VOLUME I

SUMMARY AND CONCLUSIONS

DRAFT FINAL REPORT 1987

PHYSICAL/CHEMICAL OCEANOGRAPHY PROGRAM AT SONGS

Submitted to: Marine Review Committee
531 Encinitas Blvd., #105
Encinitas, CA 92024

Submitted by: John Reitzel
Hany Elwany
Karel Zabloudil
M. Rustin Erdman
Principal Investigators

ECOSystems Management Assoc., Inc.
531 Encinitas Blvd., Suite 119
Encinitas, CA 92024

January 27, 1988

VOLUME I

SUMMARY AND CONCLUSIONS

TABLE OF CONTENTS

Page No.

SUMMARY AND CONCLUSIONS

1. OBJECTIVES, RATIONALES, AND BRIEF HISTORY OF PHYSICAL/CHEMICAL PROGRAMS

The principal task of MRC is to assess effects of SONGS on local marine life. The principal strategy is to make statistical comparisons of the abundances of selected species and groups, between places close to SONGS and far away, and between times before and after SONGS began operation. Constant natural differences between near and far places and uniform natural changes over time are all subtracted out in these comparisons, isolating changes that took place only near SONGS and only after it began operation. This is an objective method, in the sense that it can observe this kind of change, and estimate its magnitude and statistical significance, without hypotheses about the process or mechanism that produced the change. The final step of attributing a particular change either to SONGS or to some non-uniform natural effect, however, may depend on an evaluation of processes and mechanisms to decide that one explanation is more reasonable and likely than another.

The chains of mechanisms by which SONGS may affect life in the sea begin with the physical interactions between SONGS and the natural conditions and processes that underlie the local ecosystems. These conditions, processes, and interactions are what must be understood to find the most likely explanations for statistically observed results. This is the most general reason why MRC included physical measurements in its programs from the beginning, and later on brought these together in a single physical-chemical program.

There are more immediate reasons also. Some biophysical relations are fairly clear from the start; marine plants require both light and nutrients, for example, and some fish avoid waters that are too hot or too cold for them. If relevant physical variables are measured along with abundances, the observed physical changes may be useful to refine and sharpen the statistical comparisons as well as to judge between explanations of their results. The beds of giant kelp near San Onofre present a particular case. These have a known history of non-uniform natural changes, with individual beds dying out and recovering at different times. For these, the strategy of statistical comparisons was directed not to the abundance of adults but to rates of recruitment and growth of new kelp plants in field experiments comparing before with after and near with far. The field program included measurements of temperature, irradiance, nutrients, and the flux of sediment particles in the water, and the statistical design included regressions to assess the importance of these physical factors in kelp recruitment and growth in the field, along with statistical comparisons to measure changes both in recruitment and growth and in the physical factors.

An important physical condition for most of the studies is the rate at which things are carried about in the local waters, whether by coherent currents or by random dispersion. If SONGS draws in water at a certain rate at a fixed place, killing a fraction of all the plankton that are drawn in, the size and shape of the local depression in population density, and the eventual rate at which plankton are killed, depends on the rates at which new water and new plankton are brought to the region by currents and dispersion. If the discharge of SONGS adds some substance to the local seawater, the distribution of this substance will depend on the same rates. The basic data for estimating these rates come from current measurements, arrayed in time and space to show both the organized and random parts of the currents.

In the fall of 1976, MRC mounted a brief but intensive field program to describe the physical-chemical environment in the sea off San Onofre. This program included studies of the physical and biological effects of the existing SONGS Unit 1, as a partial indicator of effects to be expected from the much larger Units 2 and 3. After this, a wave recorder and two current-measuring stations were set up off San Onofre. A study of the long-range coherency of currents (sponsored by SCE) was carried out south of San Onofre to evaluate the exchange of water across the shelf. In the years 1978-80, the current measurements at San Onofre were expanded to an array of seven stations to give a spatial description of the local current field, and a study of the local coherency directly off San Onofre was carried out.

Meanwhile the biological programs were under way, with some associated physical measurements. Besides the measurements going with the kelp experiments, there were regular measurements of temperature, irradiance, and dissolved nitrogen on the cruises made to collect plankton, and regular analyses of grain-size and organic components of sediment cores collected along with samples of bottom-dwelling animals.

At this time, MRC saw a need to evaluate the qualitative idea that the plume of SONGS would carry suspended particles offshore over the San Onofre kelp bed, reducing the light available to kelp plants near the bottom. The first point to settle was the actual relation between the extinction of light (the fractional decrease per meter of depth) and the size and concentration of suspended particles (seston) in the water. A program of field observations was carried out in 1980, in which extinction was measured at many places and depths by a pair of light sensors while samples were taken from the water between the sensors. These measurements showed it was valid to say that the re-distribution of extinction by SONGS is similar to the re-distribution of seston, and to predict changes in irradiance on that basis. A numerical simulation from local data on natural extinction and currents, and from a hydraulic model of the SONGS discharge, predicted that the reduction of average irradiance in the kelp bed would probably be large enough to matter, so that a considerable effort to observe the actual change was in order.

In 1981, MRC brought together all the physical and chemical measurements in the biological programs into a single program. The main continuing tasks in this program were to measure irradiance, temperature, seston flux, and dissolved nutrients at the sites of the kelp experiments; to measure temperature, irradiance and nutrients in conjunction with the plankton-collection cruises; to analyse sediment cores; to continue the recording of current at two stations and wave-climate at one station; and to establish databases, some of them very large, for all the physical and chemical measurements. Except for the recording of currents and waves, these groups of measurements served specific needs of the biological programs.

A separate task of more general use was to carry out a series of cruises with detailed profiles of temperature, salinity, irradiance, and dissolved nitrogen species in waters from near the shore out to 100 m depth or so, to explore the relations between conditions inshore and offshore. A particular aim of these cruises was to clarify the relations of dissolved nitrogen to depth and temperature, offshore and inshore. It also turned out that the data from these cruises gave a detailed account of the local onset and early course of the 1982-1984 El Nino event. Another special study was a repetition of the coherency study south of San Onofre in the winter of 1982-83, to look for seasonal differences in cross-shelf exchange.

The occurrence of kelp and cobble substrate had been regularly mapped for SCE since 1977 by side-scan sonar. Beginning in 1981, a new method was developed for mapping the population density of adult kelp plants by downlooking sonar surveys. This method, calibrated by a series of kelp censuses by divers, was used for twice-yearly surveys of density in the San Onofre and San Mateo kelp beds, continuing from 1982 through 1987, to document the course and the pattern of population changes in these beds.

The emphasis of the physical and chemical studies changed to some degree in 1983, because both Units 2 and 3 of SONGS were now approaching a state of regular full operation and the After period of the biostatistical studies was beginning. MRC had considered a number of ways to monitor the plume of SONGS, with the objective of detecting and measuring changes that could be attributed to SONGS, more directly and in more detail than could be done by overall before-after near-far comparisons. It had already become evident that both the natural state and any effects of SONGS would be highly variable in time, and that it would not be easy to separate natural from SONGS-induced variations. The method that was adopted was another statistical comparison, between hourly values of irradiance recorded simultaneously on opposite sides of the SONGS diffusers. These comparisons would eliminate uniform variations over time, and constant differences between places, leaving the differences due to one station being downcurrent from the diffusers, or in the plume, and the other station being upcurrent. This program involved setting out a considerable array of current meters and irradiance recorders; it was combined with the continuing physical measurements at the KEP stations by using the existing kelp stations and setting up counterpart stations on the other side of the diffusers.

For a different and more direct way of looking at the plume, a number of studies of the plume at particular times were undertaken, beginning with some rapid surveys of temperature and turbidity in 1983 and 1984, and continuing later with aerial photography and dye studies in 1986 and 1987. The most important of these were dye-studies of two kinds: one to describe the velocities and displacements of water flowing toward the diffusers and away in the plume by tracking dye-patches, and the other to measure the actual near-field dilution of the discharge by injecting dye into an intake of SONGS. Other physical projects in these years included special studies of the directional and spectral distributions of light near the bottom in 14 m depth, and the development of continuous samplers of water and seston.

All physical-chemical fieldwork ended with the end of 1986, except for the dye-studies and kelp survey in 1987.

2. PHYSICAL/CHEMICAL OCEANOGRAPHY

2.1 The Natural Environment; Processes Affecting Local Marine Life

Every living thing in its habitat, however well adapted, faces limiting factors at some point in its life-cycle which set bounds to its numbers or its range. This summary discussion of oceanographic processes and conditions off San Onofre is not meant to be an overall description, but concentrates on limiting physical and chemical factors. The most fundamental are those that apply to marine plants, since practically all marine animals ultimately depend on marine plants. The main physical problem of plant life in the sea, common to drifting microscopic plants and to anchored giant kelp, is to bring together light from above and dissolved chemical nutrients from below. At the surface of the sea there is usually plenty of light, but nutrients are mostly locked up in the biomass of the existing plant populations. In deeper waters there is less light, but dissolved nutrients become available from a reservoir at depth, formed from organic matter that sank out of the light and decayed in darkness. We will consider in some detail how light falls off with depth in the shallow nearshore waters off San Onofre, and how dissolved nutrients reach these waters from the deep offshore reservoir.

The measure of light intensity used in these studies is the downward planar irradiance, in units of Einsteins per square meter per day (E/m^2-day). This unit represents one mole of photons available for photosynthetic reactions, arriving from above in the course of one day. The sunlight reaching the surface of the sea off San Onofre ranges from about 50 E/m^2-day in midsummer to about 20 E/m^2-day in winter. The intensity of light generally needed to support plant metabolism and growth lies in the range from about 0.1 to 1.0 E/m^2-day, on the order of one percent of the average surface irradiance. Light decreases by a fraction of itself with each increment of depth in the sea, because of absorption by the water itself, dissolved organic pigments, and suspended particles of all kinds, which come together under the general name of seston. This fraction, called the extinction, ranges widely from about 0.15 to nearly 1.0 per meter in the nearshore waters off San Onofre, with mid-range values between .25 and .40 commonly observed in any season. For a surface irradiance of 35 E/m^2-day, an extinction of .25 m^{-1} gives an irradiance of about 1 E/m^2-day at a depth of 14 m, and an extinction of .40 m^{-1} gives an irradiance of about 0.1 E/m^2-day at 14 m. This is the depth of the bottom in the outer part of the San Onofre kelp bed; new kelp plants starting life here have a marginal existence in the sense that they may depend on unusually low values of extinction to get enough light at critical times. New kelp plants, in fact, are not recruited every year.

Above the minimum value of about .15 m^{-1} due to absorption by water and pigments, the variations of extinction are due to widely varying amounts and sizes of suspended particles in the water. Careful measurements of extinction and seston in waters off San Onofre showed a high linear correlation of extinction with the cross-section (the volume concentration divided by the grain diameter) for seston with a wide variety of size and composition. Most of the seston is made up of inert mineral grains with diameters from a few hundredths of a millimeter down to a few thousandths. The immediate source of these grains is the sediments on the bottom, which are suspended by waves and carried further upward in the water column by turbulence in the currents. The ultimate sources are the load of fine particles carried in the runoff of local streams, and the erosion of fines from the coastal bluffs by waves. Both of these ultimate sources are highly episodic; nearly all the sediment supply from runoff comes in extreme floods, and nearly all the coastal erosion comes in extreme storms.

The flux of seston has been monitored with simple seston traps at several stations off San Onofre, along with irradiance and extinction. The traps select against the finest particles that produce most extinction for their weight, so these variables sometimes do not track closely, but it is generally useful to consider them together. Both seston flux and extinction tend to be high when waves are high, but the relations are not simple. The amount of sediment re-suspended in a wave episode is more closely related to the maximum wave height in the episode than to the average: the highest waves produce most of the re-suspension. The mean significant wave-height of about 1.2 m is about the same in summer and winter, but extinction and seston flux tend to be higher in winter because extreme waves occur more often in winter.

There are further complications: the same wave episode may bring high seston flux and extinction at one place but not another, and high waves following soon after a previous episode may not produce high extinction or seston flux at all. There are several lines of evidence indicating that extinction at any place depends on a variable supply of finer-than-normal grains to the bottom as well as on wave height, and that this variable supply comes from sporadic patches of fine sediment making their way by repeated suspension and dispersal across the inner shelf to their resting-place in deeper water. This patchiness in time and space brings yet another random factor into the course of extinction and irradiance, and the prospects for recruitment of new kelp, at any place and season.

In the topmost waters where there is a surplus of light, microscopic plants multiply until they take up nearly all the dissolved nutrients, and then survive at low population densities on a small supply of nutrients recycled locally from excreta and dead organisms. Much organic matter is lost from this cycle by sinking out of the illuminated waters; this matter is oxidised to nitrate, phosphate, and other oxidized forms of dissolved nutrients by bacteria that can live in the dark. Over the long history of life in the ocean, this process has formed a vast reservoir of nutrients in the deep sea; the top of this reservoir is locally and intermittently tapped by plants through physical processes that bring deeper waters back up to the illuminated zone. The chief processes are vertical mixing and upwelling; these are controlled in different ways by the stratification of density, which largely depends on temperature in the upper waters near San Onofre.

A uniform water column can be stirred with no loss of energy except to viscosity, but a stratified column with hotter water overlying colder and denser water cannot be mixed without expending considerable further energy in raising its center of mass. This energy is taken from the vertical turbulence, which is strongly inhibited in stratified water. There is a continual battle in the upper layers of the sea between solar heating, which tends to produce stratification with hotter and lighter water on top, and mixing by winds, which tends to make the water column uniform.

In the sea off Southern California, the sun has the edge, and the water column is more or less stratified except for short periods in the windier winters. In nearshore waters off San Onofre, the water at 14 m depth will generally be five or six degrees Celsius colder than the surface in midsummer, and a little under one degree colder in winter; only rarely is the difference in winter as small as one or two tenths of a degree. In deeper water offshore, there is a fairly stable permanent stratification. The top of the nitrate reservoir generally coincides with the level of the isothermal surface at 14°C: nitrate is low, on the order of 1 micromole per liter or less, in waters hotter than 14°C, and rises linearly as temperature falls below 14°C, reaching about 28 micromoles per liter in water at 10°C. This local nitrate-temperature relation has been found to be stable through very large excursions of the depth of the 14°C isotherm.

At 14 m depth off San Onofre, about 2 kilometers offshore, the mean bottom temperature in ordinary years is in the range 14 to 15°C. Most of the supply of nutrients to these shallow waters comes by horizontal mixing from offshore waters at times of lower-than-average temperature. Some comes from upward mixing when stratification is at a minimum in winter, but still more comes from particular events called upwellings, in which the isothermal surfaces in stratified water rise toward the coast so that water colder than 14°C encroaches on the nearshore zone. These events occur when the current flows persistently downcoast with a stratification of velocity, faster at the top than at the bottom. In water much deeper than 20 m or so, such stratified currents are mostly due to local winds, but in shallower water all currents are more or less stratified because of bottom friction. The rotation of the earth accelerates moving water to the right of its path, in proportion to its velocity; a vertically-uniform current moving downcoast near the shore will adjust its flow to set up a small slope of the ocean surface downward toward the shore, balancing the acceleration with the horizontal pressure-gradient due to the slope. With a stratified current in density-stratified water, the seaward acceleration will decrease from top to bottom, and a pressure-gradient that balances the acceleration at all depths can only be set up by a flow that produces both a surface slope downward toward shore and much larger opposite slopes of isothermal surfaces in the water, upward toward the shore. Upwelling is often described much more succinctly as a flow of deep water to replace coastal surface water driven offshore by the wind; this would not fully represent the situation at San Onofre, where some of the strongest upwellings come from offshore current patterns impinging on the coast, with little or no relation to local winds.

Upwellings that reach the inshore waters off San Onofre often occur in March and April as the summer stratification begins to develop, and may occur as late as midsummer, in the time of maximum insolation. In late summer, upwellings rarely extend to shallow nearshore waters, and events of the opposite kind, called downwellings, are often seen in August and September. These are associated with upcoast currents; they involve a slope of the isotherms downward toward shore, with a wedge of warm surface water at or above 20°C occupying the nearshore zone to depths of 15 m or more and excluding nutrients from this zone. In extreme years, surface temperature in August or September may remain above 23°C for many days together; this may cause direct damage to kelp canopy, aside from any effect of excluding nutrients.

El Nino events are an extreme form of downwelling which occur when the perennial easterly trade-winds over the tropical Pacific slack off for a time, and the belts of westerly winds in the temperate zones encroach on the sub-tropics. This results in a mass-movement of warm nutrient-poor surface water to the eastern side of the Pacific, where it forms a very deep wedge against the coast, actually raising mean sea-level by 10 cm or more. This condition can last as long as two years, and the depression of nutrient-bearing water to many tens of meters below the surface drastically reduces the populations of microscopic plants and all the the animals in the food-webs that depend on these plants. Another effect is the extreme rainstorms produced by westerly winds blowing from the ocean to subtropical coasts.

Minor or moderate El Nino events occur at irregular intervals averaging about five years. Major El Nino events in this century came in 1914-15, 1941-42, and 1957-58, followed by the most recent and perhaps the greatest, which arrived in the fall of 1982 and stayed through the summer of 1984. Starting in August of 1982, the normal nearshore water off San Onofre was replaced in rapid stages by surface water from several hundred kilometers offshore to the west, identifiable by its low salinity. For the next two years, temperature was abnormally high in all seasons and nutrients were generally depressed to depths below 30 m, inaccessible to plants in the nearshore waters, except for brief remissions during upwellings in the early summers of 1983 and 1984. The winter of 1982-3 was a time of intense storms in Southern California, with waves at San Onofre sometimes exceeding 3 m in height.

This El Nino, like its major predecessors, gravely reduced marine populations of plankton, fish, and birds over vast regions, illustrating again that the dependence of nearly all life in the sea on plants makes itself felt quickly. Occurring in the very years in which SONGS Units 2 and 3 went from intermittent testing to full operation, it produced large but widespread natural changes in the conditions and populations in the waters off San Onofre, which would have confounded any statistical method of detecting SONGS effects less complete than the before-after-near-far comparisons applied in MRC's studies.

2.2 Interactions of the SONGS Cooling System with Natural Processes

SONGS Units 2 and 3 together draw in 104 m^3/sec of cooling water at intakes in water about 9 m deep, about 1 km from shore. This water is heated by about 10.7°C in the powerplant and is discharged back to the sea through staged diffusers, which are assemblies of jets (126 in all) mounted on pipes in line offshore, starting in 10 m depth at 1 km from shore and going out to 15 m depth at 2.5 km from shore. The individual jets have an initial diameter of .5 m and an initial velocity of 4 m/sec; they are mounted 2.2 m above the bottom, and are aimed 20°C upward from the horizontal and 25°C upcoast and downcoast in alternation.

The staged diffuser design is intended to limit the local rise of temperature in the receiving waters by producing maximum entrainment and mixing of ambient water into the discharge, and also to convey the discharge offshore at times when currents are weak close to shore. Within two or three hundred meters of the diffusers, the discharge is diluted by about 10 times its volume of ambient water entrained in the jets. At this distance the individual jets have approached the surface and coalesced into a dilute plume with a temperature contrast on the order of 1°C or less and a velocity contrast on the order of 10 cm/sec or less relative to the surrounding waters.

The configuration and behavior of the plume depends strongly on the current and on the stratification of temperature and density. When the longshore current is slow, say 3 cm/sec or less, the plume goes offshore along the diffusers, and may spread from a pool beyond the end of the diffusers. With faster currents the water is carried farther downstream as it moves offshore, until in a current of 20 cm/sec or more it makes only a small angle to the shoreline. In weakly-stratified water, the diluted plume will be hotter and less dense than ambient surface water, and will form a layer in the uppermost few meters. With strong stratification, the plume will often be cooler and denser than surface water. After coming initially to the surface it may sink again and spread in the stratum of matching temperature and density. Since the depth of the discharge ports increases from about 8 to 13 m along the length of the diffusers, it is even possible for the plume to split, with the offshore part moving along the bottom, while the inshore part moves on the surface.

The plume continues to entrain ambient water as long as the velocity contrast is appreciable, and the discharge is found to be diluted by about 20 parts of ambient water at distances of about a kilometer from the diffusers. At distances beyond three kilometers or so, the plume is carried passively by the current and entrainment becomes indistinguishable from ordinary oceanic mixing. Instantaneous values of dilution have not been measured at these ranges, but it is roughly estimated from statistics of the current that the long-term mean dilution of the discharge at places within a kilometer or two of the shore rises to about 100 to 1 at 6 km downcoast or 3 km upcoast from the diffusers, and to about 200 to 1 at 11 km downcoast or 7 km upcoast. The asymmetry is due to the long-term mean current of 3 cm/sec downcoast.

With this amount of dilution, the temperature contrast between a surface plume and underlying unstratified water will fall off to a few tenths of a degree Celsius within the first kilometer or so, even if there is no loss of heat by exchange with the atmosphere. A subsurface plume in stratified water will show only as a small step or change of slope in the stratification at the equilibrium depth, which will similarly fall off and be lost in the background variation beyond about one kilometer.

The water entrained close to the diffusers, making up about 90% of the water in the plume, is carried at least a few hundred meters offshore in a few hours by the original momentum of the jets, along with its seston and the associated extinction. Since ambient extinction generally decreases to seaward, the water in the plume will generally have higher extinction than ambient water at the same distance from shore. This seaward translocation of nearshore water and seston is what brings about the main effects of SONGS on underwater irradiance.

The flow of discharged and entrained water in the plume away from the neighborhood of the diffusers is only half of the total flow field due to SONGS, however. An equal flow of about 1000 m^3/sec or more toward the diffusers and intakes is required to make up the ingested and entrained water. At some distance, the make-up flow by itself is more or less radially inward to the diffusers from all seaward directions, with most of the water coming from the deeper sectors more directly offshore. With a strong longshore current superimposed, the make-up water comes immediately from whichever direction is upstream at the time. Since the inward radial make-up flow persists through all current reversals, though, practically all of the make-up water that reaches the intakes or diffusers will have been ultimately brought from some distance offshore. A shoreward component of the flow upcurrent from the diffusers is observed as a persistent pattern in the records from current meters near the diffusers.

If the make-up water moved toward shore slowly enough, it would mix with so much nearshore water on the way that it would not be distinguishable from nearshore water. If it moved inshore quickly enough, it could retain its original clarity and other properties of offshore water. It is a difficult problem to estimate quantitatively the extent to which the make-up water preserves its original properties in transit, but it can be expected that make-up water will have properties somewhere between those of ambient nearshore and offshore waters.

With no ambient current, water near the diffusers will flow toward the diffusers from both sides at about 5 cm/sec to supply the plume going offshore. In an overall longshore current of 10 cm/sec say, the velocity near the diffusers will be increased to about 15 cm/sec, just upstream from the diffusers, and reduced to about 5 cm/sec in the water under the plume just downstream from the diffusers. In general, some water will flow across the diffuser lines and escape under the plume when the longshore current exceeds 5 cm/sec or so, but this water will have its velocity reduced by about 10 cm/sec. The turbulence due to bottom friction, which lets the current keep seston in suspension, will be correspondingly reduced, and some particles can settle out downcurrent from the diffusers. Some of these may be re-suspended and carried back to the diffusers with the next reversal of the current. Again, some of them will be entrained and carried away, and some will get through the diffusers to settle out once more as the velocity drops. This mechanism for trapping seston in the vicinity of the diffusers will not necessarily lead to continued accumulation of sediment, for two reasons: entrainment of seston may keep pace with the trapping, and the ambient regime of waves and currents can still re-suspend the trapped seston from time to time and disperse it offshore. The reduction of velocity across the diffusers may, however, lead to greater local concentrations and fluxes of seston near SONGS. Since the current flows downcoast more than 60% of the time, more seston may be trapped on the downcoast side of the diffusers than on the upcoast side.

There is direct evidence from a dye study that stagnation of the flow between the separate plumes of Units 2 and 3 can occur in the region between the Unit 2 diffuser and the San Onofre kelp bed downcoast. The results of the dye study also show that the velocity in the plume itself can be markedly reduced when the plume impinges on the upcoast and inshore boundaries of this kelp bed (as it was in April 1987). These particular regions of reduced velocity may act as local seston traps.