ELSEVIER

Effects of a Large Sewage Spill on a Kelp Forest Community: Catastrophe or Disturbance?

M. J. Tegner,[a]* P. K. Dayton,[a] P. B. Edwards,[a] K. L. Riser,[a]
D. B. Chadwick,[b] T. A. Dean[c] & L. Deysher[c]

[a]Scripps Institution of Oceanography, University of California, San Diego, La Jolla,
California 92093-0201, USA
[b]Naval Command, Control, and Ocean Surveillance Center, Marine Environmental
Quality Branch, San Diego, California, USA
[c]Coastal Resources Associates, Inc., 1185 Park Center Drive, Suite A, Vista,
California 92083, USA

ABSTRACT

*San Diego's sewage outfall broke during winter 1992, spilling 7.1×10^8 litres/d of treated effluent in kelp forest depths for a two month period during an El Niño event. The ecological implications for the Point Loma kelp forest community were studied by comparing long term data with conditions during and after the spill. Surface ammonium concentrations within 1 km of the break were at potentially toxic levels, and light levels were reduced enough to have inhibited kelp germination and growth. However, because of El Niño conditions, it is unlikely that kelp would have germinated in the absence of a spill. Beyond 1 km, high ammonium concentrations benefitted the nutrient-depleted surface canopy of giant kelp (*Macrocystis pyrifera*). Measured sedimentation rates were significantly higher near the outfall during the spill and were strongly related to wave height; water motion, however, prevented sediment accumulation. Bioassays were conducted on a grid of stations surrounding the outfall. There were significant reductions in the density and growth of microscopic sporophytes of* Macrocystis *out-planted near the outfall during the spill, but this pattern disappeared in samples collected 11 d after the repair was completed and was not observed again. Sediments collected near the outfall during the spill significantly reduced* Macrocystis *germ tube elongation; a post repair assay showed no differences with respect to the outfall. No significant effects were observed in outplants of juvenile* Macrocystis *sporophytes, cup corals, and juvenile abalones. Video transects during the spill and subsequent diving observations provided no evidence of sediment accumulation or negative impacts on*

*To whom correspondence should be addressed.

established animal populations. Kelp population dynamics at the permanent sites were predictable from existing population structure and El Niño conditions. Damage to kelps, apparently resulting from a combination of low light and nutrient conditions with mechanical damage from storms, construction activity, and barge anchor cables, was observed along the outfall immediately adjacent to the break point. Shortly after the outfall was repaired, upwelling improved conditions for kelp germination and growth, and the zone of maximum impact developed into a dense kelp forest. Suspension feeders, detritivores and sea urchins, whose natural history indicates they could have been affected by the spill, showed no unusual population changes. In the context of the continuum of disturbances observed in two decades of population studies at Point Loma, the spill was a modest disturbance similar to the natural vagaries of kelp recruitment. We emphasize that this spill was an intense but not chronic impact during an El Niño event that also stressed control areas. However, it is representative of massive spills in coastal regions, and the fact that a sewage spill of this magnitude had no lasting effects on a kelp forest community is of general interest.

INTRODUCTION

The City of San Diego's sewage outfall pipe ruptured 1 km from shore in a depth of 12 m about 2 February 1992. For a two month period, an average of 7.1×10^8 litres/d with an estimated sediment load of 66.5 MT/d was released from a point source within the Point Loma kelp forest. Repair of the broken outfall was completed on 4 April 1992.

Forests of giant kelp (*Macrocystis pyrifera*) have a long history of disturbance in Southern California. Like the Palos Verdes kelp forest near Los Angeles, the Point Loma forest was decimated during the late 1950s/ early 1960s when poorly treated wastes were discharged nearby (California State Water Quality Control Board, 1964). Surface canopies of both forests disappeared in the face of the 1957–59 El Niño and intense sea urchin grazing. Large scale recovery of the Point Loma forest began after the sewage discharge was moved to its present offshore location in 1963 (Wilson *et al.*, 1977). Recovery was aided by kelp restoration and sea urchin control efforts (Leighton *et al.*, 1966; North, 1965; North, 1983). Subsequently there have been major technical improvements in sewage treatment (US NRC 1993) and a large sea urchin fishery has developed (Tegner & Dayton, 1991); the canopy area of the Point Loma forest stabilized in the 1970s. Large scale fluctuations during the 1980s were due to natural disturbances (Dayton *et al.*, 1992); nevertheless, strongly held perceptions of negative impacts of modern sewage disposal on the kelp forest community continue to affect public policy (Sun, 1989).

Because of the history of kelp forest susceptibility to sewage pollution and because the Point Loma kelp forest has experienced several large fluctuations in the last decade, this massive spill offers a rare opportunity to study the impacts of sewage subject to modern advanced primary treatment (US NRC 1993) in relation to natural variability documented in two decades of time series data (Dayton *et al.*, 1984;Dayton *et al.*, 1992) and general studies dating to the mid 1950s (e.g. North, 1971).

Past impacts of sewage discharge and recent ecological studies structured our approach. In addition to effects on giant kelp during the period of strong sewage influence at Palos Verdes, there were changes in algal species composition, dramatic reductions in both inter-and subtidal algal diversity, and reduced algal standing stocks (North, 1964; Strachan & Koski, 1969; Grigg & Kiwala, 1970; Harris, 1983). The area of the canopy at Palos Verdes was strongly negatively correlated with the mass emission rate of suspended solids from the Los Angeles County outfall during both its decline and subsequent recovery (Stull & Haydock, 1989). Thus we focused on population-level consequences for the laminariales at Point Loma. While community level indicators are not the most sensitive measures of pollution, they are better indicators of the consequences of pollution to processes of economic and social value in this important nearshore ecosystem (Underwood & Peterson, 1988). Because of the central role of *Macrocystis* in providing food, shelter, and substrate for many of the organisms in the community (e.g. North 1971) as well as its susceptibility to disturbance (e.g. Dayton *et al.* 1992), it is critical to understand the effects of the sewage spill on all life stages of this species. We also considered effects on animals potentially sensitive to sewage or associated sedimentation. To separate the natural effects of the recent past history of the Point Loma kelp forest and El Niño conditions from the effects of the sewage spill, we relied on long term population data and measurements of temperature, dissolved oxygen, sedimentation, transmissivity, irradiance, wave height, and chemical analyses of water and sediments. There were impacts of the 1992 sewage spill on the Point Loma kelp forest, but they were short lived and insignificant in comparison with the natural catastrophes of the 1980s.

STUDY SITES AND METHODS

The City of San Diego provides sewage treatment for about 1.7 million people. The flow is 90% domestic in origin and industrial contributions are subject to source control programs. Sewage treated to the advanced primary level is normally discharged through an outfall which transects

the Point Loma kelp forest (Fig. 1). Discharge begins in 60 m depths 3.5 km from shore, 1.6 km west of the kelp forest, and is accomplished through two 366 m multiport diffuser pipes arranged in a 'Y' configuration. Advanced primary treatment entails use of coagulants and flocculating agents to increase removal of suspended solids; about 75% of the suspended solids were recovered from the effluent before discharge during the spill. The break was repaired from a large (30 x 91 m) construction barge and various support vessels. The barge was repositioned along the outfall by adjustment of multiple anchor cables. Because of high bacteria levels, the kelp forest was quarantined to divers with standard scuba gear until 8 April 1992.

The Point Loma kelp forest, generally about 8–10 km long by 1 km wide, is located on a broad, mudstone-sandstone terrace (Fig. 1). Permanent stations have been used for long-term population studies
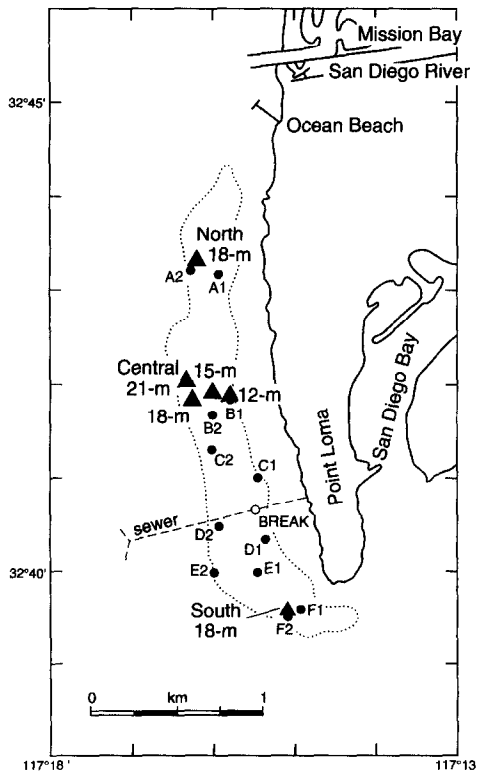
Fig. 1. The Point Loma kelp forest. Permanent study sites are marked with triangles; circles indicate the grid established to study the sewage spill. The dotted line represents a general outline of the *Macrocystis pyrifera* canopy; there is considerable temporal variation.

(Tegner & Dayton, 1981; Dayton *et al.*, 1984; Tegner & Dayton, 1987; Tegner & Dayton, 1991; Dayton *et al.*, 1992). There are four parallel 25 m transects at 12, 15, and 18 m in the center and at 18 m at each end of the forest. Kelps have been mapped quarterly since 1983. Benthic macro-invertebrate populations have been censused annually in spring along the lines, and sea urchin recruitment rates assessed twice a year during this period. Additional observations are reported from sites at 8 and 21 m in the center of the Point Loma kelp forest and from 15 m in the La Jolla kelp forest, outside the range of the sewage spill. About 160 hectares of the southwestern region of the Point Loma kelp forest (Fig. 2) became a sea urchin barren (*sensu* Lawrence, 1975) in the months following the January 1988 storm (Dayton *et al.* 1992; D. Glantz, Kelco, pers. comm.). During 1991, a massive sea urchin die-off occurred in about half this area, including 18 m South; urchin populations were not affected adjacent to stands of giant kelp. Kelp recruited in barren areas distant from urchin fronts in 1991.
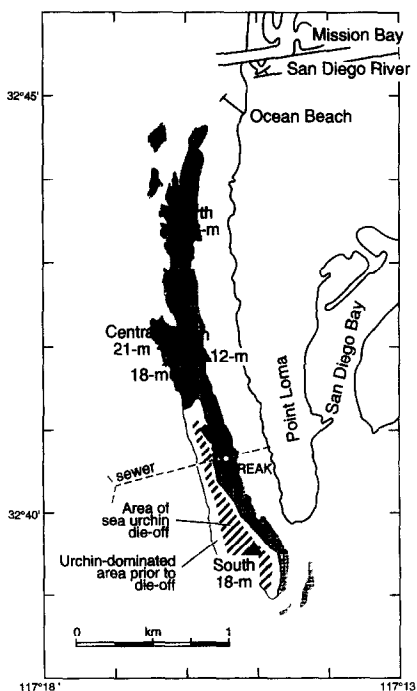
Fig. 2. The Point Loma *Macrocystis pyrifera* canopy in August 1990. The outlined area in the south represents the sea urchin barren that developed after the 1988 storm. During 1991, a massive sea urchin die-off occurred in the hatched area within the barren which subsequently underwent *Macrocystis* recruitment. Sea urchins adjacent to stands of kelp remained healthy. Data courtesy of D. Glantz, Kelco.

Temperature is inversely related to the concentration of nitrate, the nutrient which limits kelp growth; nitrate is not detectable above about 16°C in this region (Jackson, 1977; Gerard, 1982; Zimmerman & Kremer, 1984). This strong inverse relationship allows use of temperature as a surrogate for nitrogen availability or stress. In-situ temperatures were collected at the permanent sites with recording thermographs (Ryan Instruments, Inc., Kirkland, WA). Thermographs, generally deployed for three months at a time, were calibrated at the beginning and end of each deployment. Temperatures were determined every 3 h from the continuous record (8 values per day), adjusted for calibration, and averaged by month.

Plume dispersion and rate of dilution were determined on 27 February, 17 March, and 31 March 1992 via near-surface mapping and vertical casts with the Navy's Marine Environmental Survey Capability (MESC). The MESC was configured with a flowthrough sensor system that provides a continuous stream of near surface (1 m) seawater to the sensors. The in-situ sensor array contains hydrographic sensors (Sea-bird Electronics, Inc.) for measuring salinity, temperature, water depth, pH, dissolved oxygen, and transmittance. The seawater flowthrough system consists of a 1.27 cm i.d. Teflon^R tube embedded within the array's telemetry cable and connected to a centrifugal pump mounted on the deck of the vessel; water is pumped at about 5 litres/min. During surface mapping, the in-situ sensors were carried onboard and used in flowthrough mode to avoid kelp fouling. For vertical profiles, the sensor array was lowered through the water column.

Sensor measurements were combined with the ship's navigation and bathymetric data (Innerspace Model 440 digital fathometer) using the MESC real-time data acquisition and processing system. Data were recorded at a 4 sec acquisition rate which corresponds to a spatial resolution of approximately 8 m (at a ship speed of 6 kt). Position data were acquired using the global positioning system with typical accuracy of 5–15 m. All data were processed with appropriate calibrations to provide the final mapped results.

An important constituent of sewage is ammonium, a source of nitrogen for kelps, especially valuable under conditions of reduced nitrate availability. Ammonium is toxic to juvenile *Macrocystis* sporophytes at concentrations of 10–30 μM (Haines & Wheeler, 1978), but higher levels have been used to fertilize giant kelp canopies (North *et al.*, 1982). Surface water samples were collected on 1 April 1992 and analyzed for ammonium using the method of Parsons *et al.* (1984) by the City of San Diego's Metro Wastewater Division.

In addition to the long term stations, a grid of 12 sites, centered on the outfall along the 12 and 18 m depth contours, was established to study the

sewage spill (Fig. 1). Given the location of the break, the impact was potentially greatest at 12 m. The 18 m contour is near the outer boundary of the forest where light is most likely to be limiting for kelp germination. Spill site F2 is located at permanent station 18 m South; A2 and B1 are near 18 m North and 12 m Central respectively. The four northern sites (A1, A2, B1, and B2) were within the kelp canopy at the time of the spill. The irregular spacing of site C2 was dictated by repair vessel moorings. Sites were relocated by marker buoys and Loran C coordinates. Instruments and bioassays were attached to weighted (16 kg) plastic trays (74 × 66 × 9 cm) and deployed 5–6 March 1992 on buoyed lines adjacent to the marker buoys. Both buoys at site D2 were lost before 11 March, probably to construction vessel activity. Divers relocated the missing tray on 13 May.

To assess sedimentation, two 41 × 4 cm PVC tubes with sealed bases were attached to each tray, and collected weekly, weather permitting. Settled volumes were determined in graduated cylinders. Such tall tubes do not allow resuspension and thus are not representative of sediment levels on the substrate, but can be used to assess the total particulates available for sedimentation (Weaver, 1977). Differences in sedimentation rates along a depth contour were examined using a two factor ANOVA without replication using station and sampling dates as factors. The data, from three collections before and three after the spill, were log transformed (Zar, 1984). Because we have only six time points, there may not be complete independence among dates. Only five sites were examined on the 18 m contour because of the loss of the tray at D2. Sedimentation rates were compared with average wave height (Coastal Data Information Program 1992) during the same period with linear regressions using wave height as the independent variable. Significance of the regressions was tested against the null hypothesis of zero slope. Some sediment samples were analyzed for chlorinated pesticides, polychlorinated biphenyls, heavy metals, volatile solids, and sediment grain size distributions by the Metro Wastewater Division's chemistry laboratory using standard methods (US EPA, 1986).

The impact of the sewage spill on light was assessed in two ways. Secchi depths (e.g. Conversi & McGowan, 1992) were collected at the spill sites and at additional sites near the break on the 12 m contour. Four sets of measurements during the spill and four in the month following the repair were compared. Differences in Secchi depths were examined with a two factor ANOVA without replication using stations and sampling dates as factors after log transformation of the data (Zar, 1984). Again, because there are only eight time points, there may not be complete independence among dates. Kruskall–Wallis tests were used to analyze spatial variability

before and after the repair. Integrated quantum irradiance was measured using LI-COR 192-S flat-plate, cosine-corrected sensors (LI-COR Inc., Lincoln, NE) attached periodically to the trays. These sensors measure photosynthetically active radiation (400 to 700 nm). Data were integrated over time and stored using an irradiance integrator/data logger designed by Ecosystems Management (Carlsbad, CA).

To evaluate effects of the spill on organisms, experimental outplants of microscopic and juvenile *Macrocystis* sporophytes, cup corals, and abalones were attached to the trays. Artificial substrata (nylon lines) were inoculated with *Macrocystis* zoospores cultured in the laboratory until sporophytes were produced, then outplanted along the 12 m contour. These inoculated substrata provided a defined population of sporophytes from which growth and survival could be assessed. Eleven pieces of nylon line (10 cm long, 0.64 cm diameter) were fastened to acrylic plates (30.5 × 10.2 × 0.6 cm) with plastic cable ties, allowing for the simultaneous inoculation of a large number of sampling units which could then be individually removed for analysis. Zoospores used in the inoculations were obtained from the La Jolla kelp forest. Inoculation and culture methods are detailed in Foster *et al.* (1985) and Deysher & Dean (1986).

Two sets of microscopic sporophyte experiments were conducted. The first substrata were inoculated on 19 February 1992 and outplanted on 4 March, one plate per station. The second set was inoculated on 24 April and outplanted on 11 May. Five lines were removed from each plate three weeks after outplanting and the remainder at six weeks. For the March experiment, substrata were collected on 25 March and on 15 April; May outplants were collected on 3 June and 24 June. The mean density of sporophytes on each line was determined by counting the number within 10 haphazardly selected 6.25 mm^2 quadrats. If fewer than 10 sporophytes were observed, the remaining area of each line segment was scanned systematically until 10 sporophytes were observed, or until the total area of line within the segment was scanned. Differences in mean sporophyte density and mean lengths were examined using Bonferroni's multiple range test (Milliken & Johnson, 1984). Separate analyses were conducted for each collection.

Juvenile (9–35 cm) *Macrocystis* were collected in the La Jolla kelp forest and six individuals were outplanted at each spill site. Holdfasts were individually threaded into three ply nylon lines and attached to sheets of polystyrene cube-louver light diffusers with plastic cable ties. Primary stipe and total length were measured when the trays were brought to the surface each week.

Corals are suspension feeders subject to mortality from excessive sediment buildup or scour (Weaver, 1977), or potentially from sediment toxicity.

Brown cup corals (*Paracyathus stearnsi*) were collected off La Jolla and outplanted beginning 11 March at 10 of the 12 sites, five animals per site. Corals were fastened into rings (sections of PVC pipe 11 mm deep, 15 mm i.d.) glued onto PVC plates with three screws per ring. Abalones were also outplanted because the juveniles live under rocks and ledges where sediments accumulate naturally. Cultured juvenile (average size 20 mm) red (*Haliotis rufescens*) abalones from McCormick and Associates (Ojai, CA) were outplanted 5–6 March. Eight animals were deployed per site in cages of plastic mesh containing an adult abalone shell for substrate; these were fed weekly with *Macrocystis* blades.

Standardized laboratory bioassays were conducted to examine potential toxic effects of sewage sediments on the germination and growth of *Macrocystis* spores (Anderson *et al.*, 1990b). Sediments tested came from the sediment tubes recovered from the 12 m contour on 25 March; control sediments from La Jolla were collected from the surface of the substratum by a diver. Additional samples were collected in July, four months after the outfall was repaired. Because sedimentation rates were greatly reduced by summer, nine sediment tubes each were placed at A1 and D1 as examples of sites far and near to the outfall, respectively. Divers also collected sediments from the substratum at each of the stations where sediment bioassays were conducted in March. Tests were performed on elutriates prepared from sediments using guidelines given in US EPA (1990). In most cases, a single elutriate was made from each sediment sample. For the multiple tube collections in July, sediments were composited, mixed thoroughly, and a sub-sample taken for elutriate preparation. Differences in mean germination rate and lengths of germ tubes among the stations were examined using Bonferroni's multiple range test (Milliken & Johnson, 1984).

To make in-situ observations during the quarantine, appropriately-equipped divers from Pelagos Corporation conducted video transects perpendicular to the outfall. Six 100 m transects, one on each side of the outfall in 12, 15, and 18 m, were taped 7–8 March, about a month after the break was discovered.

Aerial photographs (W. North, California Institute of Technology, pers. comm.) and boat level observations were made of the *Macrocystis* surface canopy during the spill. The former are useful for determining total canopy area and the latter for noting physiological condition. In-situ field observations began after the quarantine was lifted. Kelps at the permanent study sites were mapped quarterly as previously described (Dayton *et al.*, 1992). The spill and La Jolla sites were surveyed in May and June, followed by sites along the outfall. At the spill sites, 50 × 2 m transects were run using cardinal point directions from the marker buoy, for a minimum of 400 m^2 per site. Adult kelps, dead *Macrocystis*

holdfasts/holdfast scars, and plants with two stipes, as well as seastars and sea cucumbers were enumerated along these transects. Randomly placed 1 m² quadrats were used to assess kelp recruits, percent cover of turf algae, and other benthic macroinvertebrates, with a minimum of 10 m² per site. Similar transects were run perpendicular to the outfall pipe near the break site. When data from these transects suggested patterns varying with distance from the outfall, a series of stratified transects was conducted at four depths (10, 13, 16, and 19 m) on each side of the pipe, employing 40×2 m transects oriented parallel to the outfall at 5, 15, and 50 m distances from the pipe. Four or five 1 m² quadrats per transect were used to sample the lower standing algae and invertebrates as above.

Benthic macroinvertebrates were also censused at the permanent sites after the spill. All animals visible with a light without disrupting the substrate were counted. Sea urchin densities in 1991 and 1992 were compared using a Mann–Whitney U-test. Urchin recruitment rates were assessed from size frequency distributions at the permanent and some of the spill sites, and at sites 100m north and south of the outfall in 12 and 18 m. A 1 m² frame was haphazardly placed over aggregations of urchins in boulder piles (away from the transects at permanent sites) and the boulder piles were torn apart to search for urchins. We attempted to measure a minimum of 100 individuals each of purple (*Strongylocentrotus purpuratus*) and red (*Strongylocentrotus franciscanus*) urchins per sample. If one species greatly outnumbered the other, additional 1 m² samples of only the latter species were taken to obtain an adequate sample size. Test diameter was measured to the nearest millimeter with vernier calipers. Urchins smaller than about 10 mm are not quantitatively sampled by this method (Tegner & Dayton, 1981). Young-of-the year urchins are defined as red urchins $\leqslant 35$ mm and purple urchins $\leqslant 25$ mm (Tegner & Dayton, 1991).

RESULTS

Ambient physical conditions

High seawater temperature and high sea level, an indication of altered coastal currents, together are characteristic of El Niño events (Chelton *et al.*, 1982). Hayward (1993) reviews the evidence for El Niño conditions in the California Current region in 1991–1992. Sea level at the Scripps Institution of Oceanography (SIO) pier, 9 km north of Point Loma, was above normal for several months; the values for February thru April 1992 were the highest ever observed for these months, indicating that at least for the period of the spill, this El Niño was a strong event. There was

rapid change in California Current structure in April–May 1992; sea level and temperature declined and strong southward flow returned. Both sea level and temperature increased later in the year, but the relationship to El Niño was not clear (Hayward, 1993). The NOAA El Niño Watch (NOAA, 1992) reported that the reintensification of sea surface temperature anomalies off Southern California observed in fall 1992 was probably not due to a re-establishment of El Niño, but a result of variability in North Pacific atmospheric pressure distribution patterns and resulting wind, air–sea interaction, and regional/local oceanic processes.

El Niño conditions were also reflected in temperature data. SIO pier surface temperatures (Fig. 3) were well above the 68 yr mean for much of 1992. Surface temperatures exceeded 16°C, a level normally reached in May, by mid February and temperatures in May were up to 6°C above average. Bottom temperatures at Point Loma, which vary with depth and position in the forest (Tegner & Dayton, 1991, Dayton *et al.*, 1992), were also well above normal. Average monthly temperatures for February and March 1992 were warmer than all previous years of our in-situ records dating to mid 1983 (data not shown). Very warm bottom temperatures through March were followed by a marked drop in early April at 21 m
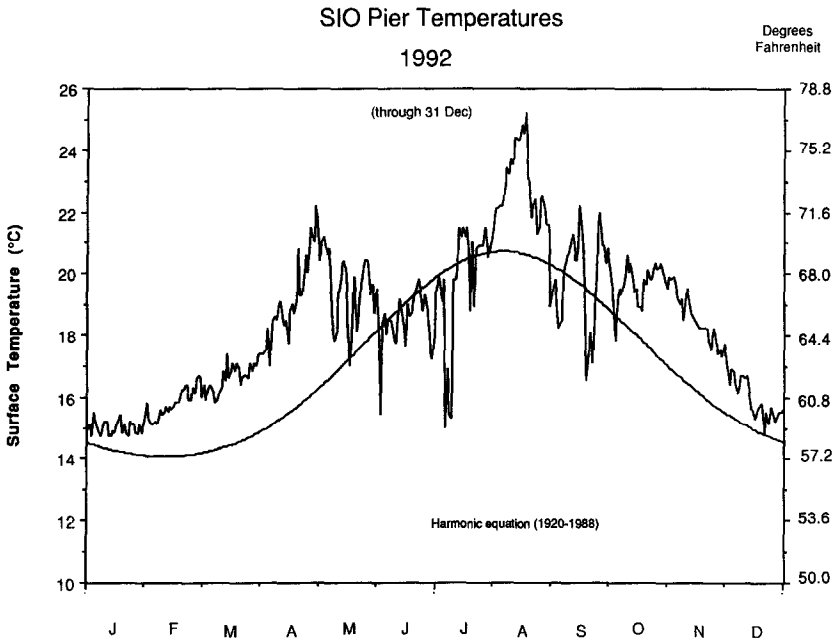
Fig. 3. Surface temperatures from the Scripps Institution of Oceanography pier, 9 km north of Point Loma. The smoothed line represents the daily average from 1920 to 1988; the irregular line is the daily record for 1992.

and in May at 8 m (Fig. 4). While there was considerable fluctuation, temperatures under the thermocline were optimal for kelp germination and growth from April through mid July; hand-held thermometer readings for this period ranged from 11.5–14.8°C at all Point Loma stations deeper than 8 m. Bottom temperatures exhibited their typical mid summer-fall rise (see Dayton *et al.*, 1992); the major anomaly during 1992 encompassed the period of the spill.

Large waves are a major source of *Macrocystis* mortality at Point Loma (Dayton *et al.* 1984; Seymour *et al.*, 1989; Dayton *et al.*, 1992). Wave data from the Mission Bay buoy (Lat. 32° 45.9', Long. 117° 22.5', about 13 km offshore of the entrance to Mission Bay) were collected by the Coastal Data Information Program, 1991, 1992; see Seymour *et al.*, 1985 for a description of the data gathering system and analysis techniques. In November and December 1991, significant wave height (average of the 1/3 highest waves) exceeded 3.0 m on two days, both with values of 3.2 m but separated by 35 days; all other values were 2.5 m or less. Waves during
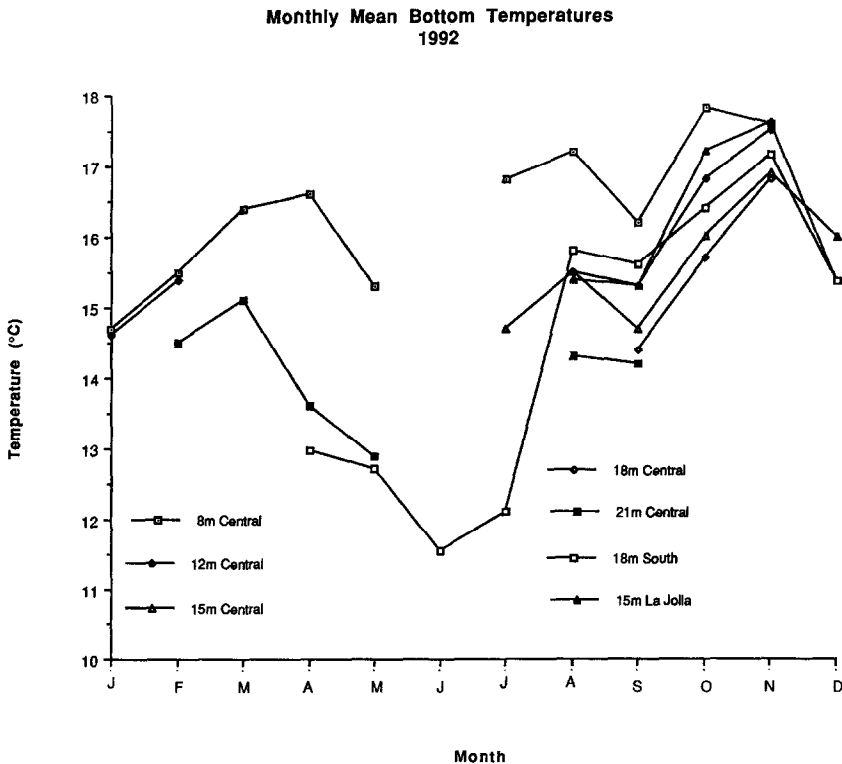
Fig. 4. Summary of the available in-situ temperature records for 1992. Points represent monthly averages. The quarantine and equipment failures caused gaps in the data.

the first quarter of 1992 were less than 3.0 m significant wave height; from April through August 1992 no waves exceeded 2.0 m significant wave height. Thus waves during the 1991–92 storm season were modest in size in comparison with events during the past decade which produced massive giant kelp mortality at Point Loma (Seymour *et al.*, 1989), but apparently were strong enough to cause some canopy reduction and mortality of nutrient-stressed plants, especially in the inshore region of the forest (see Field Observations).

Physical description of the sewage spill

The path and speed of the sewage plume during the spill were highly variable, depending on the speed and direction of wind and currents. The
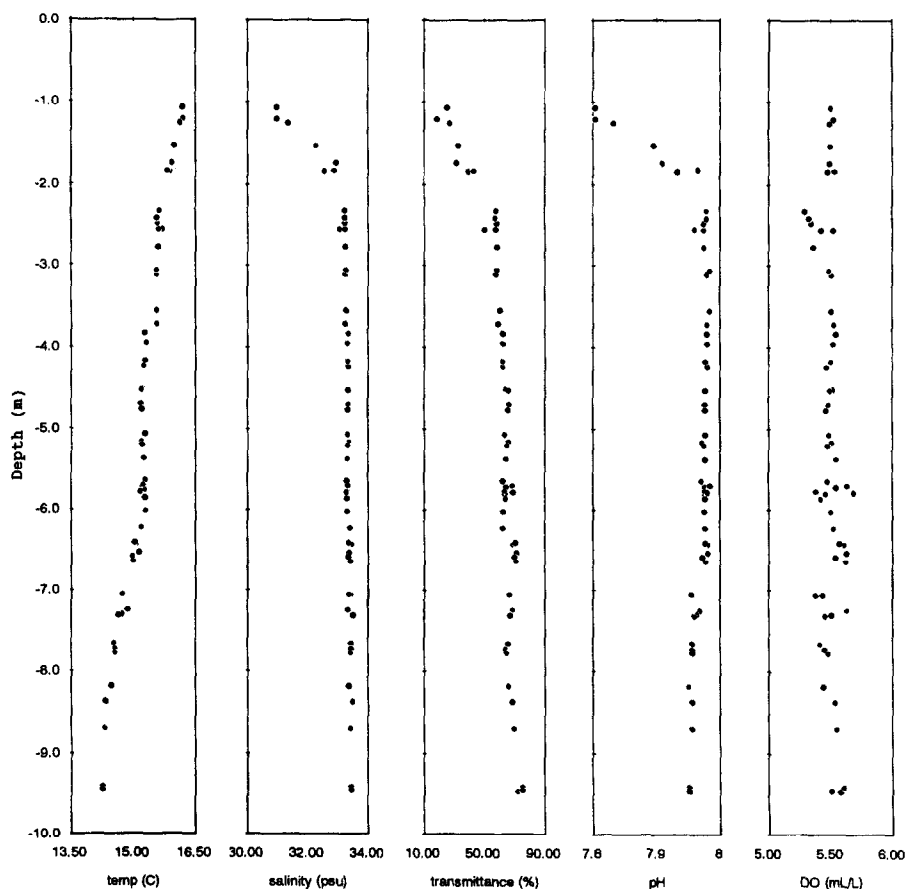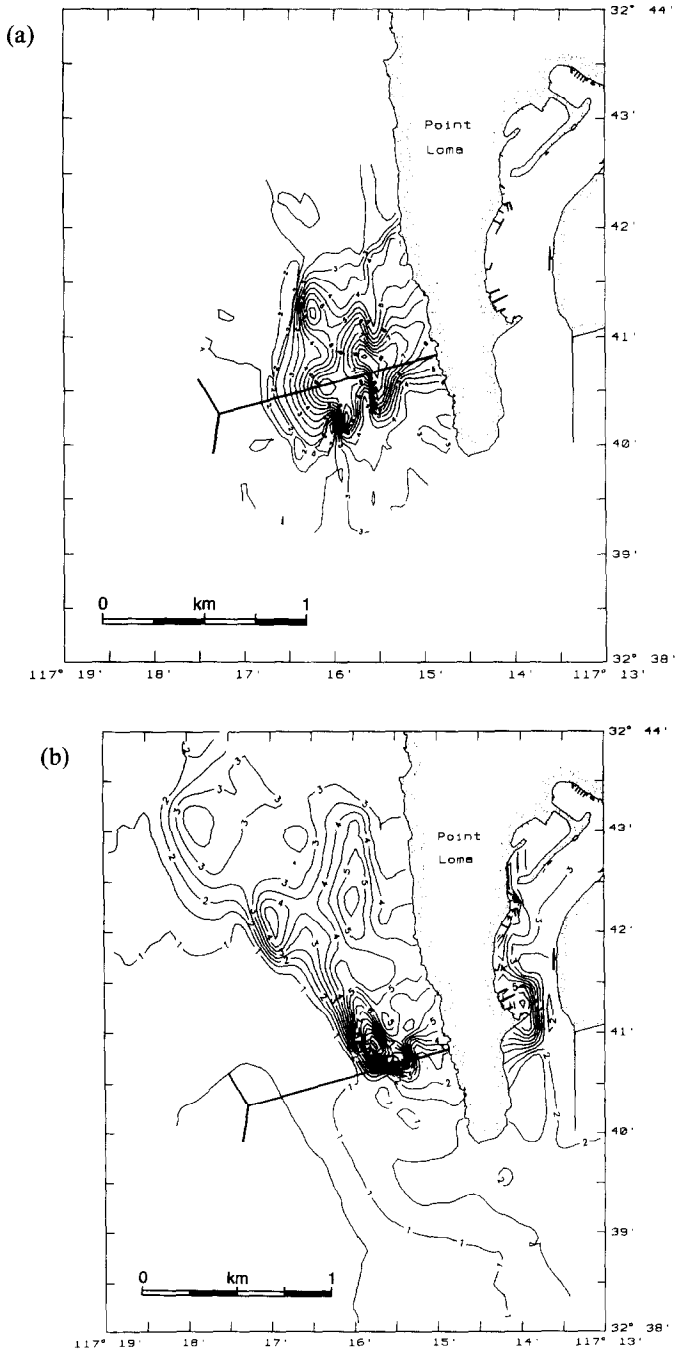
Fig. 5. Vertical profiles of temperature, salinity, transmittance, pH, and dissolved oxygen taken about 14 m from the edge of the sewage boil.

Fig. 6. Surface isopleths of salinity (expressed as percent freshwater, pure sewage = 100%) on (a) March 17, 1992 and (b) March 31, 1992.

dominant wind was out of the northwest, but wind changes subjected the entire Point Loma kelp forest to the plume. Despite release from a point source, buoyancy and momentum of the effluent led to rapid mixing as the plume boiled to the surface; the maximum salinity depression measured on the surface was only 9% below background. Minimum oxygen values observed were above 5.0 ml/litre; oxygen depletion outside the boil was not significant. A vertical cast about 14 m from the edge of the boil indicated that the plume was spreading on the surface; changes in salinity, dissolved oxygen, % transmission, temperature, and pH were confined to the upper 2–4 m of the water column (Fig. 5). Similar results were obtained in five additional vertical casts about 100 m from the spill.

The variable spatial dispersal of the plume is shown in Fig. 6. On 17 March there was little wind, whereas on 31 March the wind blew out of the south as a weather front moved through. On the 17th effluent contours
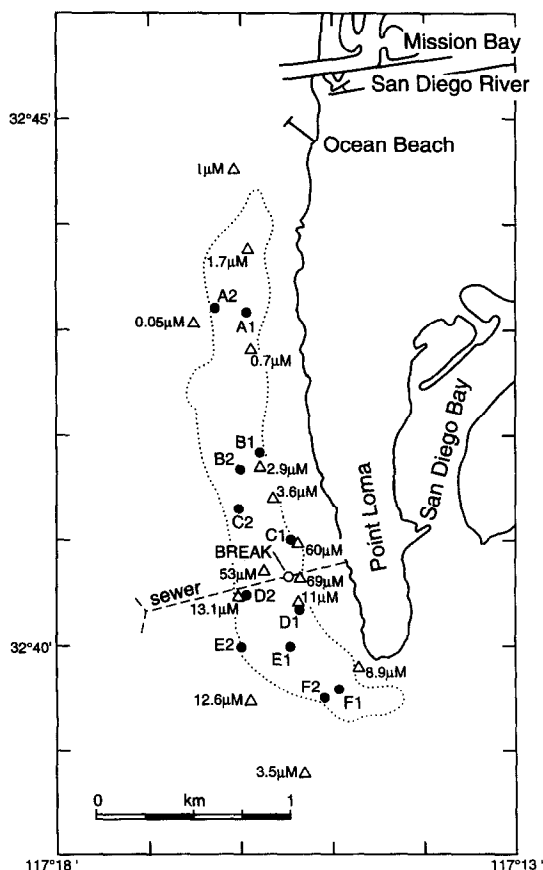

Fig. 7. Ammonium concentrations in surface waters, 1 April 1992.

were centered over the outfall; on the 31st the contours were strongly displaced to the north and, with the exception of the immediate vicinity of the break, salinity was normal south of the outfall and offshore of the break.

The concentration of ammonium in the effluent averaged 1.72 mM during the spill (W. Konopka, Point Loma Wastewater Laboratory, pers. comm.). Surface concentrations on 1 April ranged from 69 μM near the break to 0.05 μM in the north offshore region of the forest (Fig. 7). The latter value is an order of magnitude below the average background level of 0.5 μM for the Southern California Bight (Eppley, 1986), but is consistent with El Niño conditions. Three values within 1 km of the break were over 50 μM, a level likely to be harmful to adult *Macrocystis* fronds (R. Zimmerman, pers. comm.). The actual effects on the surface canopy within this radius would have depended on how persistent the plume was in that location; it is likely that canopy fronds very near the break were harmed by high ammonium concentrations (see Field Observations). However, ammonium concentrations quickly diluted to values beneficial to *Macrocystis* (North *et al.*, 1982), and were above average background levels from just south of Ocean Beach to well south of the kelp forest (Fig. 7).

Sedimentation was expected to be a major impact of the sewage spill because excessive particulate matter settling from the plume could clog feeding apparatuses of some animals, contain toxic substances, cause scouring damage, or accumulate on the bottom preventing kelp germination. Sedimentation rates are illustrated in Fig. 8. Three sediment tube collections from during the spill were compared with three immediately after the repair was completed. Sedimentation rates varied significantly with time along both depth contours ($p < 0.001$), by a factor of about three. The high correlations ($p < 0.001$) between average wave height (Coastal Data Information Program 1992) and sedimentation rate at five of the six 12 m stations (Fig. 9) indicate that much of the difference between the spill and the recovery periods was related to decreasing wave motion. Site A1, the most distant from the outfall, apparently had additional sedimentation from cliff erosion, the San Diego River, or the outflow from Mission Bay; this explanation was supported by a local minimum in the MESC transmissivity data. Despite the high correlations with wave height, there was a significant difference in sedimentation rate among stations along the 12 m contour ($p < 0.001$) and visual inspection of Fig. 10 indicates that the pattern was related to the outfall break. There was also significant spatial variation along the 18 m contour ($0.01 < p < 0.025$). While the outfall pipe repair was completed on 4 April 1992, the addition of 700,000 tons of rock ballast continued until late May. This rock work did not appear to affect sedimentation as daily rates at site D1,
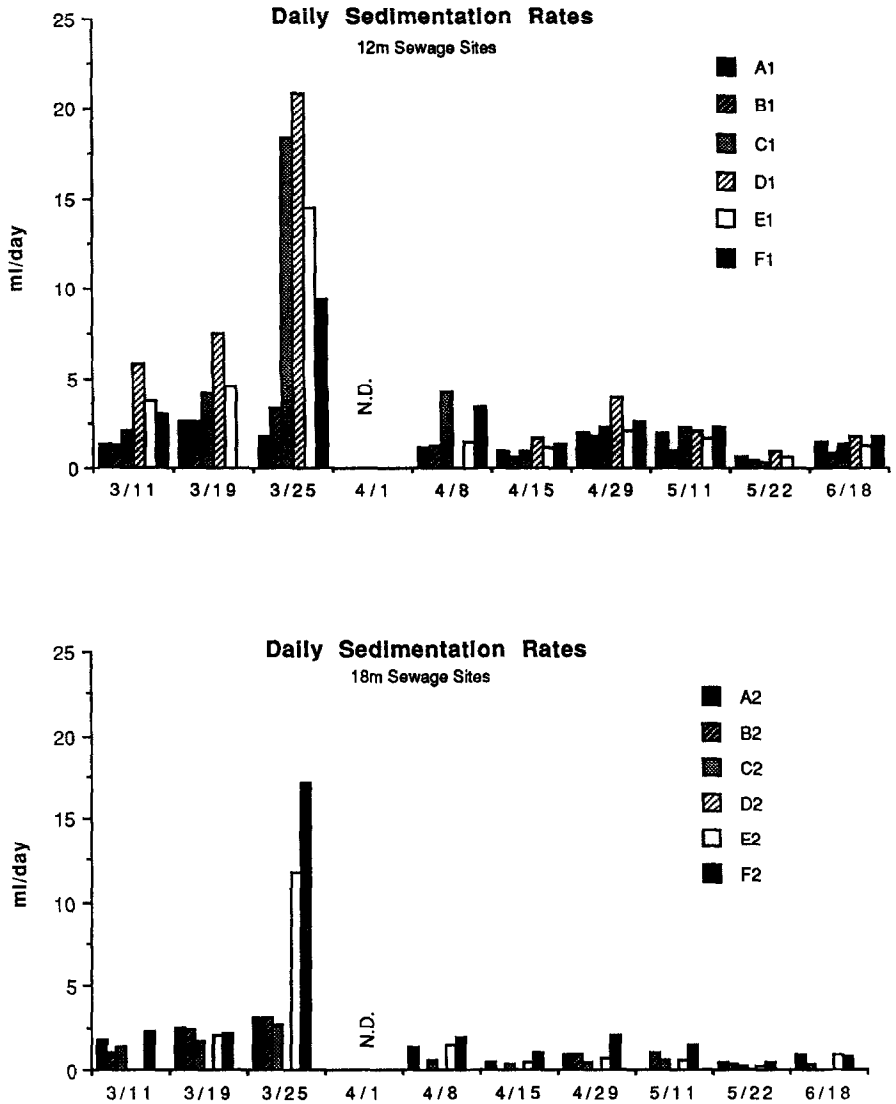
Fig. 8. Daily sedimentation rates along the 12 and 18 m contours, 11 March–18 June 1992. No data are available for the week ending 1 April 1992. Site D2 was lost and not relocated until mid May.

nearest the construction barge, were similar in April, May, June (Fig. 8), and July.

Qualitative changes in the sediments also suggested the effects of the outfall break. Sediments collected during the spill were dark and often smelled strongly of sewage. Particle size distributions were determined
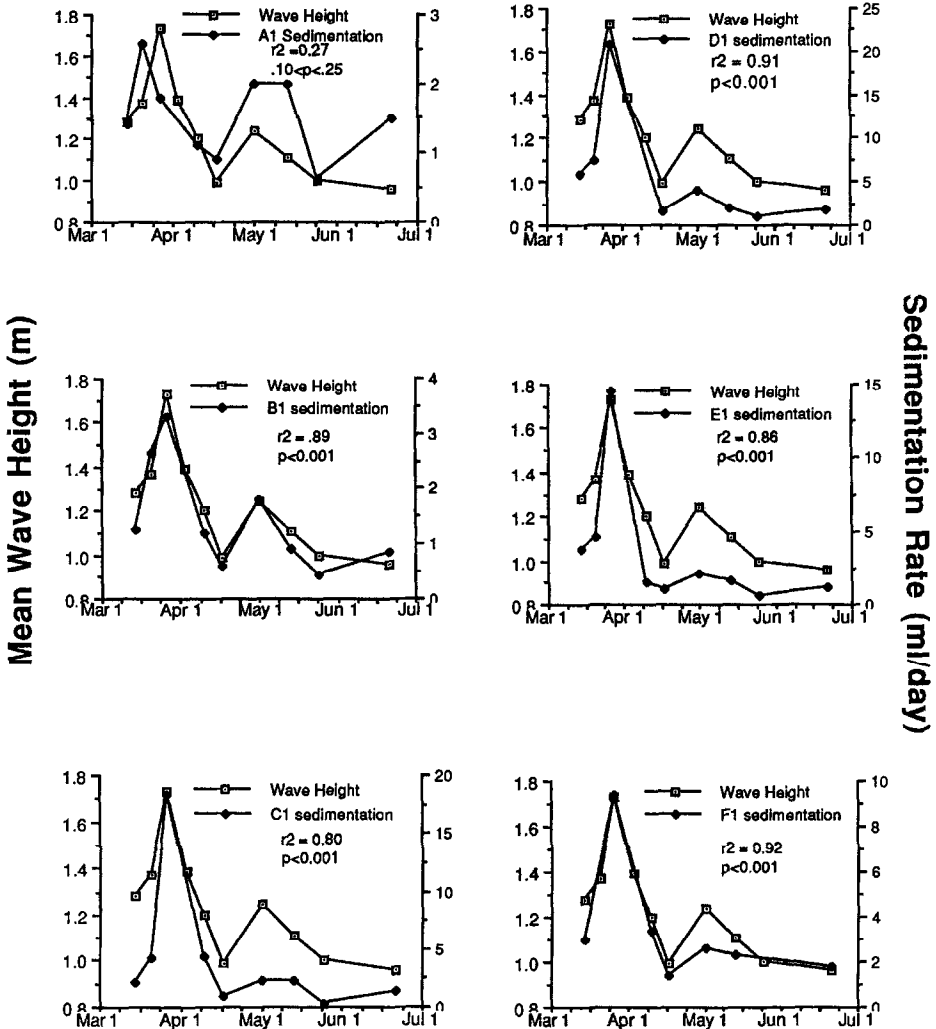
Fig. 9. Sedimentation rate versus mean wave height (Coastal Data Information Program 1992) for the six spill stations along the 12 m contour. Note changes in scale for sedimentation rate. Coefficients of determination (r^2) were determined from simple linear regressions using wave height as the independent variable. Significance was tested against the null hypothesis of zero slope.

once during the spill and again after the repair was completed by averaging samples from both depth contours. Median particle size distribution increased from 23 μm on 1 April to 70 μm on 22 May, about a factor of three, with the reduction in fine-grained sewage particles (W. Konopka, pers. comm.).

The Point Loma Wastewater Chemistry Laboratory analyzed sediments collected in the tubes on 1 April. Test results for 39 chlorinated pesticides and polychlorinated biphenyls (PCBs) were all below detection limits (US EPA 1986). Copper and zinc are toxic to microscopic stages of *Macrocystis* (Anderson & Hunt, 1988; Anderson *et al.*, 1990a; Anderson *et al.*, 1990*b*). There was evidence of an outfall-centered pattern for both metals in sediment samples collected on 1 April from the 12 m contour but not from 18 m. Copper and zinc values in the sediment tubes ranged from 21–41 mg/kg and 66–97 mg/kg, respectively. Percent volatile solids, an index of organic content, was determined on sediment tube samples collected on 19 March. The suspended solids in the effluent during the spill averaged about 70% volatile content on a dry weight basis. Volatile content in the sediments from the spill sites ranged from 8 to 13%. These data showed
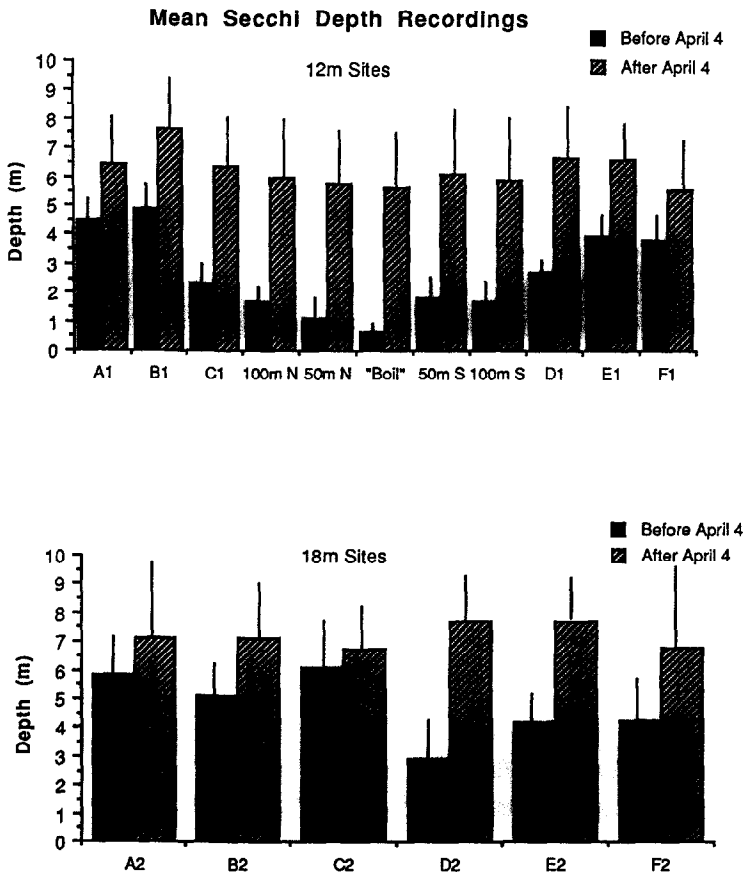

Fig. 10. Average Secchi depths measured on four dates before and four dates after the outfall repair was completed along the 12 m and 18 m contours. Error bars represent ± one standard deviation.

no evidence of an outfall-centered pattern and the trend was for the highest percent volatile solid content at sites within the *Macrocystis* canopy. The presence of plant matter in the sediments further suggests that the trapped sediments were a mixture of natural and sewage sediments (W. Konopka, pers. comm.).

Averaged Secchi data from four dates before and four dates after the outfall was repaired showed a dramatic depression in light penetration at the sites closest to the outfall break during the spill (Fig. 10), an effect which decreased with distance. Shallow stations were more strongly affected than the deeper sites. Secchi depths varied significantly ($p < 0.001$) both spatially and temporally along the 12 m contour. Stations near the break had relatively shallow Secchi depths during the spill which increased after the repair. The increase in Secchi depths at 12 m after the repair cannot be attributed solely to the reduction in mean wave heights. There was significant spatial variation before ($p < 0.001$) but not after ($p = 0.89$) the repair was completed; decreases in wave-induced turbidity should be similar spatially. On the 18 m contour, there was no significant difference between stations ($p > 0.25$), but there was significant difference in time ($p < 0.001$). This suggests two possibilities: (1) that the 18 m stations were uniformly affected by the spill, and that after the repair was completed, Secchi depths increased significantly at all sites, or (2) that there was no effect of the spill on Secchi depth at this depth and differences may relate to wave activity.

Similar patterns were observed with light meters deployed on the instrument trays. In March, we had successful deployments for twelve days at seven sites (Fig. 11(a)). In shallow water, there was a large depression in light reaching the bottom at D1, the station due south of the outfall break, where the average was 0.12 Einsteins per m^2 per day. Previous studies have found some kelp recruitment at 0.1 $E/m^2/d$, but light levels greater than 0.4 $E/m^2/d$ are required for 95% germination (Deysher & Dean, 1986). In deeper water, the lowest light levels observed (0.23 $E/m^2/d$) were at A2, where the study site was under the kelp canopy; here light interception by adult plants would probably have precluded kelp germination. The other sites (B1, F1, C2, E2, and F2) were above the light threshold for germination. Thus for the period of 11–23 March, the impact of the sewage plume on light was strongest along the 12 m depth contour. All successful recordings along the 12 m contour in April and May after the pipe was repaired were above the light threshold for kelp germination (Fig. 11).

Light levels are also important for algal growth. The compensation irradiation (the level below which no growth occurs) for juvenile *Macrocystis* is 0.4 $E/m^2/d$ under good temperature and nutrient conditions.
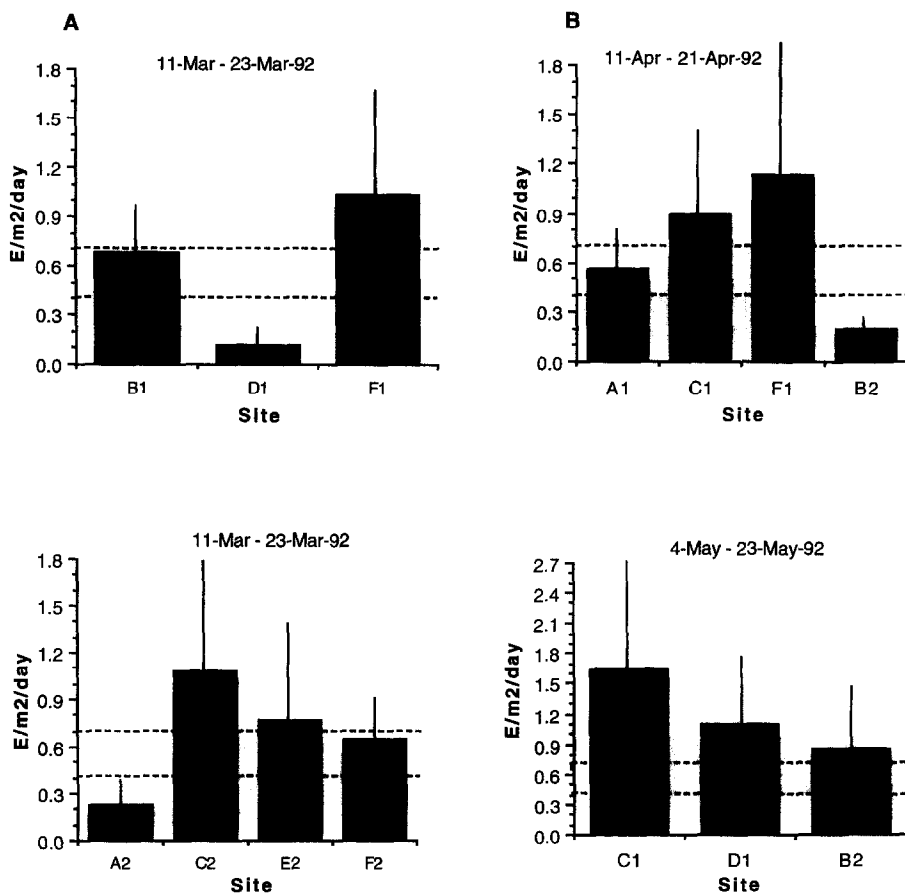
Fig. 11. Mean total daily irradiance levels measured (a) 11–23 March 1992 during the sewage spill, and (b) 11–21 April and 4–23 May after the outfall repair was completed. Error bars indicate standard deviations. Horizontal lines indicate thresholds for giant kelps. Significant *Macrocystis* germination takes place when the light is above 0.4 Einsteins/m^2/day (Deysher & Dean, 1986a). The light level below which juvenile *Macrocystis* plants do not grow is 0.4 E/m^2/day when temperature/nutrient conditions are optimal and 0.7 E/m^2/day when El Niño conditions prevail, as in February–March 1992 (Dean & Jacobsen, 1984).

However, when temperatures are high, the compensation level rises to 0.7 E/m^2/day (Dean & Jacobsen, 1984). Thus, the combination of reduced light with El Niño conditions during the spill was very poor for growth as well as germination.

An intense phytoplankton bloom affected light conditions at Point Loma after the repair was completed. Two samples collected near station C1 on 20 May 1992 yielded chlorophyll values of 55 and 84 µg/liter; a concurrent collection from the SIO pier had 7 µg/litre chlorophyll

(P. Walker, pers. comm.). These samples were a virtual monoculture of the dinoflagellate *Gonyaulax polyhedra* (F. Reid, pers. comm.), a common red tide organism which blooms after the ocean becomes highly stratified following nutrient inputs into the mixed layer (Eppley & Harrison, 1975; Thomas & Gibson, 1990).

Bioassays

Microscopic sporophytes of *Macrocystis* were outplanted along the 12 m contour to evaluate conditions for growth of this sensitive life history stage during and after the sewage spill. In samples collected on 25 March 1992, the density of sporophytes increased with distance from the outfall break (Table 1). The density of sporophytes was significantly lower at Station D1 than at Stations A1 and E1; densities at the other sites did not differ. At all stations the densities were substantially lower than when the lines were outplanted; an estimated 1 to 5% of the sporophytes survived after three weeks. This is below average, but within the normal range of mortality obtained at other kelp forests in San Diego County (Dean *et al.*, 1987). Lengths of these sporophytes showed a similar trend with respect to distance from the outfall (Table 1). Lines from stations close to the outfall had significantly smaller sporophytes than the two most distant sites. There was a net decrease in the length of sporophytes from the time of initial outplanting until the first collection three weeks later. This indicates that many of the larger sporophytes were lost, probably due to generally stormy conditions during this period.

Eleven days after the outfall was repaired, there was no apparent relationship between the survival of sporophytes and relative distance from the break (Table 1). The density of sporophytes was significantly greater at Stations C1 and E1 than at Stations A1, D1, and F1. All stations except A1 and F1 showed an increase in density between 25 March and 15 April. There were obvious signs of grazing on the lines, especially at Station A1. There were no significant differences in the lengths of sporophytes collected on 15 April. The average increase in length between 25 March and 15 April, however, was greatest at the two stations closest to the outfall break.

There were no apparent effects of the outfall break on microscopic sporophytes outplanted in May 1992, about two months after the repair was completed. Mean densities did not differ significantly among stations in the collection of 3 June, and in the collection of 24 June, Station C1 had higher densities than Stations A1, D1, and E1. Station E1 had larger sporophytes than at other stations on 3 June; there were no significant differences in sporophyte length among stations in the collection of 24 June.

TABLE 1

Mean Densities and Lengths of Microscopic Sporophytes of *Macrocystis Pyrifera* Outplanted to Sites Along the 12 m Contour. Vertical Lines Indicate Means that did not Differ Significantly at $p < 0.05$. ND Indicates no Data: these Substrata were lost Prior to Collection

	Density (#/mm^2)		Length (μm)
Station	*Density*	*Station*	*Length*
	Initial density and length, 3 March 1992		
E1	8.96	F1	0.30
C1	8.32	A1	0.28
A1	8.03	C1	0.28
D1	7.78	B1	0.28
F1	7.23	D1	0.28
B1	7.10	E1	0.26
	Collection of 25 March 1992		
A1	0.35	A1	0.13
E1	0.30	F1	0.12
F1	0.27	E1	0.10
B1	0.26	B1	0.10
C1	0.22	C1	0.09
D1	0.08	D1	0.09
	Collection of 15 April 1992		
C1	0.52	C1	0.13
E1	0.44	E1	0.13
B1	0.35	B1	0.12
D1	0.23	F1	0.12
F1	0.21	D1	0.12
A1	0.18	A1	0.11
	Initial density and length 11 May 1992		
A1	6.77	C1	0.49
F1	6.11	D1	0.43
B1	5.94	E1	0.43
D1	5.76	A1	0.40
C1	4.85	F1	0.39
E1	3.44	B1	0.34
	Collection of 3 June 1992		
B1	0.36	E1	0.21
A1	0.27	B1	0.18
C1	0.24	D1	0.14
E1	0.17	A1	0.14
D1	0.13	C1	0.14
F1	ND	F1	ND
	Collection of 24 June 1992		
C1	0.15	C1	0.21
B1	0.10	B1	0.19
A1	0.08	A1	0.18
D1	0.06	D1	0.17
E1	0.03	E1	0.15
F1	ND	F1	ND

Juvenile (9–35 cm) *Macrocystis* were also attached to the trays to study the impacts of the outfall break on their survival and growth. The data were compromised as some of the trays were blindly placed in areas with dense populations of grazing sea urchins or amphipods. The juvenile *Macrocystis* showed no apparent differences in growth or survivorship associated with proximity to the spill. Some survival was observed at sites closest to the outfall on both depth contours. There was no growth through 8 April (many plants lost tissue and some were completely eaten by amphipods), but there was growth in late April which then accelerated as light and temperature conditions continued to improve, and amphipod grazing apparently decreased. The change was most pronounced on the 12 m contour, where the change in light conditions was the greatest.

Brown cup corals (*Paracyathus stearnsi*) transplanted on 11 March 1992 showed no apparent effects from the outfall break. As of 10 July, three months after the outfall repair was completed, there were no deaths as indicated by loss of pigment. After the diving quarantine was lifted, we observed normal feeding behavior in the test animals and often very large numbers of healthy cup corals, especially *Balanophyllia elegans*, on the bottom. These included many small corals, indicating that even the more vulnerable juveniles were not affected by the spill.

Juvenile red abalones were outplanted on 5–6 March. Discounting three escapees (as indicated by no shell remains), 13% mortality was observed as of 10 July, and these showed no relationship with distance from the outfall break. Seven of the 12 observed mortalities were found at site B1 when a piece of *Macrocystis* holdfast was found lodged under the abalone container in the tray on 8 April; predators associated with the holdfast probably preyed on these abalones. Significantly, the tray at D2 adjacent to the outfall was lost sometime before 11 March and not relocated until 13 May; all eight abalones were still alive despite the spill and two months without kelp.

Potential toxicity of sewage sediments to the germination and growth of spores was evaluated in laboratory tests. For elutriates of sediments collected on 25 March 1992, germination generally decreased from North to South, and showed no pattern with respect to the outfall (Table 2). Sediments from the La Jolla kelp forest, outside the range of the spill, were intermediate in germination rate. Germ tube lengths of spores, however, were significantly smaller in elutriates of sediments collected around the outfall break at Stations C1 and D1. Elutriates of sediments collected in July 1992, both from the bottom and in sediment tubes, showed no trends with respect to distance from the outfall break (Table 2). There were no significant differences in either germination rate or germ tube lengths in elutriates from sediment tubes collected from immediately south of the outfall break and at the northern end of the Point Loma kelp forest. In the

TABLE 2

Mean Germination Rates and Lengths of Germ Tubes of *Macrocystis Pyrifera* Cultured in Elutriates of Sediment Samples Collected from Six Stations along the 12 m Depth Contour in the Point Loma Kelp Forest and from a Control Station at La Jolla. Vertical Lines Indicate that Means did not Differ Significantly at $p < 0.05$

Germination rate (%)		Germ tube length (μm)	
Station	*Germination*	*Station*	*Length*
Sediments from sediment tubes collected 25 March 1992			
F1	87.5	B1	18.2
E1	80.8	E1	18.0
D1	74.5	Control	17.4
Control	54.3	A1	17.0
C1	50.4	F1	15.7
B1	49.8	C1	12.1
A1	21.9	D1	10.7
Sediments from sediment tubes collected 13 July 1992			
A1	78.8	A1	11.0
D1	56.5	D1	10.9
Sediments from the bottom collected 13 July 1992			
A1	92.4	A1	15.9
F1	92.0	D1	15.6
E1	88.8	B1	15.1
D1	76.8	E1	14.9
C1	59.1	C1	13.3
B1	43.8	F1	12.0

elutriates from sediments collected from the bottom, only station B1 had a mean germination rate lower than other stations, and germ tube lengths were significantly lower only at station F1.

Field observations

Video surveys

Non-quantitative video transects provide several important observations. First, videos taken a month into the spill (7–8 March 1992) in the immediate vicinity of the break showed high turbidity but no accumulation of sediments. Even at 18 m, where surge was least likely to keep particles in suspension, there was no evidence of deposition on either the open bottom or in pockets and crevices. Visible surface sediments were coarse white shell sand; there was no evidence of the fine black material collected in sediment tubes. Second, some giant kelp plants exhibited varying degrees of broken stipes, probably a result of mechanical damage caused

by storms (Dayton *et al.* 1992) or construction barge anchor lines. However, nearby *Macrocystis* and lower standing plants appeared normal, arguing against effluent effects. Reproductively ripe sori of *Macrocystis*, *Pterygophora californica*, and *Cystoseira osmundacea* were clearly visible. Third, the video documented the presence and activities of many animals; with the exception of a few sea urchin tests, no dead animals were observed. Animals most likely to take up sewage particulates are suspension feeders and detritivores. Suspension feeders shown by the video included sponges, cup corals, gorgonians, bryozoans, hydroids, and tunicates, all in apparent good health. Behavioral shifts were observed in the seastars *Asterina miniata* which usually prey on bottom animals; during the spill they were commonly observed with the tips of their arms raised up in the water column in ciliary-suspension feeding position (Mauzey *et al.*, 1968). Sea cucumbers, *Parastichopus parvimensis*, the most conspicuous detritivores, exhibited normal foraging behavior, including many on the outfall and its ballast rocks. Other macroinvertebrates observed include the polychaete *Diopatra ornata,* several anenomes, molluscs *Megathura crenulata, Norissia norrisii, Mitra idae, Kelletia kelletii,* two *Aplysia vaccaria* with nearby egg masses, and an unidentified nudibranch. Red sea urchins, including one holding drift kelp, were seen in crevices in reefs or the ballast rock. Seastars included *Pisaster giganteus, Astrometis sertulifera, Pycnopodia helianthoides*, and *Asterina.* Several spiny lobsters, *Panulirus interruptus*, were observed in the open at 12 m, unusual behavior probably reflecting the very low light conditions near the break. In summary, the videos suggested that established plants and animals were coping with the sewage spill. Such observations offer no information about the fate of plant or animal recruits, the stages probably most sensitive to pollution effects.

Kelp studies
Throughout the spill, the *Macrocystis* canopy at Point Loma away from the immediate vicinity of the break appeared healthy, as indicated by color, the presence of new fronds, and an increase in density during this period. Near the break some fronds were frayed, pale, and deteriorating in mid–February. We observed black slimy sediment accumulation on a few blades and some older tissues were heavily epiphytized with filamentous algae. However, isolated plants were found on the surface near the break throughout the spill; the mixture of healthy fronds with growth tips and bladeless stipes on these plants suggested that the plants were still growing into but not lasting in the surface layer. Growth tips near the plume appeared less planar, or 'curlier' than normal, but tissues were dark (indicating high nitrogen content) and apparently healthy. The growth in

both area and density of the Point Loma canopy in March was especially apparent in comparison with the La Jolla forest which was pale (low nitrogen content), had few growth tips, and appeared to be declining in area. *Macrocystis* is not capable of storing nitrogen for more than two to four weeks (Gerard, 1982) and, with the persistence of El Niño conditions, the Point Loma canopy began to fade in color in late April.

Comparison of the December 1991 and mid March 1992 composites of aerial photographs of Point Loma indicated loss of about two linear kilometers of surface canopy along the inner margin of the southern end of the forest, centered over the outfall (Fig. 12). The next flight, on 12 April after the northern end of the forest had been harvested (D. Glantz, Kelco, pers. comm.), showed only the central portion intact but still with considerable density. By 2 May, the now completely harvested Point Loma canopy consisted of scattered individuals. Significantly, there was a band of plants reaching the surface along the inner margin of the bed south of the outfall. The La Jolla canopy underwent major decline between December and April; by May only scattered plants were visible from the air. This decline was due to a combination of winter storms, harvesting, and warm surface temperatures inhibiting regrowth. Both kelp forests exhibited considerable regrowth by October and especially December 1992.

The majority of the adult (defined as four or more stipes) plants at Point Loma recruited after the severe storm of January 1988, and abundance has been declining for several years due to self thinning and storm mortality (Dayton *et al.*, 1992). The changes in *Macrocystis* abundance (Fig. 13) during 1992 were predictable from normal cycles of recruitment and decline at four of the five sites (18 m Central, 15 m Central, 12 m Central, and 18 m North); changes from January to April 1992 were modest. In contrast, 18 m South had been a sea urchin barren until early 1991 when urchin disease reduced grazing pressure and allowed kelp germination. Under normal conditions, we would have expected many more adult plants by April 1992. The combination of warm temperatures and at least partially-reduced light levels inhibited the development of this young stand of kelp. With the onset of better conditions, the density of adult *Macrocystis* at 18 m South more than doubled between July and November. Adults at the 15 m La Jolla site responded similarly to the four northern sites at Point Loma with a slow decline in density; however, prebifurcate recruits (Dayton *et al.*, 1984) of *Macrocystis* appeared in high numbers along two transects at this site in July. Recruitment of bifurcates was not substantial at any of the permanent Point Loma sites in 1992, probably because of competition with existing adults.

Kelp populations were censused at the twelve spill study sites in spring 1992. Stipeless *Macrocystis* holdfasts or holdfast scars represent plants
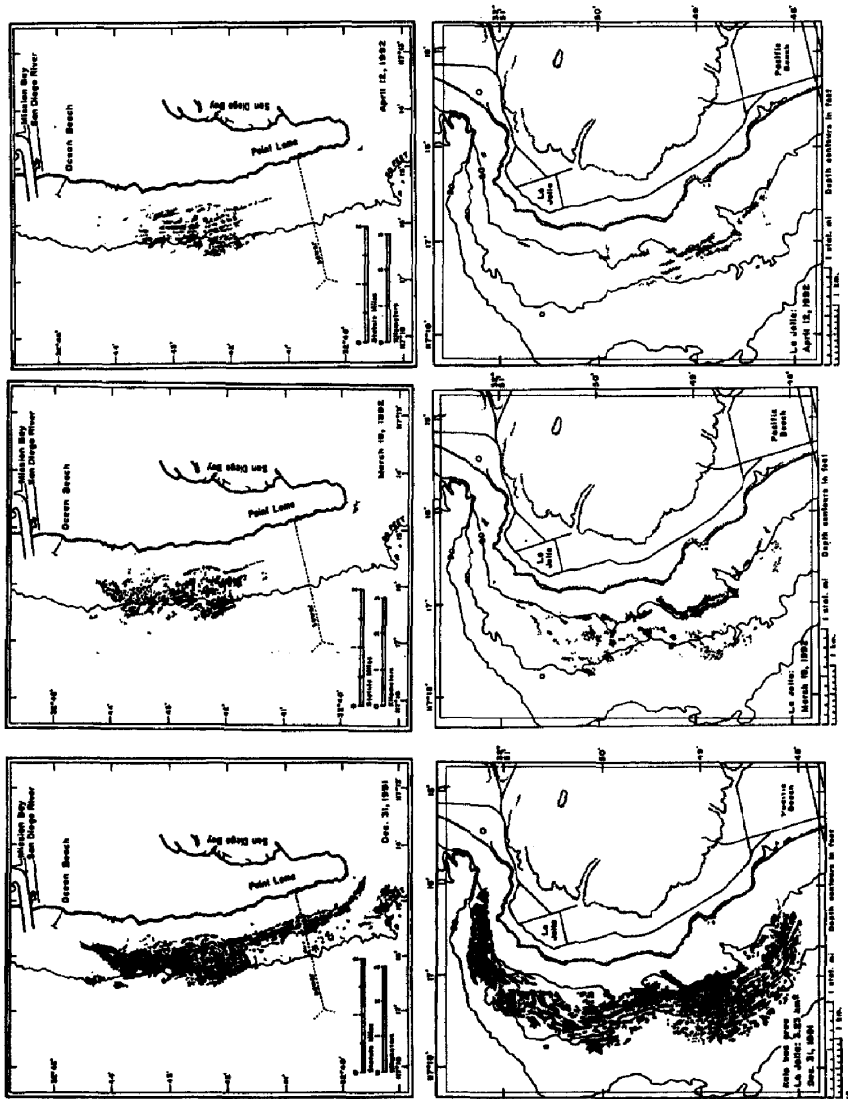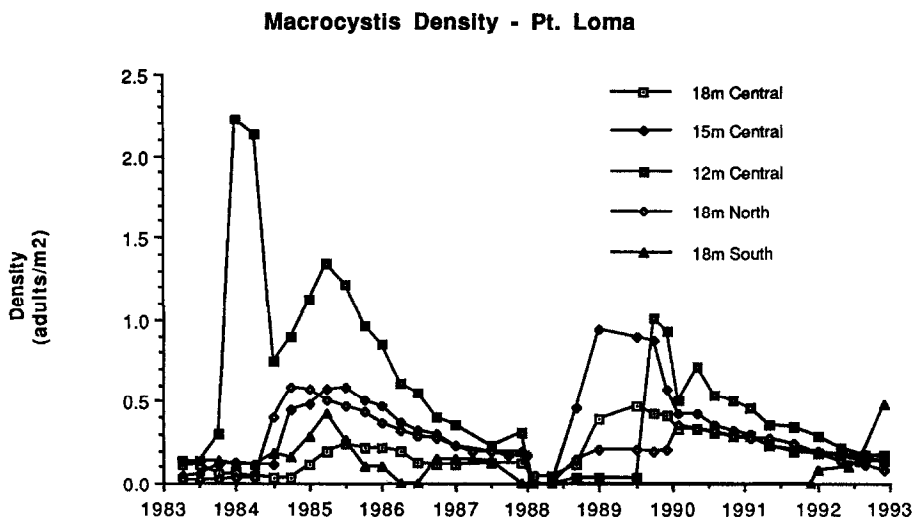
Fig. 12. Time series maps of the Point Loma and La Jolla surface canopies of giant kelp (*Macrocystis pyrifera*) compiled from aerial photographs by W. North. Note the change in scale between the smaller La Jolla forest region and Point Loma.

Macrocystis Density - Pt. Loma

Fig. 13. Abundance patterns of adult (defined as four stipes, see Dayton *et al.*, 1992) *Macrocystis pyrifera* determined quarterly at the long-term study sites. See text for an explanation. Data for 1992 were collected in January, April, July and November.

which died in the preceding few months (Dayton *et al.*, 1984; Dayton *et al.*, 1992). Holdfast density was higher on the 12 m contour, in accordance with past observations of higher storm mortality with decreasing depth (Seymour *et al.*, 1989). Site C2, the first 18 m site north of the pipe, was an urchin barren; high densities of these grazers had eliminated virtually all non calcareous algae and precluded kelp recruitment. In contrast, sites C1 and D1 on the 12 m contour and D2 on the 18 m contour had healthy subsurface populations of kelps. The lack of canopies at these sites was consistent with poor growth conditions combined with mechanical damage or possibly with ammonium toxicity; all were less than 1 km from the break. That ammonium levels were normal for three months before plants grew to the surface at the two shallower sites argues for mechanical damage as ammonium would have been at high concentrations only on the surface. Adult *Macrocystis* were rare and two stipe individuals were abundant at sites D2, E2, and F2, further indications of recovering sea urchin barrens (see Figs 1, 2). Understory kelp and turf algae data showed various patterns, but none related to the spill.

Four shallow sites were investigated along the outfall near the break, presumably the area of maximum impact, with transects perpendicular to the pipe from the base of the ballast rock. A site inshore of the break at 9 m had high densities of several species of kelps including *Macrocystis*; all

appeared healthy. Less than 100 m to the west, the 12 m transect on the south side of the outfall was dramatically different. All adult *Macrocystis* were dead, and other adult kelps were sparse and in poor condition. All surfaces within 20 m of the pipe were covered with filamentous brown algae, and juvenile kelps were recruiting on the bottom and the ballast rocks on 16 June 1992. Thus this site had been heavily disturbed but was recovering. The kelp community on the north side of the pipe at the same depth was not nearly as stressed; there were live *Macrocystis* interspersed with dead holdfasts, and the understory kelps were much healthier. The large construction barge was anchored for several weeks immediately south of the break; its activities and/or shadow may have accounted for the poor kelp condition in that area. Its many anchor cables almost certainly had an effect on giant kelp plants. Given the small distances between these sites, it is unlikely that the sewage plume caused these different effects. Juvenile kelps germinated soon after the outfall repair through much of this area. Barnacles appeared on the ballast rocks near the 12 m south transect before the algae, indicating that these early successional species probably settled during the spill.

A series of stratified transects was conducted along the outfall to systematically investigate the severity of impacts on macroalgal populations with distance from the pipe (Table 3). The results show patterns relating to biology of the individual species (Dayton *et al.*, 1992), the recent sea urchin barren (Fig. 2), and the disturbances of 1992. *Agarum fimbriatum* and *Pelagophycus porra* are deeper water kelps; their peak abundance at 19 m, reduced abundance at 16 m, and absence at 13 and 10 m followed expectations. Similarly, *Pterygophora* and *Laminaria* are most abundant at sites 15 m and shallower in undisturbed situations at Point Loma, and at 10 m in this survey. *Desmarestia ligulata*, an indicator of disturbance, was rare relative to its abundances after the 1983 and 1988 storms. The deeper sites along the outfall were within the urchin barren, which probably explains the very low number of live *Macrocystis* and *Macrocystis* holdfasts at 19 and 16 m. Other than a few cable scars and ballast rocks which landed away from the outfall, there was no evidence of construction damage at these depths. The very low densities of macroalgae generally, wind rows of detached *Pterygophora* stipes, cables and cable scars, and other debris at 13 m suggest that this site was very heavily impacted, and 13 m south may have been underneath the barge. By late June there were patches of 100% cover of juvenile and on the 13 m transects, including all of the 40 × 2 m transect 15 m south. The density of dead *Macrocystis* exceeded that of live plants at both 13 m south and 10 m north, but the abundance of lower standing algae suggests that the latter site was more heavily affected by mechanical damage than direct effects of the spill. With

TABLE 3

Macroalgal Densities (Number per m^2) with Distance from Both Sides of the Outfall at Four Depths

A. 19 m		South			North		
		50 m	15 m	5 m	5 m	15 m	50 m
Macrocystis pyrifera							
	live plants	0.15	0.03	0	0	0	0.01
	holdfasts	0	0	0	0	0	0
Pterygophora californica		0.08	0	0	0.1	0.16	0.08
Eisenia arborea		0	0	0	0	0	0
Laminaria farlowii		0.53	0.11	0.16	2.8	0.45	0.85
Agarum fimbriatum		0.05	0.03	0.03	0	0.01	0.02
Pelagophycus porra		0.53	0.28	0.09	0	0.01	0.16
Cystoseira osmundacea		0.08	0.06	0	3.05	0.44	0.04
Desmarestia ligulata		0.01	0.01	0	0	0	0
Desmarestia tabacoides		0.16	0.04	0	0	0	0.08

B. 16 m		South			North		
		50 m	15 m	5 m	5 m	15 m	50 m
Macrocystis pyrifera							
	live plants	0.05	0.20	0.11	0	0	0
	holdfasts	0.01	0.03	0.05	0	0	0
Pterygophora californica		0.73	0.78	0.88	0.44	0.49	0.19
Eisenia arborea		0	0	0	0	0	0
Laminaria farlowii		0.62	0.88	0.56	0.21	0.43	0.46
Agarum fimbriatum		0	0	0.01	0	0	0
Pelagophycus porra		0.41	0.01	0.02	0.03	0.02	0.03
Cystoseira osmundacea		0.05	0.08	0.12	0.20	0.13	0.43
Desmarestia ligulata		0.83	0	0	0	0	0
Desmarestia tabacoides		0.01	0	0	0	0	0.02

C. 13 m		South			North		
		50 m*	15 m*	5 m	5 m	15 m*	50 m
Macrocystis pyrifera							
	live plants	0.04	0	0	0	0.08	0.06
	holdfasts	0	0	0	0.12	0.16	0.18
Pterygophora californica		0.06	0	0	0.26	0.79	2.10
Eisenia arborea		0	0	0	0	0	0
Laminaria farlowii		0	0	0	0	0	0
Agarum fimbriatum		0	0	0	0	0	0
Pelagophycus porra		0	0	0	0	0	0
Cystoseira osmundacea		0	0	0	0	0	0
Desmarestia ligulata		0	0	0	0	0	0
Desmarestia tabacoides		0	0	0	0	0	0

*These transects had patches of 100% cover of a mixture of juvenile *Macrocystis* and *Pterygophora*, > 1000 m^{-2}

D. 10 m		South			North		
		50 m	15 m	5 m	5 m	15 m	50 m
Macrocystis pyrifera							
	live plants	0.06	0.41	0.33	0	0	0.05
	holdfasts	0.03	0.06	0.16	0.03	0.03	0.06
Pterygophora californica		2.15	1.53	2.63	2.20	2.54	2.83
Eisenia arborea		0	0	0	0.08	0	0.01
Laminaria farlowii		0.43	1.61	1.48	0.14	0.11	1.33
Agarum fimbriatum		0	0	0	0	0	0
Pelagophycus porra		0	0	0	0	0	0
Cystoseira osmundacea		0	0	0	0	0.23	0.25
Desmarestia ligulata		2.50	0	0	0	0	0
Desmarestia tabacoides		0	0	0	0	0	0

the exception of *Pterygophora* at 13 m, there is no evidence of outfall-centered patterns of abundance for these species.

Eight months later (30 November 1992), the heavily impacted area at 13 m had become a dense *Macrocystis* forest. Assorted construction debris and the greatly expanded ballast rock pile were the only evidence of the spill. Some of the *Macrocystis* were reproductive. Other kelps present were *Pterygophora*, *Laminaria* and *Egregia menziesii*. This forest also supported an abundance of fishes including 14 species in 13 genera and a mix of large and small individuals, presumably migrants and recent settlers, respectively. Abundant macroinvertebrates which had invaded the ballast rocks included wavy turban snails (*Astraea undosa*), giant keyhole limpets (*Megathura crenulata*), seastars (*P. giganteus*, *P. ochraceus*, *Astrometis*) and sea cucumbers, as well as a few sea urchins and spiny lobsters.

Benthic invertebrates
Sea urchins showed no unusual changes in abundance or foraging behavior in 1992. A comparison of 1991 and 1992 densities at the five permanent sites indicated that red urchin abundance declined significantly ($p = 0.05$) at 18 m Central, probably because of commercial fishing, and that purple urchins increased significantly ($p = 0.05$) at 18 m North; there were no other changes. This is within the normal range of variability (Tegner & Dayton, 1991).

Surface deposit feeding sea cucumbers are known to take up sewage-derived material (Van Dover *et al.*, 1992). *Parastichopus parvimensis*, the most conspicuous holothurian at Point Loma, consumes soft sediments and digests the contained organic detritus and small organisms (Brumbaugh, 1980). Its abundance increased at two permanent sites between 1991 and 1992 and remained about the same at the other three sites, suggesting no detrimental effects of the sewage spill on population size (Fig. 14). *Parastichopus* densities at the spill sites showed no pattern related to the outfall.

Other macroinvertebrates showed various patterns of abundance, but none were related to distance from the outfall break. For example, the cup coral *Balanophyllia* was more abundant in deeper water, perhaps because of reduced scour (Weaver, 1977), and in areas which had been sea urchin barrens. This species thrives on open bottoms and does poorly in the presence of algae (Dayton *et al.*, 1984; Coyer *et al.*, 1993). Distribution patterns of the seastars *P. giganteus* and *Asterina* reflected the different depth-related recoveries of these species following die-offs associated with warm temperatures in 1978 and especially during the 1982–84 El Niño (Tegner & Dayton, 1987). For both species recovery either continued or abundances remained the same in 1992. Since 1970 we have observed
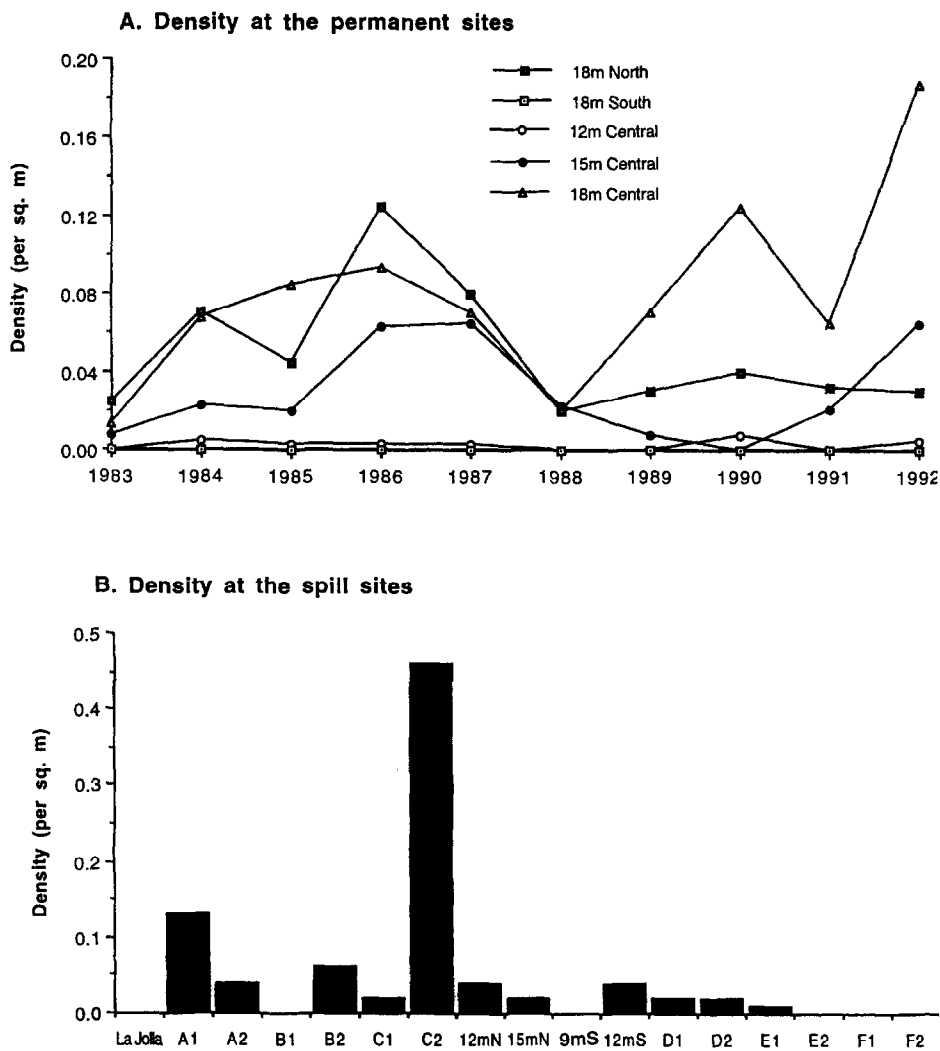
Parastichopus parvimensis

A. Density at the permanent sites

B. Density at the spill sites

Fig. 14. Abundance patterns of *Parastichopus parvimensis* through time at the permanent sites (a) and at the spill sites in 1992 (b).

several sea urchin and asteroid die-offs. Despite the spill and El Niño conditions, there was no evidence of asteroid disease in 1992; the sea urchin die-off which began in 1991 continued through 1992, notably at site C2.

Sea urchin recruitment rates were determined in summer 1992 and spring 1993. As was observed during the 1982-84 El Niño (Tegner & Dayton, 1991), the number of recruits was very low, especially in shallower water. There were virtually no recruits at 12 and 15 m Central. Both species recruited to all of the 18 m permanent sites, with increasing abundance from north to south. The same patterns of lower recruitment rates in shallower water and increasing abundance to the south were observed when La Jolla, two spill sites, and sites 100 m north and south of the outfall at 12 and 18 m were added to the data set; the sites adjacent to the outfall were not anomalous (Fig. 15).
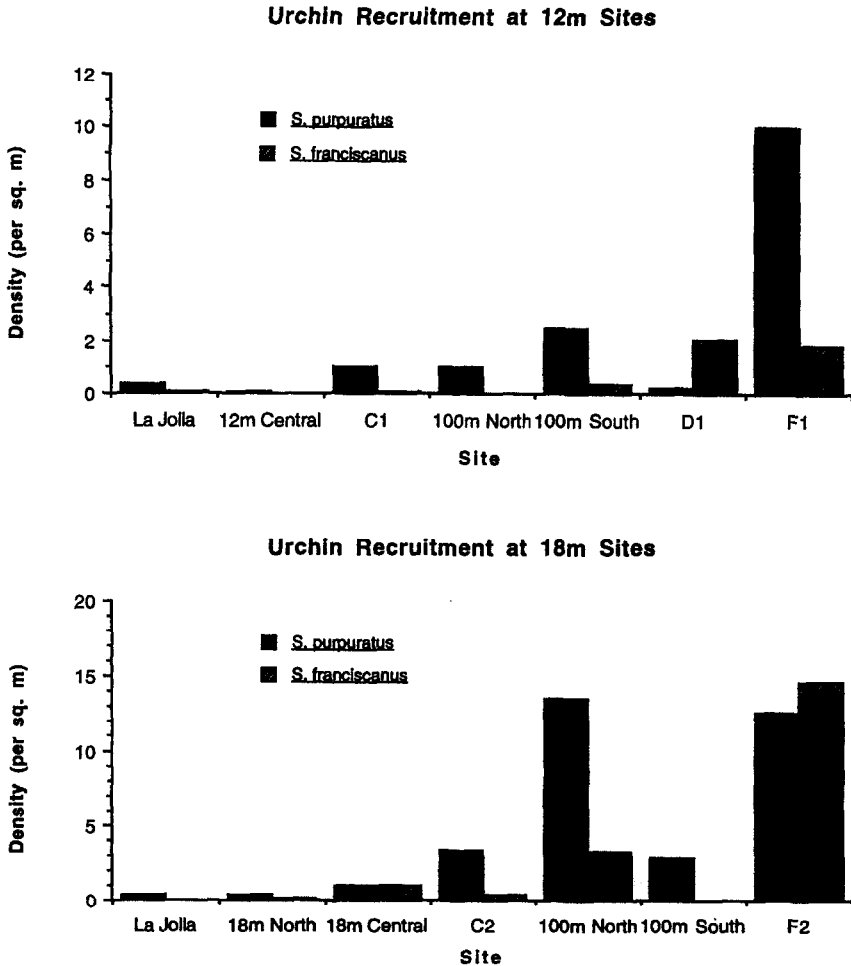
Urchin Recruitment at 12m Sites

Urchin Recruitment at 18m Sites

Fig. 15.   Sea urchin recruitment rates at La Jolla and along the 12 and 18 m contours *determined in summer 1992.*

DISCUSSION

The 1992 Point Loma sewage spill was a short term but concentrated pollution episode in which sewage treated to the advanced primary level was released from a point source within the kelp forest. The sewage that devastated the Point Loma and especially the Palos Verdes kelp forests in the 1950s/1960s was chronic, treated at lower levels, and the Los Angeles County discharge was heavily industrial. Thus, while it was unlikely that the 1992 spill would cause the drastic impacts described for the earlier period, an episode such as this has not been reported, and it is representative of isolated spills of various materials leaving no toxic residue.

The sewage spill had no apparent effect on the survivorship or diversity of established plants and animals beyond the immediate vicinity of the outfall break. Sites in 12 m along the outfall, especially on the south side where the construction barge was anchored, were heavily damaged. Mechanical damage from construction and anchor cables contributed to these problems as lower standing kelps were generally in better condition than *Macrocystis*. Mechanical damage was probably exacerbated by the warm water and reduced light conditions during the spill. Kelp mortality at the long term sites was consistent with that expected for the age structure of the plants, and trivial in comparison with the mortality caused by the 1982/83 storm season, the very warm El Niño summer of 1983, or the 1988 storm (Dayton *et al.*, 1992). Potential sublethal effects of the spill on algal growth and reproduction were overshadowed by the effects of El Niño conditions (e. g. Gerard, 1984, Tegner & Dayton, 1987; Dayton *et al.*, 1992). Similarly there was no evidence of increased mortality of benthic macroinvertebrates from the outplants, the video transects, or censuses of permanent and spill sites. We have no data regarding the effects of the spill on holoplankton or animal gametes and larvae. The City of San Diego (1992), however, conducts monthly bioassays of the effluent, including larval development (48 h) of red abalones. These bioassays indicated no significant differences from controls at effluent concentrations of 1% or less for the period of the spill.

Advances since the 1950s/1960s (reviewed by Foster and Schiel 1985, Lobban *et al.*, 1985) offer insight into the sublethal mechanisms by which disturbances affect the kelp community. Temperature, light, and sediments are critical physical variables for the germination of kelp spores and for the growth of all kelp stages. An extensive study of the effects of physical factors on kelp germination conducted near San Onofre in northern San Diego County found that temperature was negatively correlated with sporophyte germination and explained more of the variability than light levels or sedimentation rates (Deysher & Dean, 1986). While some

Macrocystis germination took place at temperatures as high as 18.3°C, significant numbers of gametophytes produced sporophytes only at temperatures less than 14°C. The effects of warm, nutrient-depleted waters (nitrate is not detectable above a temperature of about 16°C, Jackson, 1977; Gerard, 1982; Zimmerman & Kremer, 1984) on local giant kelp forests range from some deterioration of the canopy most summers when surface waters undergo normal seasonal heating to significant mortality of established plants during strong El Niño events when bottom waters warm for an extended period (Dayton *et al.*, 1992). Nutrients from sewage may cause increases in phytoplankton populations and concommitant increases in turbidity and sedimentation affecting benthic light levels and kelp germination. Sludge particles may also increase turbidity, sedimentation rate, and sediment thickness on the bottom (Foster & Schiel, 1985). Sediments can prevent kelp spore attachment to the substrate, cause smothering, or reduce success of microscopic stages via abrasive scour (Devinny & Volse, 1978).

Light levels were clearly reduced during the sewage spill to levels too low to support *Macrocystis* germination and growth (Fig. 11). Because of El Niño conditions, however, it is highly unlikely that germination would have taken place during this period regardless of a spill. In a year of normal temperatures this spill would have delayed kelp germination within the affected area until the repair was completed. The effects of the spill were short lived; outplanted microscopic stages of *Macrocystis* showed no outfall-related pattern 11 days after the break was repaired (Table 1). There was no accumulation of sediments during the outfall break. The results might have been different if the spill had occurred during the late summer-fall period when there is generally less wave action; sediment accumulation increases as water motion decreases (Weaver, 1977).

Heavy metals in sewage are a concern; e.g. copper and zinc are both essential micronutrients for algae which are toxic at higher concentrations (Lobban *et al.*, 1985). The copper concentrations in the sediments trapped by the sediment tubes may have elevated levels in elutriates enough to cause the significant effect on germ tube elongation rates in sites near the outfall break seen in the toxicity studies (Table 2). In accordance with our observations, Anderson *et al.* (1990a) report that germ tube growth is five times more sensitive to copper concentration than germination. While sediments collected during the spill clearly reduced *Macrocystis* germ tube elongation, the effect was short lived; when the test was repeated in July, there was no evidence of an outfall effect. Hunt & Anderson (1989) demonstrated sublethal effects of zinc and municipal effluents on red abalone larvae, but the City of San Diego's (1992) routine tests with water from near the outfall break were not statistically different from reference station samples.

In contrast with the negative impacts on microscopic stages of giant kelp detected in the bioassays, the spill had a positive effect on nitrogen-stressed *Macrocystis* beyond 1 km from the break. The contrast between the La Jolla canopy, which was sparse; pale, and had few new fronds, with the considerably healthier Point Loma canopy was clear indication that Point Loma canopy fronds were making use of elevated ammonium levels (Fig. 7) from the sewage. Kelco began harvesting Point Loma on 9 April after the quarantine was lifted. Despite strong El Niño conditions, the delay did not decrease yield; the amount of kelp harvested was about normal for February and March (D. Glantz, Kelco, pers. comm.). This was not unexpected as North *et al.* (1982) successfully used ammonium to fertilize *Macrocystis* in field experiments. Furthermore, the Palos Verdes kelp forest adjacent to the Los Angeles County outfall supported healthy, dense canopies of young *Macrocystis* in fall 1983, a period during the recent very strong El Niño when the Point Loma canopy was completely eliminated, yet both sites had anomalously high temperatures (Tegner & Dayton, 1987). Jones *et al.* (1990) recently reported that ammonium from the outfall was elevated above background levels in appropriate depths for the Palos Verdes forest to benefit from the advection of sewage effluent by the ambient flow field. Thus, like Point Loma beyond the immediate zone of the break, the health of this kelp forest was decoupled from El Niño-associated nutrient depletion by the Los Angeles County discharge.

It is interesting to compare the relative health of the Point Loma kelp forest in 1992 with 1983. While the 1982–84 El Niño remains the largest such event ever studied, surface temperatures at the SIO pier were actually warmer in 1992 (Fig. 16). Nevertheless the canopy persisted, albeit in a thinned condition, and mortality of adult giant kelp plants was not unusual. In contrast, the Point Loma canopy disintegrated by late 1983 and the summer-fall mortality of adult *Macrocystis* was the highest we have observed (Dayton *et al.*, 1992). Certainly one explanation involves the unprecedented number of severe storms during the winter of 1982–83 (Seymour *et al.*, 1989); giant kelp plants which survived the storms had been subjected to much mechanical stress before the summer onset of warm temperatures. The winter of 1991–92 was comparatively mild. Second, while there was spring upwelling in both years, the cold water period may have lasted significantly longer during 1992. We do not have complete records of in-situ temperatures for either year, but the greater than 3°C temperature differential at 18m South in June and July (Fig. 16) doubtlessly aided the plants in 1992 relative to 1983. Finally, nitrogen from the sewage may also have contributed to the better health of *Macrocystis* in 1992.

Because sea urchins have the potential for destructively overgrazing kelps (e.g. Lawrence, 1975; Harrold & Pearse, 1987), they were of concern

A   **SIO Pier Surface Temperatures**

Month

B   **Bottom Temperature - 18m South**
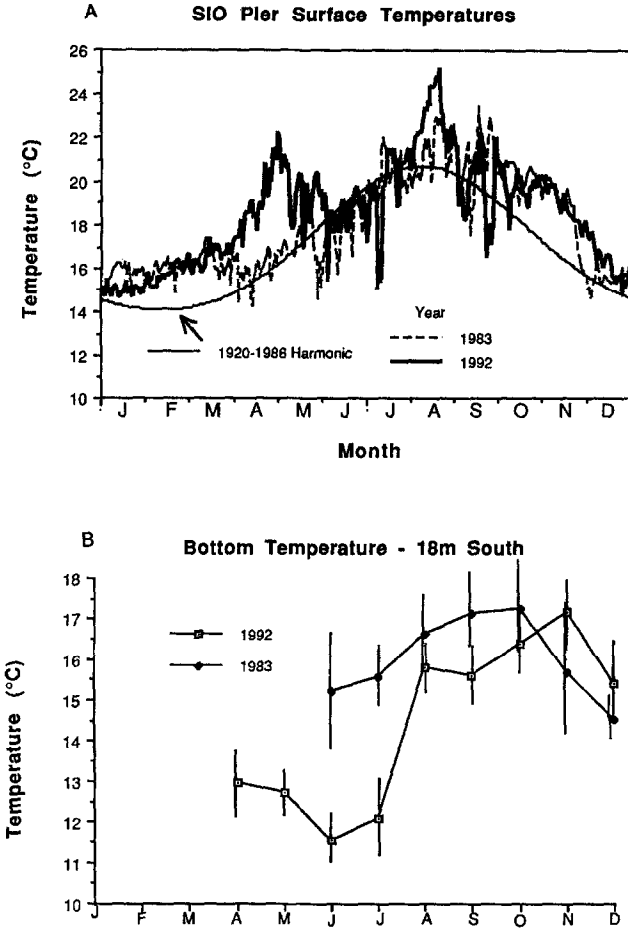
Fig. 16. (a) Comparison of 1983, a strong El Niño year, and 1992 surface temperatures from the Scripps Institution of Oceanography pier. The smoothed line represents the daily average from 1920 to 1988. (b) Monthly averages of in situ temperatures at 18 m South in 1983 and 1992. Error bars represent ± one standard deviation.

during the sewage spill as urchin grazing episodes can be triggered by disturbance (Ebeling et al., 1985), and their recruitment and nutrition may be enhanced by sewage (North, 1983). A major sea urchin barren (Fig. 2) developed after the 1988 storm when extensive kelp loss drastically reduced drift food availability, triggering destructive grazing on the remaining plants (Dayton et al., 1992; D. Glantz, Kelco, pers. comm.). Given no important changes in kelp populations in 1992, it is not surprising that there were no unusual changes in sea urchin populations. Urchin fronts remain active around the periphery of the former barren

where food availability apparently protected those animals from disease (Fig. 2). Sea urchin recruitment rates showed no outfall-related patterns in 1992 or 1993.

Several efforts expected to describe construction or spill effects in fact showed no outfall-related pattern. One example was the stratified survey along each side of the pipe in which we expected to see disturbance effects within at least 5 m from the ballast rocks whereas 50 m was obviously well beyond important construction influence (Table 3). But no persistent patterns were observed against the background of natural variation. That is, the distribution and abundance of the relevant flora and fauna are influenced by a myriad of often species-specific environmental factors such as substratum, canopy, presence of sea urchins, and many types of natural disturbances, themselves very patchy at that scale. These natural environmental factors seemed to swamp any effects of the spill or construction. The important message is not whether one can find any evidence of anthropogenic disturbance, but whether local populations are measurably affected and whether these effects are important in relation to natural variability.

What was the status of the Point Loma kelp forest at the end of 1992? Using the areal extent of *Macrocystis* canopy as an index, the condition was not optimal. While new patches of canopy appeared along the inner margin of the forest, in the region around D2 and further south where sea urchins died in 1991, and over the shallow parts of the outfall ballast rock, the canopy in the established parts of the forest was relatively thin and pale. Several factors appear to be important. First, the very warm 1992 temperatures indicate prolonged nutrient stress. A several week delay in the onset of new hapteral growth on adult *Macrocystis* generally after upwelling began and the delayed appearance of new adult *Macrocystis* at 18 m South suggest that stress created a physiological lag in the kelps' ability to respond to nutrient availability. Second is the advanced age of most of the adult *Macrocystis*; younger plants produce healthier canopies after disturbance (Dayton *et al.*, 1992). Third, the existing canopy and plankton blooms in May, perhaps stimulated by the sewage spill, produced poor light conditions during the spring when temperatures were optimal. However, many kelps were reproductive at the end of 1992; if the water cools and storms open up the remaining canopy, growth and recruitment will ensue.

In summary, the 1992 sewage spill caused significant but short lived changes in light, sedimentation, and nutrient availability within the Point Loma kelp forest. We investigated population-level changes of selected species affected by these physical changes as well as concurrent El Niño conditions. In particular we evaluated the effects on abundance, diversity,

survivorship of established kelps and benthic invertebrates, and recruitment of kelps and sea urchins. With the exception of construction-related mechanical damage and shading by the barge in the immediate vicinity of the break, there were no apparent effects of the sewage spill on abundance, diversity, survivorship in our study organisms, or sea urchin recruitment. *Macrocystis* germination was clearly inhibited very close to the break point but this effect disappeared within a few days. Measurements at the whole organism level showed three effects. Germ tube elongation was significantly depressed at sites closest to the outfall break in the sediment toxicity studies, perhaps because of elevated metal levels in the sediments; this effect was also short lived. The development of juvenile to adult categories was delayed at one site (18 m South); here we cannot separate the effects of the spill from those of El Niño conditions and it is likely that both were important. Finally, ammonium from the sewage clearly benefitted the surface canopy at Point Loma relative the La Jolla forest.

The effects of this spill on kelp forest function can be considered in terms of a moderate reduction in kelp recruitment. *Macrocystis* zoospore release occurs throughout the year, but Deysher & Dean (1986) demonstrated that conditions for sporophyte recruitment are rare. They found that greater than 1.0% of gametophytes produced sporophytes only at temperatures less than 14°C and at irradiances greater than 0.4 $E/m^2/d$, although some production was detected up to 18.3°C. While irradiance is often high enough and temperature low enough for recruitment in Southern California, their joint probability is quite low. Dean & Jacobsen (1984) described the variability of light in a four year study at San Onofre; irradiation levels occasionally dropped below the compensation level for several months at a time. Thus, for this community, a two month disturbance of the light regime is not unusual even in the absence of El Niño conditions.

With the perspective offered by two decades of population studies at Point Loma (Dayton *et al.*, 1992), the impact of the 1992 sewage spill can be placed along the continuum of natural variability from minor disturbance to catastrophe. The effects of the spill were similar to the natural vagaries of recruitment and were very much less than the catastrophic losses of plant biomass associated with the strong El Niño of 1982–84 or the 1988 storm. The two month period and the limited spatial extent of the significant effects were no doubt important to this conclusion, despite the massive volume of the spill. While this unfortunate event had serious economic and social implications, it is critical that preconceived ideas about ecological effects of sewage subjected to modern treatment on the kelp forest community be both tested scientifically and placed in a long term perspective.

ACKNOWLEDGEMENTS

REFERENCES

Anderson, B.D. & Hunt, J.W. (1988). Bioassay methods for evaluating the toxicity of heavy metals, biocides and sewage effluent using microscopic stages of giant kelp *Macrocystis pyrifera* (Agardh): A preliminary report. *Mar. Env. Res.*, **26**, 113–34.

Anderson, B. S., Hunt, J. W., Turpen, S. L., Coulen, A. R. & Martin, M. (1990*a*). Copper toxicity to microscopic stages of giant kelp *Macrocystis pyrifera*: Interpopulation comparisons and temporal variability. *Mar. Ecol. Prog. Ser.*, **68**, 147–56.

Anderson, B. S., Hunt, J. W., Turpen, S. L., Coulen, A. R., Martin, M., McKeown, D. & Palmer, F. (1990*b*). Procedures Manual for Conducting Toxicity Tests Developed by the Marine Bioassay Project. Report to the Water Resources Control Board, State of California, Sacramento, California.

Brumbaugh, J. H. (1980). Holothuroidea: The sea cucumbers. In: Morris, R. H., Abbott, D. P., Haderlie, E. C. (eds.) *Intertidal Invertebrates of California*. Stanford University Press, Stanford, CA, pp. 136–45.

California State Water Quality Control Board (1964). An investigation of the effects of discharged wastes on kelp. California State Water Quality Control Board, Sacramento, Pub. 26.

Chelton, D. B., Bernal, P. A. & McGowan, J. A. (1982). Large-scale interannual and physical biological interactions in the California Current. *J. Mar. Res.*, **40**(1), 1-125.

City of San Diego (1992). Toxicity/Bioassay Testing Report. January –April 1992. Point Loma ocean outfall break environmental assessment program. City of San Diego, Water Utilities Department, Metro Wastewater Division.

Coastal Data Information Program (1991). Monthly reports, November 1991– August 1992. U. S. Army Corps of Engineers, Waterways Experiment Station, Coastal Engineering Research Center, Monthly Summary Reports No. 189–97.

Coastal Data Information Program (1992) Monthly reports, November 1991– August 1992. U. S. Army Corps of Engineers, Waterways Experiment Station, Coastal Engineering Research Center, Monthly Summary Reports No. 189–97.

Conversi, A. & McGowan, J. A. (1992). Variability of water column transparency, volume flow and suspended solids near San Diego sewage outfall (California): 15 years of data. *Chemistry and Ecology* **6**, 133–47.

Coyer, J. A., Ambrose, R. F., Engle, J. M. & Carroll, J. C. (1993). Interactions between corals and algae on a temperate zone rocky reef: Mediation by sea urchins. *J. Exp. Mar. Biol. Ecol.*, **167**; 21–37.

Dayton, P. K., Currie, V., Gerrodetta, T., Keller, B. D., Rosenthal, R. & Van Tresca, D. (1984). Patch dynamics and stability of some California kelp communities. *Ecol. Monogr.*, **54**, 253–89.

Dayton, P. K., Tegner, M. J., Parnell, P. E. & Edwards, P. B. (1992). Temporal and spatial patterns of disturbance and recovery in a kelp community. *Ecol. Monogr.*, **62**, 421–45.

Dean, T. A. & Jacobsen, F. R. (1984). Growth of juvenile *Macrocystis pryrifera* (Laminariales) in relation to environmental factors. *Mar. Biol.*, **83**, 301–11.

Dean, T. A., Schroeter, S. & Dixon, J. (1987) The Effects of the San Onofre Nuclear Generation Station on the Giant Kelp, *Macrocystis pyrifera*. Report to the Marine Review Committee, Inc. December, 1987.

Davinny, J. S. & Volce, L. A. (1978). Effects of sediments on the development of *Macrocystis pyrifera* gametophytes. *Mar. Biol.*, **48**, 343–8.

Deysher, L. E. & Dean, T. A. (1986). In-situ recruitment of sporophytes of the giant kelp, *Macrocystis pyrifera* (L.) C. A. Agardh: Effects of physical factors. *J. Exp. Mar. Biol. Ecol.*, **103**, 41–63.

Ebeling, A. W., Laur, D. R. & Rowley, R. J. (1985). Severe storm disturbances and reversal of community structure in a Southern California kelp forest. *Mar. Biol.*, **84**, 287–94.

Eppley, R. W. (1986). Chp. 8. People and the plankton. In: Eppley, R. W. (ed.) *Plankton Dynamics of the Southern California Bight*. Springer-Verlag, Berlin, pp. 289–303.

Eppley, R. W. & Harrison, W. G. (1975). Physiological ecology of *Gonyaulax polyhedra*, a red water dinoflagellate of Southern California. In: LoCiero, V. R. (ed.) Proc. of the 1st Inter. Conf. on Toxic Dinoflagellated Blooms. MTSF, Wakefield, MA, pp. 11–22.

Foster, M. S. & Schiel, D. R. (1985). The ecology of giant kelp forests in California: A community profile. *US Fish Wildl. Serv. Biol. Rep.*, **85**(7.2), 152 pp.

Foster, M. S., Dean, T. A. & Deysher, L. E. (1985). Subtidal techniques. In: Littler, M. M., Littler, D. S. (eds) *Handbook of Phycological Methods. Ecological Field Methods: Macroalgae*. CUP, Cambridge, UK, pp. 199–232.

Gerard, V. (1982). Growth and utilization of internal nitrogen reserves by the giant kelp *Macrocystis pyrifera* in a low-nitrogen environment. *Mar. Biol.*, **66**, 27–35.

Gerard, V. (1984) Physiological effects of El Niño on giant kelp in Southern California. *Mar. Biol. Lett.*, **5**, 317–22.

Grigg, R. W. & Kiwala, R. S. (1970). Some ecological effects of discharged wastes on marine life. *Calif. Fish and Game*, **56**, 145–55.

Haines, K. C. & Wheeler, P. A. (1978). Ammonium and nitrate uptake by the marine macrophytes *Hypnea musciformis* (Rhodophyta) and *Macrocystis pyrifera* (Phaeophyta). *J. Phycol.*, **14**, 319–24.

Harris, L. H. (1983). Changes in intertidal algae at Palos Verdes, California. In: Bascom, W. (ed.) *The Effects of Waste Disposal on Kelp Communities*. Institute of Marine Resources, University of California, La Jolla, pp. 274–81.

Harrold, C. & Pearse, J. S. (1987). The ecological role of echinoderms in kelp forests. *Echinoderm Studies*, **2**, 137–233.

Hayward, T. L. (1993). Preliminary observations of the 1991–1992 El Niño in the California Current. *Calif. Cooperative Oceanic Fisheries Investigations Reps*, **34**, 21–29.

Hunt, J. W. & Anderson, B. S. (1989). Sublethal effects of zinc and municipal effluents on larvae of the red abalone *Haliotis rufescens*. *Mar. Biol.*, **101**, 545–52.

Jackson, G. A. (1977). Nutrients and production of the giant kelp *Macrocystis pyrifera*, off Southern California. *Limnol. Oceanogr.*, **22**, 979–95.

Jones, B. H., Bratkovich, A., Dickey, T., Kleppel, G., Steele, A., Iturriaga, R. & Haydock, I. (1990). Variability of physical, chemical, and biological parameters in the vicinity of an ocean outfall plume. In: List, E. J., Jirka, G. H. (eds.) *Stratified Flows: Proceedings of the Third International Conference on Stratified Flows*. Am. Soc. Civil Eng., NY, pp. 877–90.

Lawrence, J. M. (1975). On the relationships between marine plants and sea urchins. *Oceanogr. Mar. Biol. Ann. Rev.*, **13**, 213–86.

Leighton, D. L., Jones, L. G. & North, W. J. (1966). Ecological relationships between giant kelp and sea urchins in Southern California. In: Young, E., McLachlan, J. L. (eds.) *Proc. Fifth Annual Seaweed Symp.* Pergammon Press, Oxford, pp. 141–53.

Lobban, C. S., Harrison, P. J. & Duncan, M. J. (1985). *The Physiological Ecology of Seaweeds*. CUP, Cambridge, pp. 132–53.

Mauzey, K. P.I Birkeland, C. & Dayton, P. K. (1968). Feeding behavior of asteroids and escape responses of their prey in the Puget Sound region. *Ecol.*, **49**, 603–19.

Milliken, G. A. & Johnson, D. E. (1984). *Analysis of Messy Data*, Vol. 1, Designed Experiments. Van Norstrand Reinhold Co., NY.

NOAA (1992). El Niño Watch, Advisory no. 92-10. NOAA Coastal Ocean Program, Coast Watch, National Marine Fisheries Service, La Jolla, Calif. 92038.

North, W. J. (1964). Ecology of the rocky nearshore environment in Southern California and possible influences of discharged wastes. *Adv. Water Poll. Res.*, **3**, 247–74.

North, W. J. (ed.) (1965). Kelp Habitat Improvement Project. Annual Report, 1 February 1964-31 March 1965. W. M. Keck Laboratory of Environmental Engineering, California Institute of Technology, Pasadena, CA.

North, W. J. (ed.) The biology of giant kelp beds (*Macrocystis*) in California. *Nova Nedwigia*, **32**, 1–600.

North, W. J. (1983). The sea uchin problem. In: Bascom, W. (ed.) *The Effects of Waste Disposal on Kelp Communities*. Institute of Marine Resources, University of California, La Jolla, pp. 147–62.

North, W. J., Gerard, V. & Kuwabara, J. (1982). Farming *Macrocystis* at coastal and oceanic sites. In: Srivastava, L. M. (ed.) *Synthetic and Degradative Processes in Marine Macrophytes*. Walter de Gruyter and Co., Berlin, pp. 247–62.

Parsons, T. R., Maita, Y. & Lalli, C. M. (1984). Manual of chemical and biological methods for seawater analysis. Pergammon Press, NY, pp. 14–17.

Seymour, R. J., Sessions, M. H. & Castel, D. (1985). Automated remote recording and analysis of coastal data. *J. Waterway, Port, Coastal and Ocean Eng., ASCE*, **111**(2), 388–400.

Seymour, R. J., Tegner, M. J., Dayton, P. K. & Parnell, P. E. (1989). Storm wave induced mortality of giant kelp, *Macrocystis pyrifera*, in Southern California. *Estuarine, Coastal and Shelf Sci.*, **28**, 277–92.

Strachan, A. R. & Koski, R. T. (1969). A survey of algae of Palos Verdes Point, California. Calif. *Fish and Game*, **55**, 47–52.

Stull, J. K. & Haydock, C. I. (1989). Discharges and environmental responses: The Palos Verdes case. In: *Managing Inflows in California's Bays and Estuaries*. The Bay Institute, Sausalito, CA, pp. 44–9.

Sun, M. (1989). Mud-slinging over sewage technology. *Science*, **246**, 440–43.

Tegner, M. J. & Dayton, P. K. (1981). Population structure, recruitment, and mortality of two sea urchins (*Strongylocentrotus franciscanus* and *S. purpuratus*) in a kelp forest. *Mar. Ecol. Prog. Ser.*, **5**, 255–268.

Tegner, M. J. & Dayton, P. K. (1987). El Niño effects on Southern California kelp forest communities. *Adv. Ecol. Res.*, **17**, 243–79.

Tegner, M. J. & Dayton, P. K. (1991). Sea urchins, El Niños, and the long term stability of Southern California kelp forests. *Mar. Ecol. Prog. Ser.*, **77**, 49–63.

Thomas, W. H. & Gibson, C. H. (1990). Quantified small-scale turbulence inhibits a red tide dinoflagellate, *Gonyaulax polyedra* Stein. *Deep Sea Res.*, **37**, 1583–93.

Underwood, A. J. & Peterson, C. H. (1988). Towards an ecological framework for investigation pollution. *Mar. Ecol. Prog. Ser.*, **46**, 227–34.

US EPA (1986). *Test Methods for Evaluating Solid Waste, Physical/Chemical Methods*, 3rd edn. US EPA Office of Solid Wastes and Emergency Response, Washington, D.C. S.W.846.

US EPA (1990). Draft Ecological Evaluation of Proposed Discharge of Dredged Material into Ocean Waters. EPA-503-90/002.

Van Dover, C. L., Grassle, J. F., Fry, B., Garritt, R. H. & Starczak, V. R. (1992). Stable isotope evidence for entry of sewage-derived organic material into a deep-sea food web. *Nature*, **360**, 153–56.

Weaver, A. M. (1977). Aspects of the Effects of Particulate Matter on the Ecology of a Kelp Forest (*Macrocystis pyrifera* (L.) C. A. Agardh) near a Small Domestic Sewer Outfall. Ph.D. Dissertation, Stanford University, Stanford, CA, 174pp.

Wilson, K. C., Haaker, P. L. & Hanan, D. A. (1977). Kelp restoration in Southern California. In: Krauss, R. (ed.) *The Marine Plant Biomass of the Pacific Northwest Coast*. Oregon State University Press, Corvallis, pp. 183–202.

Zar, J. H. (1984). *Biostatistical Analysis*. Prentice Hall, Inc., Englewood Cliffs, NJ, 718pp.

Zimmerman, R. C. & Kremer, J. N. (1984). Episodic nutrient supply to a kelp forest ecosystem in Southern California. *J. Mar. Res.*, **42**, 591–604.