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# IN SITU MEASUREMENTS OF INITIAL DILUTION

During the past year, the Project participated in studies of initial dilution processes at the four major ocean outfalls in the southern California area. The purposes of this investigation were (1) to compare various methods of predicting initial dilution, measure the actual dilutions produced by existing outfall systems, and compare the predicted and actual performances, (2) to examine the behavior of buoyant plumes and surface wastefields in the sea, and (3) to determine the suitability of various tracers for field studies of plume and wastefield behavior.

These studies were funded by the California Water Resources Control Board through a contract with the Institute of Marine Resources, University of California. Our task was to provide independent field measurements using tracers and measurement techniques that would complement conductivity and temperature measurements to be carried out by Prof. Carl Gibson's group from University of California, San Diego (UCSD).

Our results to date indicate that the "minimum initial dilutions" (to be defined later in this article) associated with the Hyperion, Whites Point, Orange County, and Point Loma outfalls ranged from a low of 100:1 to a high of 290:1 for the well-stratified conditions existing during October 1976. These values are considerably larger (140 to 360 percent) than the dilutions predicted for these outfalls using the EPA numerical model "PLUME,"\* which does not account for the effects of currents. However, the values are comparable (95 to 135 percent) to those predicted from laboratory simulations (Roberts 1977) of the dilution of a surfacing wastefield in the presence of an ocean current— we assumed that the surfacing wastefield results could be generalized to include the subsurface wastefield conditions of southern California.

Model and sea comparisons are particularly important because, although various models have been used extensively to predict the performance of diffuser systems that produce subsurface wastefields, remarkably few of these predictions have been tested.

\*C. Gibson, University of California, San Diego personal communication.

## METHODS

The plan was to map the distribution of effluent in the area around an outfall. The UCSD group would use towed sensors to measure conductivity and temperature at very short intervals and thus define the horizontal extent of the waste-field. The Project (in a different ship at the same time) would obtain water column profiles at a number of stations to determine the vertical distribution of the wastefield. Because the towed-sensor system had not become operational at the time of the first set of surveys, the profiling station locations were chosen on the basis of the diffuser configuration and the direction of movement of current drogues. Generally, there were stations immediately over the diffuser and within 30 to 150 meters of the diffuser; additional stations at distances greater than 150 meters served as control stations. (Both towed-sensor and pro-filing operations will be carried out during subsequent surveys.)

The tracers used in these studies were constituents naturally present in the effluent and expected to be present after dilution at concentrations significantly higher than the background ocean concentrations. These constituents included turbidity, ammonia, and optical brightener fluorescence. In addition, during four of the six studies, we injected an artificial tracer, Rhodamine WT dye (WT does not attach to particulates) into the effluent. A comparison of the effluent and receiving water concentrations of these tracers formed the basis of our dilution measurements.

To make these comparisons, effluent samples were collected at the treatment plant during the study. In addition, the effluent flow rate was recorded at regular intervals so that the model comparisons could be made and so that we could calculate the transit time in the outfall pipe. With this information, the receiving water samples could be compared with the appropriate effluent sample. During the Rhodamine dye studies, the dye was injected into the effluent at a constant rate for a period of 70 to 90 minutes.

Field operations consisted of collecting water column samples, measuring the currents at several depths, and using parachute or windowshade drogues to follow the wastefield (Figure 1). A submerged pump and hose was used to bring a continuous flow of water from various depths to the deck of the survey vessel, where it was analyzed for turbidity or fluorescence using a continuous-flow nephelometer or fluorometer. (The turbidity (or fluorescence) values at discrete depths were noted during the first surveys; later a mechanical recorder was added to produce continuous pro-files.) Discrete water samples were also collected from the discharge of the analyzer, frozen, and returned to the laboratory for ammonia analysis using the phenolhypochlorite colorimetric method. Where appropriate, these samples were also analyzed for turbidity and optical brightener and Rhodamine dye fluorescence.

## RESULTS

The profiles obtained were compared to determine the suitability of each constituent as an effluent tracer. We found that optical brighteners were not a dependable indicator of the presence of effluent because of large and variable natural fluorescence. The ammonia, turbidity, and Rhodamine dye profiles were essentially the same, except at some of the stations at the Hyperion outfall. We attribute the differences to large changes in the quality of the effluent (a mixture of primary and secondary treated waste-waters) during the tests combined with weak ocean currents along the diffuser (which may have resulted in vertical layering of the effluent, depending on the time of discharge).

Within experimental error, the dilutions based on ammonia and on Rhodamine dye were equivalent at stations in the immediate vicinity of the diffuser during discharge of the dye-tagged effluent. The finite injection period limits the validity of comparisons at the other stations. If comparison are restricted to samples with a dilution of 500 to 1 or less, the average ratio of ammonia-based dilution to Rhodamine-dye-based dilution ranged from 1.07 to 0.90, depending on whether or not the ratios were weighted by the estimated experimental error.

The turbidity measurements resulted in dilutions that averaged about 40 percent of the ammonia or dye-based dilutions. We tentatively attribute this difference to the sensitivity of the turbidity measurement method to the changing distribution of particle sizes (there is considerable opportunity for this distribution to change during flow through the outfall, during the initial dilution process, and in passage through the sampling pump and hose).  
**DEFINITIONS** Before discussing the dilutions observed during these studies, it is appropriate that we define our terminology. By "dilution," we mean the dilution associated with the average concentration at a particular position in the water column; the averaging time must be sufficiently long so that fluctuations associated with the turbulent mixing process are averaged out but short enough so that variations associated with a changing flow rate and currents are negligible. As a practical matter, we chose the averaging time to be on the order of 5 seconds, which is the characteristic mixing time of our pump and hose system (fluctuations over longer periods of time were small, and those over shorter times could not be resolved with our system). At our pumping rate of 315 ml/sec, this time corresponds to a sampling volume represented by a sphere 14 cm (6 inches) in diameter.

"Initial dilution" is defined as the observed dilution at the approximate equilibrium depth of the wastefield (see Figure 1); initial dilution will be infinite if no trace of effluent is observed at that depth at a particular station. "Minimum dilution" is defined as the smallest dilution associated with a profile, and "minimum initial dilution" is the smallest observed initial dilution.

Because of the manner in which the sampling was carried out, there is a close correspondence between our "minimum initial dilution" and the

"centerline initial dilution" defined in model studies. Our definitions may, however, result in values that are higher than those based on a distinction between the "stirring" and "diffusion" aspects of the initial dilution mixing process. Stirring, which is the commingling of two different types of water (effluent and ocean water), results in a sample that appears to have the volume-weighted average characteristics of the two types. If, however, sufficiently small subsamples are taken, it will be obvious that the two distinct water types are still present. Diffusion refers to the actual molecular exchange of material between the two water types and results in sub-samples with characteristics intermediate to those of the two original water types. Diffusion is an irreversible process; stirring is a potentially reversible process. "Mixing" is the combination of the two processes, which generally proceed simultaneously, so that the inhomogeneity associated with the stirring is diminished by the molecular exchange of diffusion; however, the inhomogeneity may not be eliminated entirely during the time interval associated with the buoyant rise of the plume.

Other definitions of the initial dilution process are also possible (Gibson 1976), and our values may be lower than the values associated with these alternate definitions. Our definition is consistent with the typical model definition, which equates the end of the Initial dilution process with the rise of the buoyant plume to its equilibrium depth. In actual practice, the momentum of the plume may cause it to overshoot the equilibrium depth, and additional dilution may occur until these oscillations and the motions associated with density imbalances within the wastefield die out or become secondary to oceanic mixing processes. This additional mixing is ignored by our sampling procedure and in the definitions above. Inhomogeneities within the plume would also be expected to diminish during the additional time interval.

## DISCUSSION

Figure 2 illustrates typical turbidity and ammonia profiles at an outfall station. The first profile shown was observed approximately 150 meters from the end of the Orange County diffuser (Station A, Figure 3d). The profiles are normalized so that the minimum observed concentration corresponds to a plotted value of 0, and the maximum to 1; hence, different tracers can be shown on the same scale. The temperature profile of the water column during this survey is also shown. The minimum initial dilution associated with this profile is about 300 to 1. Bacterial examination of this sample by Mike Heinz of the Orange County Sanitation Districts resulted in an estimated dilution of 330 to 1, which is remarkably good agreement with the ammonia-based value.

Figure 2 also illustrates the conditions at a second station occupied at this outfall (Station B, Figure 3d) and shows the change in the plume behavior when a strong current flows across a diffuser rather than parallel to it. This difference in the plume behavior was observed earlier in Robert's laboratory simulations of the effects of the currents on the initial dilution process. In

these studies, one of the important parameters is the ratio,  $F$ , of the cube of the current speed to the discharge rate of buoyancy (due to the low salinity of the effluent) per unit length of the diffuser, i.e.:

$$F = \frac{s^3}{\left(\frac{Q}{L}\right) \left(\frac{\rho_o - \rho_e}{\rho_o}\right) g}$$

where

- $s$  = current speed,
- $Q$  = volumetric discharge rate of effluent,
- $L$  = length of the diffuser,
- $g$  = gravitational acceleration (e.g., 9.8 m/sec<sup>2</sup>),
- $\rho_o$  = density of the ocean water, and
- $\rho_e$  = density of the effluent.

As  $F$  increases, the model studies predict that there will be an increase in the initial dilution and, when the flow is transverse to the diffuser, a tendency for the plume to remain "attached" to the ocean bottom for some distance downstream from the diffuser, as was observed at Station B. The ammonia-based dilution for this profile is about 450 to 1, and the bacterial-based dilution, about 600 to 1.

Figures 3a through 3d show the location of minimum dilution measurements made during the October 1976 surveys at each of the outfalls. In all but two cases, these minimum dilutions are also the initial dilutions for that station—the values for which this is not the case are in italics. The arrows indicate the predominant direction of flow during the survey, and a typical speed during that period is given. The tail of the current arrow is positioned at the approximate location of the current meter string. The quantity " $F$ " is the model parameter discussed in the previous paragraph and is based on the indicated speed and the maximum rate of discharge during the study period. In general, the initial dilution values reflect the water movement measured by the current meters, but there are a few anomalies, such as the value downstream from the 90-inch ("wye") diffuser at Whites Point. These anomalies may be the result of the relatively slow lateral spreading of the wastefield that has been observed during some of these studies; under these conditions, the station—although generally downstream from the outfall—may actually be outside the main body of the wastefield.

The ultimate spatial resolution of our pumping system is on the order of 14 cm (6 inches); however, this resolution can be significantly degraded during periods of sea or swell due to the vertical motion of the vessel during the 5-second sampling period. Thus, it is of interest to determine if significant variations in concentration occur over distances smaller than the 30- to 100-cm field resolution of our pumping system. The smallest distance

within which we can resolve fluctuations in the concentration is limited by the 25-ml sample volume required for analysis. This corresponds to a sphere approximately 3.6 cm (1.4 inches) in diameter.

To investigate the possibility of inhomogeneities at this scale, the author designed and built a Small Incremental Profiler (SIP, Figure 4), which simultaneously collects 10 samples spaced 3.5 cm apart within a time interval of about 0.16 seconds. An analysis of 40 samples collected off the "wye" of the Point Loma diffuser with the SIP indicated that the variation in concentration about the mean was about  $\pm 19$  percent. Because part of this variation could be contributed to the error inherent in the analysis, the inhomogeneity may have been even less. Unfortunately, this sample may not have been taken in the immediate area of the plume, as the ammonia-based dilution of the mean was about 500 to 1. The question as to whether or not greater inhomogeneity is present at lower dilutions will be answered in future surveys.

The detection of fluctuation in concentrations at spatial intervals of less than 4 to 5 cm is of some interest in understanding the fluid dynamics of the initial dilution process; however, these fluctuations may have less significance from an ecological standpoint, as even a nonmotile diatom (phytoplankton) sinking at a rate of 1 meter per day will spend less than 1 hour in a sphere 4 cm in diameter. These small-scale inhomogeneities generated by the stirring of effluent and ocean water could, however, be important if pockets of low-dilution effluent separated under the influence of gravity from the surrounding relatively pure ocean water.

To examine this possibility, we deployed drogues in the wastefield at a station near the diffuser (see Figure 1) and then resampled the water column at the drogue location after an elapsed time of 1 to 2 hours. If separation occurred before concentration inhomogeneity had been significantly reduced in diffusion, we would expect the waste-field to be displaced upward, and our volume-averaged samples would show a higher concentration because of the displacement (removal) of the surrounding ocean water. Both upward and downward displacements were observed, but it is difficult to determine if these were due to separation, internal wave motion, or error in estimating the original equilibrium depth. In all cases, however, the maximum tracer concentration at the drogue station was less than at the time of deployment.

SUMMARY Measurements at the four major outfalls during a period of strong stratification indicate that initial dilutions of effluents are significantly higher than predicted by numerical models, which neglect the influence of ambient ocean currents. However, they may be comparable with the predictions generated by extrapolating laboratory simulations of the effects of currents on a surfacing wastefield to include a subsurface wastefield. Ammonia and Rhodamine WT dye dilutions were essentially equivalent, in relatively good agreement with limited bacterial comparisons, but significantly greater than estimates based on turbidity. The latter tracer is suspect due to the possibility that it was altered in the pipe, diffuser, and plume or in the sampling procedure. No significant inhomogeneities were

detected at spatial intervals as small as 5 cm, but sampling was probably not carried out in the immediate vicinity of the rising plume. No evidence of gravitational separation of any inhomogeneities that may be present at smaller spatial intervals was observed. Possible deficiencies in the choice of sampling stations, particularly in the case of flow parallel to a diffuser, will be corrected in the second series of surveys, and questions remaining relating to plume or wastefield inhomogeneities will be examined.

## REFERENCES

Gibson, C.H. 1976. Estimation of minimum initial dilution for municipal ocean outfalls: A progress report to California Water Resources Control Board, Sacramento, California.

Roberts, P.J.N. 1977. Dispersion of buoyant effluent from outfall diffusers of finite length. William Keck Laboratory of Hydraulics and Water Resources, California Institute of Technology, Los Angeles, California, Report KH-R-35.

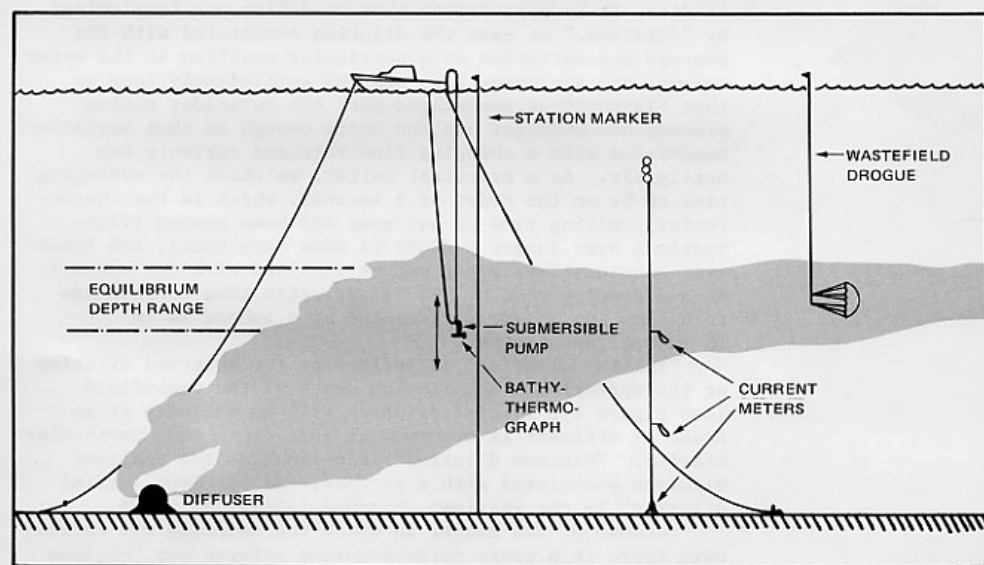


Figure 1. Field operation configuration for dilution studies, 1976.



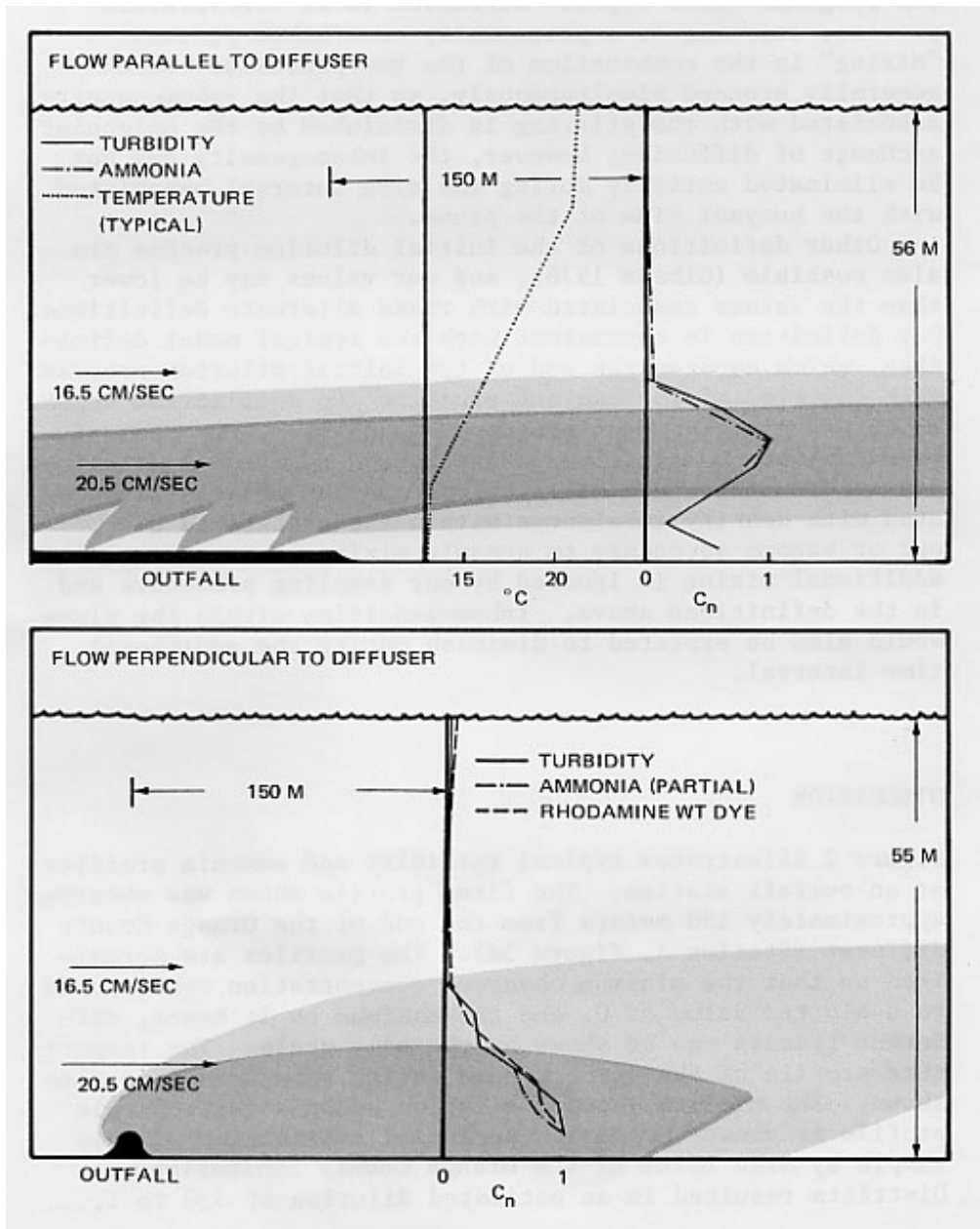


Figure 2. Concentrations profiles observed at the Orange County outfall.  $C_n$  is the normalized concentration, defined as  $(x - x_{\min}) / (x_{\max} - x_{\min})$ .

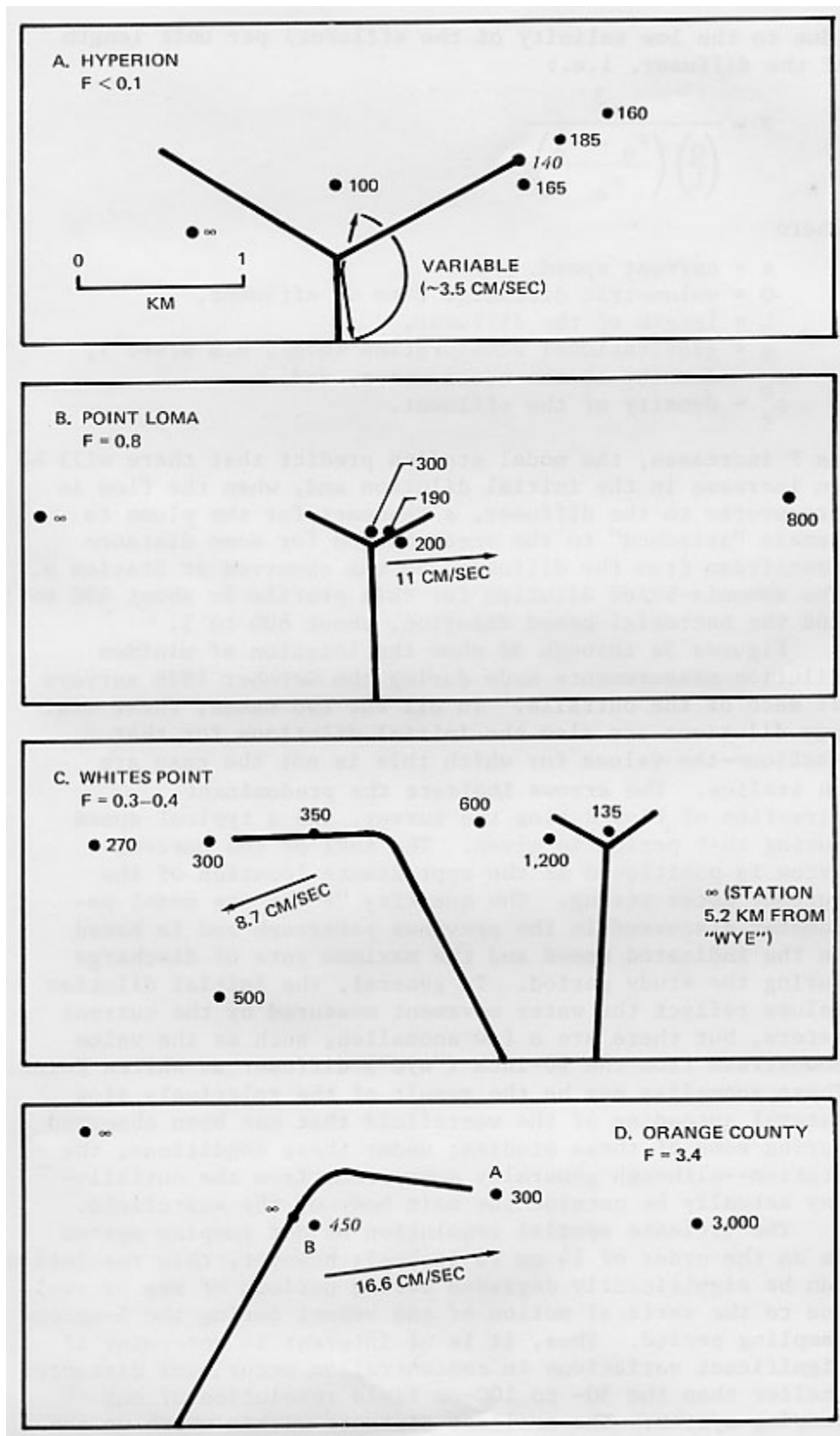
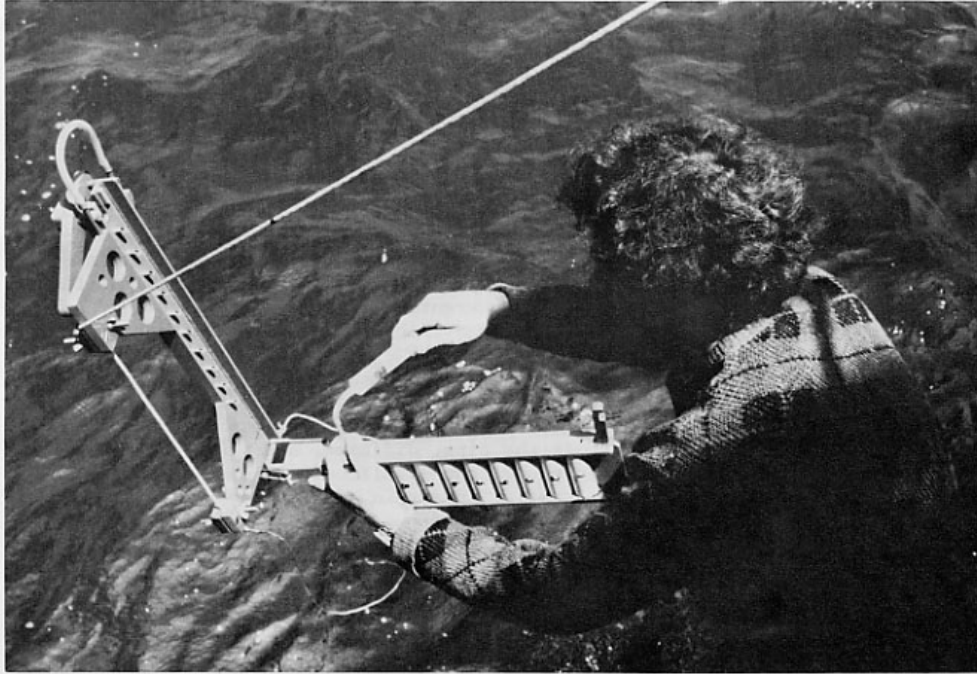


Figure 3. Initial dilution or minimum dilution (in italics) at stations sampled at each of four southern California municipal wastewater outfalls. The arrows indicate the predominant direction and typical strength of the currents about 25 meters above the bottom.



**Figure 4. Dr. Hendricks removes samples from the Small Incremental Profiler (SIP).**