamo has much less DOC. In the Sea itself, the surface waters have a slightly higher DOC content than bottom waters, as would be expected.

2. Inflow sources retain values 10 to 20% of values present within the Sea, or in other words, the Sea had values 5 to 10 times greater than what was encountered in the streams.
3. Mass ratios of elements with similar properties indicate that dissolved carbon is largely derived from in-Sea sources (78%), and at most, 22% is acquired from outside of the Sea (Schroeder & Orem, ????).

R. Dissolved Silica (DS).

1. There is a higher level of dissolved silica on the floor of the Sea than on the surface, which is to be expected.
2. The Alamo has the lowest DS value, the New River is second, and the Whitewater has the greatest DS content, but overall, the rivers retain more DS than waters of the Sea. This may be due to closer proximity to the sediment sources.
3. Settling of suspended particulate matter is probably causative in the observed decrease in DS, although the Whitewater, with the greatest DS content, also has the lowest suspended solids load. This may be due to a soil chemistry difference between the Coachella and Imperial Valleys.

S. Major Ions.

1. Total ion concentrations have and continue to increase at the Salton Sea, but the concentrations of major ions has not.
2. Sodium, chloride and sulfate ions are the most abundant ions, which is expected since sodium and chloride comprise the most abundant problem, salt, and sulfate is another problem in this eutrophic system.
3. Carbonate ions are quite low in concentration, and are probably the limiting factor on the precipitation of calcium in the Sea.
4. Tostrud (1997) reported that the Sea became saturated with bicarbonate ion within the first year after its formation, calcium ions around 1950, and sodium ions around 1980, resulting in the direct precipitation of these elements onto the floor of the Sea. These ions take the forms of calcium carbonate, calcium sulfate, and sodium sulfate, respectively.
5. Inorganic carbon level was lower in the Sea than in the rivers.
6. Bicarbonate was pretty consistent between the rivers and the Sea, but showed the greatest relative change in concentration over the lifetime of the Sea, with a net loss. This is probably due to it becoming saturated within a year after formation of the Sea, and other, more soluble ions increasing at a faster rate than bicarbonate.
7. Sulfate increased rapidly from 13.7 to 24.4% of all ions present in the Sea, but chloride decreased from 48.9 to 40.1%. These changes are attributable to the composition of Colorado River water, which contributed 2.5 times more sulfate than chloride to the basin during the lifetime of the Sea, but the rate of concentration will likely slow now if the Sea has reached a saturation point with respect to sulfate.
8. At present, the major ion composition of the Salton Sea differs from other saline lakes in its higher concentration of sulfate. If the Sea is now saturated with sulfate, two changes will occur:

a. First, the increase in salinity will not be as great as predicted by current models because sulfate precipitation will begin.
b. Second, the long-term trends of increasing sulfate concentrations and decreasing chloride will eventually reverse.

9. Irrigation water derived from the Colorado River and supplied to the Sea by the New and Alamo Rivers and by the East Highline Canal is considered "hard", or rich in calcium carbonate and calcium sulfate. The waters of the Sea, through the Saturation Index (the ratio of concentration to solubility), are likely to precipitate calcium carbonate and calcium sulfate (Schroeder and Orem, ****)

T. Sulfide results (Watts, et al., 2000).

1. Sulfides are usually present when the Salton Sea is stratified, often in concentrations high enough to deoxygenate the entire water column during a mixing event, at least in the deeper parts of the lake (>8m depth).
2. This deoxygenation would occur via oxidation of sulfides, depleting the column of oxygen without needing any other reducing agent.
3. Deoxygenation events consistently occurred in times of maximum temperatures (July to September), and most consistently in September. This is due to bottom waters being low in oxygen to begin with, their richness in reducing agents (sulfides),the presence of both dissolved and particulate organic matter, and the presence of microbial heterotrophs mixing with surface water.
4. The chemistry and kinetics of sulfide production and oxidation are the key to these deoxygenation events.
   a. In anaerobic conditions, bacteria may use nitrate, metal oxides, carbon dioxide, or sulfate to decompose organic matter.
   b. In the Sea, its high concentrations ensure that sulfate is used preferentially by bacteria for anaerobic decomposition.
   c. Reduction of sulfate coupled with organic matter decomposition generates sulfides in the anoxic bottom water. During thermal stratification, organic matter also accumulates in the bottom water.
   d. Photosynthetic bacteria normally oxidize sulfides produced by decomposition, and when the sulfides occur below the photic zone, as in most aquatic systems, wind or convection mix the sulfide-rich bottom water with oxic surface water, consuming all sulfide present through oxidation.
   e. In the Salton Sea, however, sufficient sulfide is present in the bottom water that mixing events leave surface water hypoxic and sulfide-rich.
   f. Sulfide may be present in the surface waters for a period of days following a mixing event. Sulfide oxidation half-life is estimated to be 10-50 hours in the lab, but after 3 days, sulfide levels were high enough to be considered toxic to mid-lake fish and metazoans.

5. Sulfide concentrations appear to have risen tremendously over the last 50 years, which could be the result of an increase in sulfate and biomass in the Sea. An explosion in the tilapia and phytoplankton populations is probably the cause of this major increase in biomass. Sulfide odors are one of the noted problems in recreation uses for the Sea.

U. Heavy Metals, Organics and Pesticides.

1. Heavy or trace metal concentrations were all low, which is not surprising due to high sulfide concentrations and low solubility for most heavy metal sulfides. All heavy metals were present at a higher concentration in the rivers than in the Sea.
2. Selenium is of concern in all water bodies in the American Southwest, but was present at a concentration below a level of concern for aquatic life.
3. Nearly all commonly used pesticides (organics) were found to be below detection limits for all sampling locations. This is expected due to the low water solubility of these compounds, and the high salt content of the Sea.
4. A variety of pesticides were found in waters of the Sea, but most were indicative of historical practices for the region, such as DDT, which is still found in most samples, and yet, has not been used in the US for decades.
5. Oddly enough, pesticide residues, although nowhere in excess, were still higher in concentration within the south part of the Sea.

V. Comparison to EPA Drinking Water Standards (primary and secondary).

1. All substances except salt are well below primary EPA standards.
2. Lead is slightly above EPA standards, but is not considered a health risk.
3. Selenium, in particular, is very low, approximately 4% of EPA standard.
4. Fluoride and manganese are comparable to EPA standards, but are also not considered a public health hazard.
5. pH is slightly broader in its range of values than recommended EPA standards. Generally speaking, Salton Sea water is occasionally slightly more acidic than recommended.

W. Trophic State Indices.

1. The "trophic state" rating expresses the relative biological productivity of a lake. The Trophic State Index (TSI) by Carlson (1977) is a commonly used indicator of trophic states.
2. A TSI value of 35 or less indicates oligotrophic conditions, 35-50 indicates mesotrophic conditions, and a value greater than 50 indicates a eutrophic state. A hypereutrophic lake, or excessively productive lake, has a TSI of or greater than 70, increasing the likelihood of encountering adverse conditions, such as excessive growth, algal scum, etc.
3. These values were designed for use in a different lake system (Great Lakes of the United States), and hence, are questionable, but at least they provide some measure of comparison. The summer values seemed best for comparison. The Salton Sea gets a value of 60-62 based on Secchi depth and total phosphorus count, indicating a eutrophic condition.

X. Pollutant Loading.

1. Inflow to the Sea (H&M, 2001), is 1,346,000 acre-feet, per the EIS/EIR (2000), 46.1 % coming from the Alamo, 32.5 % from the New, 5.9% from

the Whitewater, 7.9% from agricultural drains, 3.7% from groundwater, 3.5% from direct precipitation, 0.4% from San Felipe Creek, 0.1% from Salt Creek, and 1.3% from other sources.

2. Pollutant loading was found to be only 3.434 million tonnes per year, which is 73% of the load calculated in the RIS/EIR. Weghorst (2001) found the salt loading to be 3.29 million tonnes per year. Nutrient loading has increased over the life of the Sea, but the impact on nutrient concentrations is variable.
3. Nitrogen loading has increased 0-25% over the years, but total nitrogen concentration has increased 70-140%. Phosphorus loading has doubled over the past 30 years, but phosphorus concentrations have decreased.
4. Geochemical modeling shows that the Sea should occasionally be supersaturated with hydroxyapatite, and other apatite minerals. Hydroxyapatite initially precipitates on calcite crystals, and should be forming in the Salton Sea.
5. Phosphorus is probably being incorporated into fish bones and tissue, and in the shells of aquatic invertebrates. Once incorporated into bone or shell material, the insolubility of hydroxyapatite would prevent the precipitated phosphorus to go back into solution, providing a permanent removal mechanism in the Sea.

Nutrient discussion

Y. Geochemical modeling. These are predictions, not measurements!! Many other factors may be present which would inhibit precipitation of these minerals.

1. The Salton Sea should be super-saturated with calcite (calcium carbonate), gypsum (calcium sulfate), magnesite (magnesium carbonate), dolomite (Calcium-Magnesium carbonate), celestite, huntite, and several silicate minerals.
2. The Sea should also be saturated with hydroxapatite (calcium phosphate hydroxide), and fluorapatite (calcium fluorite hydroxide).
3. The rivers should be supersaturated with calcite, dolomite, magnesite, hydroxyapatite, and fluorapatite.
4. Precipitation of hydroxyapatite and fluorapatite is considered likely under the conditions present at the Salton Sea, which would form a sink for phosphorus. Celestite in a minor constituent of limestone, but may be deposited in the sulfate-rich environment of the Sea. Dolomite super-saturation is well known in hypersaline lakes, but actual dolomite precipitation occurs only under extreme saline conditions, and like magnesite and huntite, is not expected to be deposited at the Salton Sea.
5. Precipitation of calcite and gypsum, however, is expected, and gypsum deposition, in particular, was observed by independent investigators as part of the Salton Sea reconnaissance studies.
6. Sodium sulfate deposition has not been observed, and is not expected since the Sea is not saturated with sodium sulfate minerals, which usually do not occur except as evaporites, and will not precipitate out of seawater.
7. Since sodium, magnesium, potassium and chloride salts are water-soluble, precipitation is expected to be dominated by calcium, sulfate, carbonate, or calcite and gypsum as predicted by standard geochemistry. Because of

the levels present, carbonate concentrations are controlled by the formation of calcite, calcium concentrations by the formation of gypsum, with the excess of sulfate remaining in solution. Assuming precipitation of all incoming bicarbonate and calcium, 39% of the annual salt load is expected to be deposited. Depending on how this salt precipitation works out, the rise in salinity may be chemically slowed due to this mechanism.

Z. Conclusions.

1. The Salton Sea is a eutrophic system characterized by periodic low dissolved oxygen concentrations which lead to fish die-offs, particularly during the summer months.
2. Nutrient ratio studies indicate that algal growth is probably phosphorus limited, and management solutions should focus on phosphorus removal.
3. Although phosphorus loading has doubled over the last 30 years, phosphorus content in the Sea has decreased. The likely culprits are sequestering of phosphorus in biotic tissue and bone, and an abiotic sequestering of phosphorus in hydroxyapatite mineral formation.
4. Nitrate concentrations are quite high in the rivers, and denitrification is likely maintaining currently low nitrate levels.
5. Ammonia, on the other hand, shows little or no reduction, and remains above regulatory limits. Ammonia toxicity represents an additional source of stress on biota.
6. The Sea is supersaturated with calcite, gypsum, celestite, hydroxyapatite, and fluorapatite. Formation of calcite, gypsum and celestite leads to precipitation of calcium, strontium and some sulfate entering the Sea, whereas apatite formation could provide a sink for phosphorus.
7. Future rises in salinity may be slowed by the presence of calcium and gypsum, which have now reached saturation in the waters of the Salton Sea.
8. Hence, chloride, sulfate and total dissolved solids are primary problems in Salton Sea water. Chlorine and TDS are indicative of the ongoing salinity problem, and sulfate is from fertilizers used in agriculture in the vicinity.
9. Some mechanism is sequestering selenium and phosphate, which must be discovered. Also, un-ionized ammonia must be examined.
10. This may be where we state that waters of the Sea are relatively clean, and the actual problems are high salinity and over-nutrification. Sequestering and reactivation of selenium and phosphate are the keys to pollution and eutrophication stories.
11. The Salton Sea is supersaturated with calcite, gypsum and other minerals, and precipitation of these other minerals may limit the rate of salt or other substance accumulation in the Salton Sea.