

Chemistry and Microbiology of a Sewage Spill in South San Francisco Bay

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ABSTRACT: During three weeks of September 1979, the breakdown of a waste treatment plant resulted in the discharge of a large volume ($1.5 \times 10^7 \text{ m}^3$) of primary-treated sewage into a tributary of South San Francisco Bay, California. Chemical and microbial changes occurred within the tributary as decomposition and nitrification depleted dissolved oxygen. Associated with anoxia were relatively high concentrations of particulate organic carbon, dissolved CO_2 , CH_4 , C_2H_4 , NH_4^+ , and fecal bacteria, and low phytoplankton biomass and photosynthetic oxygen production. South San Francisco Bay experienced only small changes in water quality, presumably because of its large volume and the assimilation of wastes that occurred within the tributary. Water quality improved rapidly in the tributary once normal tertiary treatment resumed.

Introduction

South San Francisco Bay is a highly-urbanized estuary that receives effluents from 20 municipal waste treatment plants, as well as from numerous industrial, chemical and power generating facilities (Kahrl 1978). Circulation in the South Bay is sluggish (Conomos 1979), particularly during summer months when freshwater inflow is small and dispersal of pollutants is effected primarily by tidal mixing with coastal water. Pollutant dispersal is least efficient in the lower reaches of South Bay, and this area experienced water-quality problems (depressions of dissolved oxygen, large numbers of fecal coliform bacteria, poor fisheries; Harris et al. 1962) in the 1950's and 1960's prior to construction of secondary and tertiary waste treatment facilities. During September 1979, the largest sewage treatment plant (STP) experienced a breakdown that resulted in the discharge of $1.5 \times 10^7 \text{ m}^3$ of partly-treated waste into South San Francisco Bay through its receiving water tributary, Coyote Creek (Fig. 1). Here, we describe the results of a study that documented (i) selected chemical and microbial changes apparently resulting from this sewage spill, (ii) the geographic extent of these changes, and (iii) the recovery of the re-

ceiving waters after the STP resumed normal operations.

The San Jose-Santa Clara Waste Treatment Facility serves over one million people and discharges 100-120 mgd ($3.8-4.5 \times 10^5 \text{ m}^3$ per day) of effluent through a small tributary to Coyote Creek (Fig. 1). During normal operations wastes undergo secondary treatment, an activated sludge process that removes 85-90% of total organic loading. The tertiary process, which began March 1979, includes further removal of organic matter (to achieve 95-99% removal) by settling and the microbial oxidation of NH_4^+ to NO_3^- (nitrification). In early September 1979 (see Table 1 for chronology), performance of the activated sludge process was severely impaired by bulking (Sykes et al. 1979), presumably because of shock loadings of cannery wastes (Singer 1979). For three weeks effluent received only primary treatment (screening and settling followed by chlorination-dechlorination) and contained twenty times its normal concentration of dissolved and particulate organic matter (BOD loading was $1.4 \times 10^6 \text{ kg}$ in September, compared to $6.6 \times 10^4 \text{ kg}$ in August; Singer 1979). Dissolved oxygen became severely depressed, and fish and pelagic invertebrates were absent from Coyote

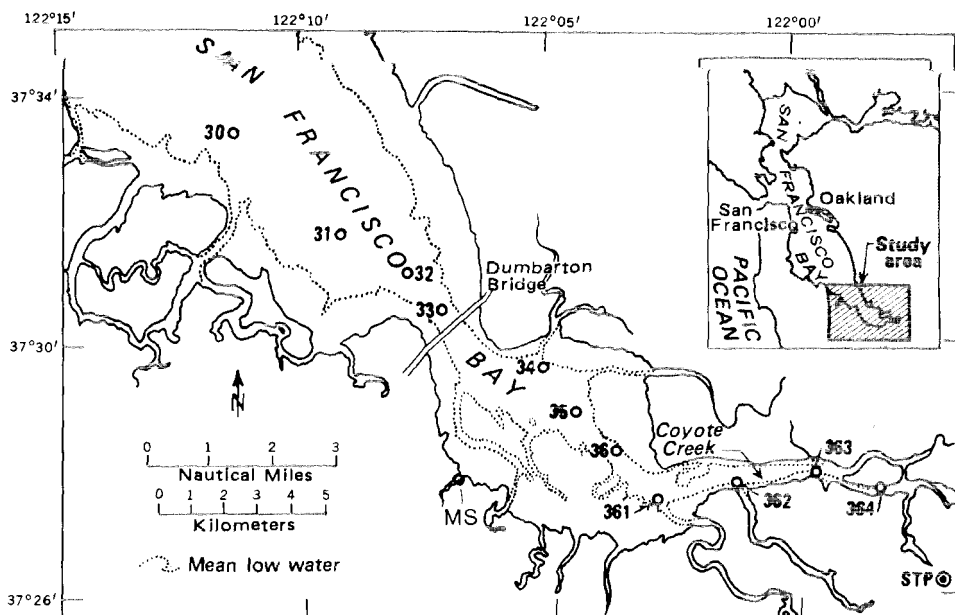


Fig. 1 Map showing locations of sampling stations in South San Francisco Bay-Coyote Creek (numbered sites) and Mayfield Slough (MS), and location of the Santa Clara-San Jose Waste Treatment Facility (STP).

Creek (W. Dahlstrom and M. Rugg, California Department of Fish and Game, pers. commun.). Our study was prompted by concerns for the impact of such a spill on the South San Francisco Bay ecosystem and to determine the likelihood and extent of hazards to human health.

Methods

Near-surface water samples were collected with a Niskin bottle at 12 sites in South Bay-Coyote Creek (Fig. 1), during low-slack tide. Analyses were performed for the following constituents: concentrations of particulate organic carbon (POC), dissolved oxygen (DO), methane (CH_4), ethylene (C_2H_4), total carbon dioxide (ΣCO_2), four species of dissolved inorganic nitrogen (DIN NO_3^- , NO_2^- , N_2O , and NH_4^+), phytoplankton biomass (chlorophyll *a*), abundances of fecal streptococci and coliform bacteria, and salinity, temperature, and Secchi depth. At selected sites, rates of photosynthetic oxygen production and community respiration were measured.

Total particulate organic carbon was determined by wet digestion of samples collected on glass fiber filters, and measure-

ment of evolved CO_2 with a Beckman IR 215A infrared analyzer (Schemel and Dardini 1979). We corrected POC values for phytoplankton, assuming a phytoplankton carbon:chlorophyll *a* ratio of 40 (K. L. J. Wong, unpublished data). Dissolved oxygen was measured by Carpenter's (1965) modification of the Winkler titration. Other dissolved gases were stripped from solution by the syringe method of Rudd et al. (1974) modified by a prior acidification with 2 ml of 6N HCl to volatilize CO_2 . CH_4 , C_2H_4 , and CO , were analyzed on a Hewlett-Packard Model 5730A gas chromatograph (GC) equipped with both flame ionization and thermal conductivity detectors. N_2O was analyzed on a Perkin-Elmer Model 3920 GC equipped with a ^{63}Ni electron capture detector.

Samples for analysis of DIN were filtered through a Gelman A/E glass fiber prefilter and then a $0.4\text{-}\mu$ Nuclepore membrane filter. Filtrates were analyzed colorimetrically for NH_4^+ , NO_2^- , and NO_3^- , using a Technicon AutoAnalyzer II (Smith et al. 1979).

Chlorophyll *a* samples were filtered onto Gelman A/E glass fiber filters with MgCO_3 (Strickland and Parsons 1972), then ground

and extracted with 90% acetone; extract absorbances were measured with a Varian 635D spectrophotometer. Equations of Lorenzen (1967) were used to calculate concentrations of chlorophyll *a* and phaeopigments. Samples for indicator bacteria were collected into sterile bottles and colonies were enumerated after incubation for 24 h (fecal coliform) or 48 h (fecal streptococci) on membrane filters with M-FC and KF media (Greeson et al. 1977).

Photosynthetic oxygen production and community respiration were measured during 3-h or 23-h incubation of replicate light- and dark-bottles in a sunlit, water-cooled incubator. Mean water-column photosynthesis was estimated from (i) these measured maximum rates, (ii) light attenuation (equating Secchi depth to the depth of 1% surface insolation), (iii) daily surface insolation, and (iv) water depth at mean tidal height.

Salinity and temperature were measured with a Beckman induction salinometer and thermistor.

Results

CONDITIONS DURING THE SPILL

On 26 September Coyote Creek exhibited the expected response of an estuary after receiving excessive loading of organic matter (Fig. 2). Distributions of POC, CH₄, and Σ CO₂ were all similar and mirrored the distribution of DO. Although POC underestimates the burden of organic matter by ignoring dissolved organics, the strong inverse correlation of DO and Σ CO₂ indicates that sewage-derived organic matter was microbially oxidized to CO₂, at the expense of oxygen. The extent of oxidation was sufficient to cause anoxia in the upper reaches of Coyote Creek as indicated by the absence of DO and the increased levels of CH₄ and Σ CO₂, the primary gases formed during anaerobic microbial sewage digestion (Mah et al. 1977). The greater abundance of CO₂ relative to CH₄ is due to its greater solubility (Lange 1967) and the oxidation of organic matter by anaerobic bacteria in addition to methanogens (i.e., sulfate-reducers, denitrifiers, fermenters, etc.). Ethylene, present in trace quantities, was most abundant near the STP (Station

TABLE 1 Chronology of events associated with the sewage spill

6 September 1979	STP begins bypassing secondary and tertiary treatment processes
10 September 1979	DO is less than 0.3 mg per l throughout Coyote Creek (Singer 1979)
13 September 1979	Commercial fishermen report the absence of fish and pelagic invertebrates from Coyote Creek
26 September 1979	Study begins
28 September 1979	STP resumes full tertiary treatment
7 October 1979	STP meets effluent standards for BOD and coliforms
18 October 1979	Fish and pelagic invertebrates are reported in Coyote Creek (W. Dahlstrom, pers. commun.)
24 October 1979	Study ends

364: 77 nM), decreased to 22 nM at the mouth of Coyote Creek, and ranged between 0–4.4 nM in the South Bay (detection limit = 1 nM). Formation of trace quantities of C₂H₄ has been reported during sludge digestion (Davis and Squires 1954) and by bacteria isolated from a variety of environments (Primrose 1976; Primrose and Dilworth 1976). C₂H₄ concentrations in Coyote Creek, however, were much higher than those previously reported in coastal waters (highest reported value was 1.3 nM; Swinnerton and Lamontagne 1974), which indicates that C₂H₄, like CH₄, was associated with anoxia created by the sewage spill.

Spatial variations in the concentration and speciation of DIN were also dramatic during the STP failure (Fig. 2b), and also reflected the importance of anaerobic processes. In Coyote Creek essentially all DIN was in the reduced form (NH₄⁺), while NO₃⁻ was undetectable. As DO increased between Coyote Creek and the South Bay, DIN speciation changed: sequential peaks of NH₄⁺, N₂O, NO₂⁻, and then NO₃⁻ represent the expected distribution in a transition zone from an area of denitrification (upper Coyote Creek) and an area of nitrification (lower Coyote Creek), and are similar to distri-

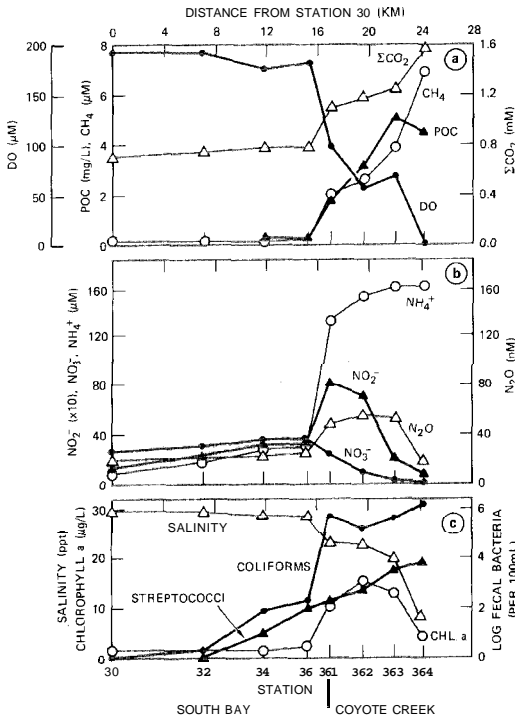


Fig. 2. Spatial distributions of selected chemical-biological constituents in the surface waters of South Bay-Coyote Creek on 26 September 1978.

butions observed in the Scheldt Estuary (Billen 1975). Our observations are also consistent with those made in the Potomac River, where supersaturated N_2O was associated with inputs of sewage-derived N (McElroy et al. 1978), and support the hypothesis that nitrification is an important source of N_2O (Bremner and Blackmer 1978). Nitrification in the water column of Coyote Creek represented a large DO sink (in addition to the oxidation of organic matter) since one mole of NH_4^+ requires two moles of O_2 :



NH_4^+ concentrations in Coyote Creek were 130–160 μM , which would require 260–320 μM O_2 for complete oxidation. This oxidation demand was sufficient to deplete the water column DO ($-200 \mu M$ in the South Bay) in the absence of replenishment by photosynthesis, mixing, and atmospheric exchange.

During the spill, phytoplankton biomass

(chlorophyll a) was low in the upper reaches of Coyote Creek (Fig. 2c), presumably because of inhibitory effects caused by the sewage spill (e.g., residual chlorine, heavy metals, S^{2-} , etc.). Our estimates of mean water-column photosynthetic rate indicate that daily oxygen production by planktonic algae (28 μM per l per day) was exceeded by the rate of community utilization (47 μM per l per day). Biological processes thus represented a net sink of DO in Coyote Creek during the STP malfunction, and the rate of net biological utilization exceeded atmospheric reaeration and tidal mixing with oxygenated South Bay water. While Coyote Creek experienced anoxia and extreme variations in dissolved constituents, South San Francisco Bay waters did not (Fig. 2).

The distributions of fecal coliforms and fecal streptococci indicated the possible presence of enteric pathogens in Coyote Creek during the treatment plant failure. Abundances of fecal coliforms greatly exceeded receiving water standards (240 total coliforms per 100 ml) throughout Coyote Creek, and the ratio of fecal coliforms: fecal streptococci exceeded ten, indicating a human origin of enteric bacteria (Geldreich 1972).

RECOVERY

After the STP resumed normal tertiary treatment, Coyote Creek experienced radical biogeochemical changes (Fig. 3) as it shifted from anaerobic to aerobic conditions. Most rapid changes were seen in the concentrations of CH_4 and C_2H_4 (Table 2), which approached background levels seen in Mayfield Slough (a tidal slough that was unaffected by the sewage spill, Fig. 1) within one week after recovery of the STP. Within two weeks, POC decreased and DO increased to apparently-normal values. Total CO₂ declined steadily and reached concentrations seen in the unaffected South Bay (Fig. 3d) and Mayfield Slough (Table 2) after four weeks. Changes in DIN were more complex (Fig. 3b), and it is not clear whether the distribution of DIN returned to normal conditions by the end of the study period. However, the decline of NH_4^+ and appearance of NO_3^- were rapid, and presumably resulted from both *in situ* nitrification as DO increased and from efficient nitrifica-

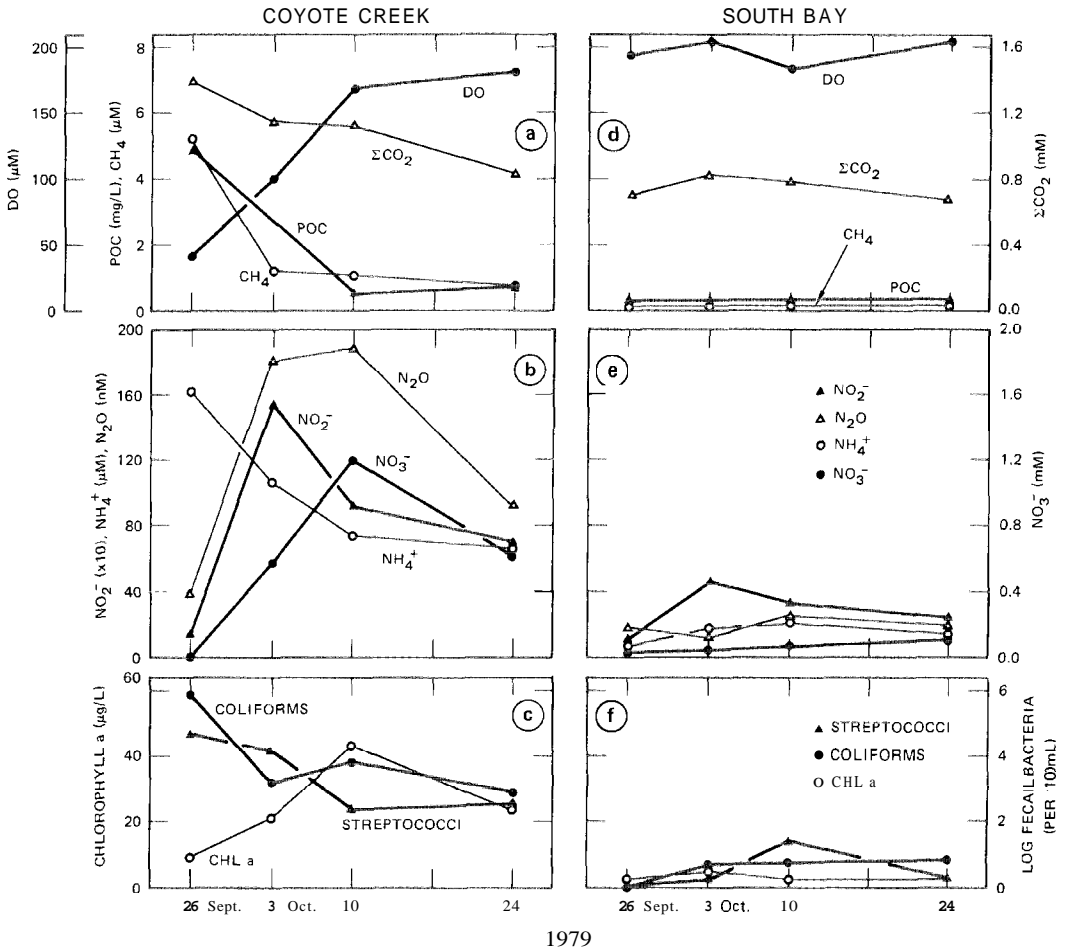


Fig 3 Temporal changes in selected chemical-biological constituents at two sites, following the resumption of tertiary waste treatment (28 September) Values are interpolated from concentration-salinity plots to represent mean conditions in Coyote Creek (15% salinity) and lower South San Francisco Bay (30‰ salinity)

tion by the STP as tertiary treatment commenced. Rapid increases in N_2O and NO_2^- , intermediates in the oxidation of NH_4^+ (Bremner and Blackmer 1978; Watson and Waterbury 1971), support the hypothesized importance of nitrification. Total DIN increased from $160 \mu M$ on 26 September to $1200 \mu M$ on 10 October. We presume that this increase reflects the near-complete decomposition and oxidation of organic N to NO_3^- by the tertiary treatment process, and that most nitrogen input to Coyote Creek during the plant failure was organic. During the study period we measured no significant chemical changes in the lower reach of South San Francisco Bay, except for a doubling of

NO_3^- (Fig. 3e); again, we presume the NO_3^- increase was accompanied by a decrease in organic N.

The rapid chemical changes in Coyote Creek were accompanied by increases in phytoplankton biomass (Fig. 3c). Measured rates of photosynthesis indicate that by 3 October daily oxygen production by phytoplankton ($69 \mu M$ per l per day) exceeded the rate of oxygen utilization ($25 \mu M$ per l per day), because of decreased decomposition and increased algal photosynthesis.

Bacterial indicators of enteric pathogens dropped by three orders of magnitude within the first two weeks after recovery of the STP (Fig. 3c). However, fecal coliforms still

TABLE 2. Concentrations of dissolved CH_4 , C_2H_6 , and ΣCO_2 in Coyote Creek (Station 364) and in Mayfield Slough.

Date	CH_4 (μM)	C_2H_6 (nM)	ΣCO_2 (mM)
Coyote Creek:			
26 Sept.	6.5	77	1.6
3 Oct.	1.2	6.3	1.2
10 Oct.	1.2	3.8	1.2
24 Oct.	1.1	2.5	0.9
Mayfield Slough:			
3 Oct.	0.2	12.5	0.9
10 Oct.	0.8	3.0	0.9

exceeded standards on 24 October. The source of these residual coliforms is not known, but records from the discharger indicate fecal coliform counts less than 2 per 100 ml in the effluent after 7 October. Ratios of fecal coliforms : fecal streptococci fell to four or less by 24 October which suggests a source of enteric coliforms other than human wastes (Geldreich 1972). Further work is needed to document normal background abundances of fecal coliforms, to determine other sources of coliforms, and to assess the potential hazards to human health in Coyote Creek and lower South Bay.

Discussion

Results of this study substantiate two principles associated with the discharge of sewage into estuaries. First, our results demonstrate the finite capacity of receiving waters to assimilate wastes. The response of an aquatic system to additions of sewage-derived organic matter depends upon the relative importance of all mechanisms that deplete dissolved oxygen (microbial oxidation of organics and other reduced substances, such as NH_4^+ , H_2S , CH_4 , Fe^{++} , etc.; respiration of benthic and pelagic animals and plants) compared to those mechanisms that reintroduce dissolved oxygen (photosynthesis, atmospheric reaeration, mixing with waters having high DO, etc.). If this capacity is exceeded, anoxia results and leads to radical, microbially-mediated chemical changes: we measured shifts in the abundance and oxidation state of DIN, end products of anaerobic bacteria (CH_4 , C_2H_6 , ΣCO_2), and we expect that other changes went unmeasured (e.g., pH, H_2S , Fe^{++} , Mn^{++} , etc.).

It is clear that during failure of the STP, sinks of DO exceeded sources in Coyote Creek, but not in the lower reach of South San Francisco Bay. What is not clear, however, are the mechanisms through which the South Bay resisted changes in DO (and, hence, other chemical and biological changes). Possibilities include: (i) a greater capacity to dilute the added load of organic matter and NH_4^+ ; (ii) the assimilation of added wastes within Coyote Creek before entering South Bay; (iii) more rapid atmospheric reaeration due to enhanced turbulence from stronger tidal currents; (iv) more rapid photosynthetic production of oxygen; and (v) faster mixing with waters of the upper South Bay where DO depressions do not occur. The large spatial gradients (including salinity) observed at the mouth of Coyote Creek (Fig. 2) suggest that enhanced dilution alone is sufficient to explain the absence of impacts in South Bay (the volume of water in lower South Bay, between Stations 33 and 36, is $3.3 \times 10^7 \text{ m}^3$, seven times the volume of water in Coyote Creek). However, spatial distributions of ΣCO_2 , POC and NH_4^+ indicate that decomposition of organics and oxidation of NH_4^+ occurred within Coyote Creek and thus lessened the burden of wastes on South Bay (see below). In effect, Coyote Creek operated as a sewage treatment plant.

The second principle substantiated by our study is that aquatic ecosystems are resilient, even to extreme perturbations. Concentrations of dissolved gases, inorganic and organic solutes, and particulate matter are governed by many physicochemical processes: inputs from STP's and tributaries, mixing, microbial transformations within the water column, microbial transformations in the sediments followed by sediment-water column exchanges, and exchanges between the water column and atmosphere. The relative importance of each process to the recovery of water quality in Coyote Creek is unknown, but we can estimate the importance of mixing between waters of Coyote Creek and South Bay compared to assimilatory processes (all *in situ* transformations and vertical exchanges). Assuming that the dominant transport process during the recovery was tidal mixing, we used Glenné's (1966) estimated diffusion coefficients to calculate characteristic time

scales of transport between stations from lower Coyote Creek into South Bay. The estimated cumulative time of diffusive transport along the length of Coyote Creek (Station 364 to 361) is 4–9 days. Therefore, dissolved and suspended constituents in Coyote Creek should have approached background South Bay levels within about a week after the resumption of tertiary treatment, assuming no *in situ* transformations or inputs from other sources. Tidal mixing alone may, therefore, explain the return of constituents to apparently normal levels within two weeks.

We also can estimate the rate of *in situ* waste assimilation based upon departures from conservative distributions. For example, if POC follows a conservative distribution, then plots of POC against salinity should decrease linearly, reflecting dilution with South Bay waters low in POC and having high salinity. However, on 26 September measured POC in Coyote Creek was 1.0–2.1 mg per l lower than predicted by conservative mixing between Stations 363 and 361. Using the range of estimated diffusive transport times between these stations, we calculated the rate of POC consumption to fall between 0.25–1.0 mg per l per day. Given a POC load of 5 mg per l, the time for complete decomposition would thus be 5–20 days (presumably the decomposition of dissolved organics occurred more rapidly). Therefore, we conclude that the observed decreases in POC in Coyote Creek resulted primarily from tidal mixing into South Bay, but that decomposition resulted in further losses of organic matter. Recovery of DO and indicator bacteria to apparently-normal levels also occurred within the time scale predicted on the basis of tidal mixing (fig. 3).

Those constituents that approached normal levels more rapidly than predicted by mixing had rapid rates of *in situ* assimilation. For example, CH_4 and C_2H_4 reached background levels in a week or less, indicating that either oxidation or atmospheric losses occurred more rapidly than horizontal diffusion. On the other hand, concentrations of I>IN and ΣCO_2 continued to change over the four-week study period, indicating that some *in situ* process delayed the recovery of these constituents. Delayed re-

covery of ΣCO_2 in Coyote Creek may have resulted from residual organic matter in the sediments that decomposed and provided a prolonged source of CO_2 to the water column. Similarly, the decline in NO_3^- between 10 October and 24 October may have reflected declining inputs from the sediments as residual organic N was decomposed and oxidized. While exact mechanisms are unknown, it is clear that a spectrum of time scales exists for the recovery of constituents within Coyote Creek, depending upon the relative importance of *in situ* assimilation compared to tidal mixing, and that water quality in Coyote Creek was apparently near-normal within a month after the STP resumed normal operations (fish and pelagic invertebrates returned within three weeks; W. Dahlstrom, Calif. Dept. Fish and Game, pers. commun.).

One practical result of our study is the demonstration that measurements of dissolved CH_4 and ΣCO_2 (in conjunction with DO) can be useful in assessing the nature and extent of events that lead to anoxia. Since these gases are easily extracted and can be analyzed in the field, they have utility as tracers for the geographic extent of anoxia. In addition, CH_4 was the most sensitive indicator of the initiation of water quality improvement in Coyote Creek, while ΣCO_2 apparently offered an index of the residual effects of sewage inputs.

Finally, we must explain that our conclusions about the impacts of waste discharge on South San Francisco Bay are biased by (i) the constituents we selected for measurement and (ii) the timing and duration of the study period. Potentially important impacts were ignored. For example, accelerated inputs of organic matter may have acutely impacted biota in Coyote Creek; little is known about the effects of the sewage spill on benthic organisms: and, juvenile elasmobranchs were surprisingly absent in trawls two months after the spill (R. A. Russo, East Bay Regional Park District, pers. commun.), indicating the possibility of deleterious effects on a year-class of sharks and rays. Our study was not initiated until after the STP began efforts to revive the secondary treatment process, and we suspect that more pervasive changes occurred in Coyote Creek prior to our study.

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