APPLIED PHYSICS LABORATORY
UNIVERSITY OF WASHINGTON

DILUTIONS OF GRANDEUR

The Final Report on Dispersion of Effluent from the West Point Outfall

by

William P. Bendiner

This work was performed for the Municipality of Metropolitan Seattle under contract #63-1543 at the University of Washington.

This report does not necessarily constitute final publication of the material presented herin.

Approved by:

Terry E. Ewart
Principal Investigator
Program Manager, Ocean Physics

1 January 1976

John B. Slaughter
Director, Applied Physics Laboratory

Abstract

We have investigated dispersion in the Puget Sound main basin by tagging, with Rhodamine dye, the effluent from Metro's West Point Water Treatment Plant. The dye concentration and water density were measured *in situ* using a towed instrument package cycled vertically. Two experiments, each 5-7 days long, were done in August and February to examine seasonal variations. We find the vertical distribution of the initially buoyant effluent controlled by the density profile over the outfall at the time of discharge; correlation between dye and density persists as far downstream as one tidal excursion (4-7 km), suggesting low vertical mixing rates. Horizontally, the dye forms a sharp-fronted filamentous plume, one tidal excursion long, superimposed on a patchy field of "old" dye from previous tidal cycles. Local peak concentrations of small extent (100 m) are diluted slowly during tidal flows (by a factor of 3-10), but much faster when, at slack water, the flow breaks up from large-scale (1 km) motions into smaller eddies. This time-dependence for the dilution of peak concentrations contradicts present estuarine models, which incorporate eddy coefficients that are either constant or proportional to the mean current. The results and conclusions from our dye experiments agree with those from the drogue studies of Ebbesmeyer et al.

Table of Contents

List of Figures

List of Tables

Cooperative Efforts

The study described herein benefited from constant and fruitful interaction with the drogue studies of Ebbesmeyer et al. Between them, the two approaches aimed at supplying the physical oceanographic background for the other Interim Studies experiments, which concerned chemical and biological aspects of Metro's impact on the Sound.

Acknowledgements

We must thank, first of all, Ernie Linger for his help in planning and coordinating, for his efforts in the execution of both experiments, and for his unfailing sense of something--usually humor. Ken Karr and René Hernandez both made monumental contributions to the data analysis, as well as to the conduct of the field work. Gaye Floyd and Nancy Johnson did most of the computer programming and nightly unravelled the mysteries of the day's tapes. All of the people from Shoreline Community College (see Appendix) who worked with us, worked. And worked.

Curt Ebbesmeyer, of Evans-Hamilton, Inc., pumped a steady flow of good ideas and suggestions into both the conduct of the experiment and its analysis, and Rich Tomlinson of Metro was helpful all the way through.

John Armstrong, Craig Staude, Ron Thom, and perhaps some others we don't know about--all of the University of Washington's College of Fisheries--generously went out and collected all of the West Point bottle samples. Le Olson (and his family) and Burt Gropper helped keep West Point green instead of red.

And at the last minute, Jeannie Johnson typed the manuscript, got the figures into some kind of order, sorted everything out, soothed a few nerves, and cooked for the entire crew the whole time we were out. Thank you, Jeannie. Again.

I. SUMMARY

Under a contract with the Municipality of Metropolitan Seattle (METRO), the University of Washington's Applied Physics Laboratory (APL), has completed two experiments designed to elucidate the dispersion of effluent from the outfall of the West Point Water Treatment plant. Specifically, this study addressed the questions enumerated below, which are followed by summary answers.

1. Over what area can effluent be found? What kind of horizontal distribution does it have? How does its concentration vary as one looks farther and farther from the outfall?

Effluent is found in detectable concentrations (i.e., greater than 0.1 ppt) over a region extending from 4 km south of the outfall, about even with Pier 91, to 8 km north, about even with Agate Pt. The effluent rarely seems to extend beyond 2.5 km west of the outfall, but often is pulled east of the outfall, sometimes all the way in to shore. This is particularly true south of the outfall on the flood tide. (On the beach at West Point, the concentration of effluent varied from the undetectable up to 4 ppt in the summer experiment; in the winter experiment no effluent was detected on the beach.

Within this 12 x 5 km area, the distribution of effluent is highly variable. During well-developed currents, there is a plume that, on closer examination, includes many intermittent filaments, some of which are substantially more concentrated (by an order of magnitude or more) than their surroundings. In the background is a field of drifting effluent patches, some of which are of demonstrably earlier origin than the concentrated filaments.

Within about 100 m of the outfall ports, the effluent is diluted by a factor of about 100, due to buoyancy-induced mixing. Thereafter, if we look at the peak filament concentrations as a function of distance north or south from the outfall (during a well-established tidal flow), we find concentrations decreasing approximately as the inverse of distance. However, even at extreme distances this dilution may amount to no more than a factor of five (occasionally even less) beyond that produced in the vicinity of the outfall: during strong tidal flow, the Sound is an inefficient mixer. The northern and southern boundaries indicated earlier are defined by "fronts" where the effluent concentration drops sharply--by an order of magnitude or more within perhaps 50 m--to a level below the detection threshold. The background patches have peak concentrations that may be as high as a third of those of the filaments. The peak concentrations of both patches and filaments are associated with horizontal length scales on the order of 100 m.

2. What is the effluent's vertical distribution?

It appears that almost without exception, the vertical distribution of effluent at a given location reflects the prevailing density profile at that location. However spotty and transient the density distribution may be, it controls the vertical movement of effluent. Where there is a prominent pycnocline, the effluent is contained below it; where stratification is absent, the effluent is more uniformly distributed in depth and may reach the surface. Because the density structure of the Sound is highly variable in space and time, so is the effluent distribution. During most of the summer experiment there was a strong pycnocline at about 50 m; only below the pycnocline did we see appreciable concentration of effluent. But on the last day of the summer experiment, we observed a lack of stratification much like "typical" winter conditions, with a correspondingly diverse effluent distribution. In winter we sometimes found individual density profiles that showed a strong pycnocline, with consequent containment of the effluent, while 100 m distant on either side we found density profiles that showed almost no gradient, with correspondingly uniform effluent distributions. Effluent rarely (but sometimes) mixed down below 70 m, the depth of the diffuser parts.

3. How do the spatial patterns described above vary in time?

It is obvious from all of the observations that tidal motion is dominant in the Sound. Plumes form in the tidal current and are later dissipated at slack water. However, there is temporal variation in both the tidal flow itself, and, consequently, in the effluent distribution. As the current increases in magnitude at the beginning of each tide, it can also change direction; for example, the flow tends to be aligned north-south at low velocities (sometimes NW or SW), while at higher velocities there is a strong tendency for the current to turn and follow the east shore, expecially downstream of West Point, carrying the effluent with it. Thus, during a given tidal flow, the effluent pattern is far from constant. There is variation from cycle to cycle as well, due to the interaction of the various tidal components, so that the pattern of flow and effluent changes from ebb to ebb and flood to flood.

A seasonal variation is also apparent in the effluent distribution, resulting from the seasonal variation in the "typical" density profile, caused by the variations in temperature, runoff, and wind conditions.

In the neighborhood of Shilshole Bay there is evidence of buildup to a steady-state background of a few tenths of a part per thousand ("steady" in the sense of pertaining to intervals greater than a tidal cycle). Of course there must be some steady-state value of effluent concentration everywhere, but our results suggest that either it lies below our detection level or else the time needed to achieve it is significantly longer than the duration of our experiment: say, much longer than five days.

4. From the foregoing observations, what can we deduce about the mechanisms responsible for horizontal dispersion of effluent?

The persistence, during established tidal currents, of high peak concentrations in patches of about 100 m implies that most of the energy in the flow manifests itself at length scales larger than 100 m: eddies much larger than a drifting patch will not stir the patch much, but will merely push it about with little dilution. That the typical length scale of the flow during this part of the tidal cycle is comparable to the local topography is confirmed by the work of Ebbesmeyer (1974, 1975) and by observation of the Puget Sound Hydraulic Model at the University of Washington's Oceanography Department. For instance, eddies of about 1 km can form downstream of West Point; these appear responsible for much of the eastward set during strong flood tides, and perhaps have to do also with the sweeping of effluent onto the beach. Near slack water the flow breaks up into smaller eddies ("transfer of energy to smaller scales"); patches which before were too small to be affected are now comparable to the smaller eddy size and are diluted at a greater rate than before. After the current reverses and picks up speed, the smaller eddies die out and the remaining patches, suffering little dilution, are swept back toward the outfall, where they mingle with the newly-emerging filaments, forming a composite and patchy field of effluent. It appears to take at least two reversals to dilute a patch to a concentration below the level of detection.

5. What implications of our work are of importance to the other components of the Puget Sound Interim Studies?

The great variability, both in space and in time, of the observed effluent distribution imposes some limitations on programs that attempt to sample both in and out of the effluent. In order to know where the samples come from with respect to the effluent, either such samples must be made simultaneously with measurements of the effluent concentration, or else the problem must be regarded as a statsitical one in which a given sample is assigned a probability of having been drawn from effluent of a given concentration. In theory, experiments such as the present one should result in a series of charts, each relating to a set of conditions (stratification, tidal current, and other parameters), that would assign to each location and depth a probability of finding effluent of a given concentration. This is far beyond what we can, in fact, produce. We have not sampled under enough conditions to arrive at such statistics. We can only sketch some of the distributions observed during our field work, from which other investigators, hopefully, can begin to design sampling strategies appropriate to their work.

One particular point of uncertainty is how, and how much, effluent reaches the beach and contacts the bottom nearshore. Although we do not understand, on the basis of the few beach and nearshore observations we were able to make, just what happens to the effluent as it approaches the beach, there is some possibility that, under stratified conditions, effluent is transported along the bottom from the depth of the pycnocline (i.e. from where the pycnocline meets the shoaling bottom) on up to the beach. Should this be the case, the benthos in that region would be exposed to considerable concentrations of effluent throughout a substantial portion of the tidal cycle. Investigators of the effects of effluent on the benthos may wish to look especially carefully at this region off West Point, where our bottle samples indicated such mechanisms might be at work.

6. What implications of our work are of importance to theoretical models and to water quality control?

The dependence of the effluent's vertical distribution on the local stratification of the water column, and the sometimes incredible variability of the latter, signifies that effluent dispersion is sometimes a three-dimensional, sometimes nearly a two-dimensional process. Many models assume two-dimensionality; our results indicate that this assumption may be invalid except in those models that consider only broad space-time averages.

We have also observed that the mixing rate is time-dependent: the peak concentrations are more rapidly diluted at slack water than at full flow, the opposite of what intuition might suggest. Furthermore, the rate of mixing is, as we have previously pointed out, dependent on what spatial scales are considered; a model concerned with predicting peak concentrations--which are certainly of interest in terms of water quality control and some biological studies--might require one kind of time-dependence, while a model considering larger-scale averages might require quite another. A model encompassing all scales would be very complicated and has not, to our knowledge, been attempted. Indeed, many models neglect the time dependence altogether.

The variability of effluent distribution subverts any water quality standard that requires that a certain concentration of pollutant never be exceeded within a given volume of receiving water. This study shows that once a patch with some concentration is released into the system (allowed to get beyond a few meters of the diffuser), it may be found almost anywhere in the system. On the other hand, it is unlikely to effect any portion of the environment for very long. A standard requiring that a certain concentration never be exceeded may thus be more harsh than need be. The environment might be protected just as adequately by a standard requiring that a certain concentration not be exceeded for more than a specified length of time in a given place.

7. To what extent can these conclusions be generalized? Are they peculiar to Puget Sound?

We suspect that the observed patchiness and variability are characteristic of most natural systems, at least where the flow is somewhat complex. In cases of steady river flow or small lakes, for instance, the situation might be somewhat simpler, but for an estuary as complicated as Puget Sound, we believe the qualitative aspects of our results are probably quite general.

If we wish to understand the distribution of effluent in the statistical sense alluded to under question 5, many more observations under differing conditions are necessary. To make these would require a rather large program. On a somewhat smaller scale, and of considerable importance in evaluating the impact of METRO's West Point facilities on the environment, would be an extension of the beach sampling that we did. The beach and shallow water sampling were a small part of our effort, which was, as a beginning experiment, more properly directed at drawing the larger picture. Because of this, we did not take enough of these samples to understand the behavior of effluent in the nearshore zone, and further work is indicated if this is thought to be a worthwhile goal.

II. INTRODUCTION

This is the final report on the Applied Physics Laboratory's dye tracer studies at the West Point Water Treatment Plant, which were designed to explore the physical aspects of effluent dispersion from the West Point outfall. We made these studies with two goals in mind: to understand the mixing processes responsible for the dispersion, the better to predict what might happen to the effluent under a variety of circumstances, and to provide other investigators in METRO's Puget Sound Interim Studies program with information of use in the design of sampling strategies for their own chemical and biological investigations.

Our experimental approach has been to tag the effluent as it entered the outfall pipe with a known mass of Rhodamine B, a fluorescent dye that can be detected in the receiving waters in extremely small concentrations. By towing a dye detector (fluorometer) while cycling it vertically over a wide depth range, we obtain a three-dimensional map of the effluent field in the Sound; by measuring the temperature and electrical conductivity simultaneously with the dye measurement, we obtain a corresponding map of the density field. From these, and their relationship to each other, we can deduce some of the details of the processes which control the distribution and dilution of the effluent. To determine the short and long-term variability of these processes, we made such measurements during as many parts of the tidal cycle as possible over a period of 5 to 7 days, under both summer and winter hydrographic conditions. To supplement the offshore samples, personnel from the University of Washington's College of Fisheries took, from the beach at West Point, a series of bottle samples which we analyzed for dye content.

Our approach to the physical aspects of the dispersion is complementary to the drogue technique of Ebbesmeyer, whose experiments were an independent component of the Interim Studies. In Chapter V of this report, we will examine the intimate relationship between Ebbesmeyer's work and our own.

We made two cruises in the Puget Sound main basin, and have completed the analysis of the resulting data. The first, from 30 August to 3 September 1974, ended two days prematurely because the instrument towing cable failed. The second, from 26 February to 5 March, lasted the planned duration, although few observations were made on the last day because of bad weather. Because of the failures and weather, we were unable to make any substantial observations during the period after the dye injection ceased; such observations were to have given information on residence times and flushing in various parts of the system. We have, however, answered a good many of the questions which we posed. Furthermore, our work has revealed some features of mixing in natural systems that were not obvious before, and that are significant not only to theoretical understanding but to the practical details of water quality and its regulation.

III. DESIGN AND TECHNIQUE OF THE EXPERIMENT

A. Design Philosophy

A quantity of tracer can represent a quantity of the substance being traced (or simulated) as long as the two quantities remain in fixed (or at least known) proportion. The proportion will remain fixed insofar as the tracer and the traced substance behave identically under the influences of the natural system; this assumption of identical behavior underlies all quantitative tracer studies. The designer of a tracer experiment therefore considers: first, what proportions are required by the goals of the study and by the limitations of his detectors; second, in what ways the tracer's behavior could depart from that of the substance being traced or simulated.

Specifically, in deciding what ratio of tracer dye to effluent would be suitable in our case, we faced the following constraints. First, there is a background level of fluorescence in the waters of the Sound, which, at the emission wavelength of Rhodamine B (the most suitable tracer dye available in the U.S.), amounts to an equivalent dye concentration of 1 to 5 x 10^{-11} g/cm^3, depending on location and season. This, then, is the threshold level for detection, even if one's instruments are capable of greater sensitivity. Second, the volume flow of effluent at West Point varies from 75 to 325 mgd* (3.3 to 14.2 x 10^6 cm^3/sec). Third, on the basis of the outfall's diffuser design, we expect a dilution of about 100 to 1 in the immediate vicinity of the outfall. If we then ask that, beyond this vicinity, the effluent emerge with a dye concentration four orders of magnitude above the detection threshold--four orders of magnitude seeming *a priori* to give a comfortable

---

*Million gallons per day.

dynamic range for the experiment--we can calculate the required average rate of dye injection: 19,000 kg of pure dye per day, or about 416 bbl/day of 40% solution, at a cost of $312,000/day at current prices. While this extraordinary result may make the calculation appear facetious, it is not. Had we had that four-magnitude dynamic range, which is not a lot to ask in a large, relatively unmeasured system, we could have discovered a great deal more about the mixing process than we did. Instead, we pumped what we economically could, 1 bbl/day, which gave us a dynamic range of about 40. In the event, we were fortunate that this was adequate for most of our purposes, but in designing a sampling strategy and in conducting the experiment, we constantly had to bear in mind our limitation to observing relatively high effluent concentrations, for we could ill afford time spent looking for features we could not possibly see.

There are many ways in which a tracer can behave differently from the substance being traced. There may be differences, for example, in the rate of loss through the surface, in chemical or photochemical reactions to the environment, or in physical characteristics such as density. These possibilities have been summarized, with respect to Rhodamine dyes, by Carter (1972). For our purposes, we need consider only three aspects of Rhodamine's behavior: its decay in bright light, its reaction to chlorine, and its adsorption onto particulate matter. Since both adsorption and the reaction with chlorine are complex, and since the effluent is, to say the least, rich in particulates, we did some preliminary testing of our own. We tested both Rhodamine B and Rhodamine WT, the latter a formulation more inert, less easily adsorbed, and more expensive than its counterpart. Over a period of five hours, we monitored the dye concentration in containers filled with various combinations of dye types and effluent" chlorinated (1 ppm) and unchlorinated, exposed and unexposed to bright sunlight. We found the adsorption and chlorine-reaction rates apparently dwarfed by the photodecay, which was, however, still small: expressed as an exponential time constant, 0.025 hr^{-1}. These results are consistent with those reported by Carter. We ignored all three effects, treating the dye as a conservative quantity.

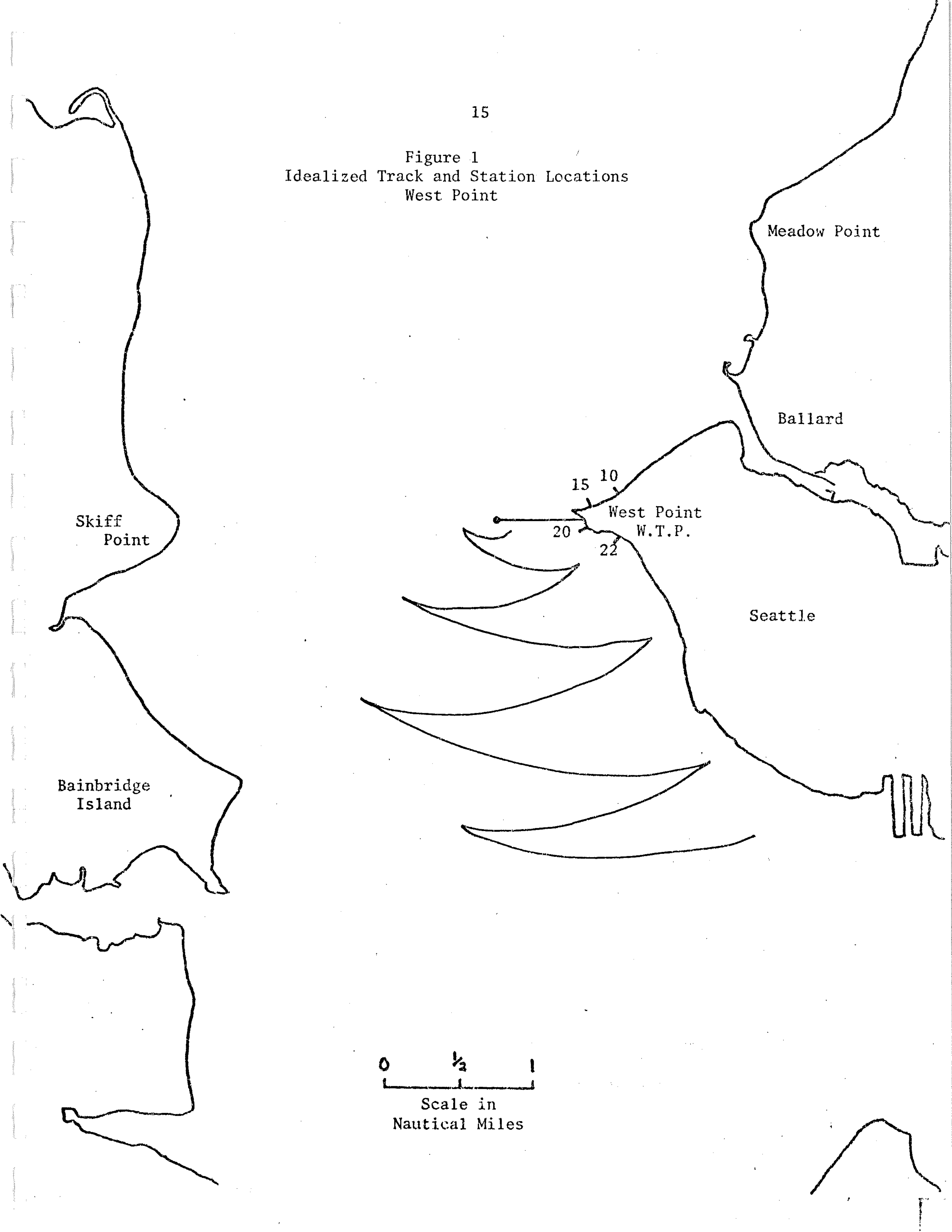
Of course, the effluent itself is not a simple substance. Many of its components are not conservative in that they undergo reactions in the environment on a time scale comparable with that of our observations. The dissolved chlorine injected by METRO, for instance, or the coliform bacteria whose presence is often the gauge of water quality, both evolve differently in the water than do, say, inorganic phosphates or suspended particulates. Thus, a certain amount of care is necessary in interpreting our results, which only pertain to the conservative, soluble parts of a complex mixture. In trying to establish both how much the environment is exposed to the effluent and how much such exposure can be tolerated, each of the effluent's components will need to be considered separately.

The size of the Puget Sound main basin, and the tidal time scales which dominate its currents, made necessary a tangle of compromises in choosing what specific features to look for and a sampling strategy aimed at finding them. In view of the small range of available dye concentrations discussed earlier, we decided to emphasize, in the first experiment, the newly released plume as it formed downstream of the outfall. Observations of the UW Oceanography Department's Puget Sound Model suggested that arcs of increasing width starting at the outfall and progressing downstream would intersect most of the plume as it emerged. An ideal track might look like that in Fig. 1, but a typical real track was more random. Having thus oriented the first experiment, we devoted most of the second to an examination of "older" effluent--that which had survived at least one turn of the tide while still remaining detectable--returning to examine the newly-formed plume only often enough to find how it differed from previous ones formed under earlier conditions. The search for "older" effluent involved some upstream mapping as well as some circling of the outfall in order to make rapid comparisons between effluent that was just being released and that which was being swept back across the outfall from the previous cycle. Unfortunately, looking at one aspect of the effluent distribution often precluded simultaneously looking at another.

The choice of a vertical sampling range embroils us in still more conflicts and compromises. We are limited by the capacity of our towing winch to vertical instrument velocities of about 1 m/sec. Therefore, if we sample 100 m vertically while we move horizontally at 2 m/sec (about 4 kn, a typical towing speed), the average horizontal sampling interval will be 200 m as the instrument package executes a vertical swatooth. If this is too large, we can reduce it by reducing our vertical range or by towing at a slower speed. The latter choice, however, means that we will sample a smaller area during a given tidal cycle.*

*The way out of this dilemma is to build a stronger winch and to sample faster. But our data rate (one per second) and winch were already as fast as we were able to get them for the present experiment.

Figure 1
Idealized Track and Station Locations
West Point



Faced with this complicated tangle, we may feel that we are, indeed, "confronted with insurmountable opportunities." If we are to emerge with any result at all, our sampling decisions must be made on the spot, on the basis of what we see, because any pattern of sampling fixed in advance and rigidly adhered to will be wasteful in some way. Support of this flexibility demands a real-time readout system, a feedback to the investigator. The next section of this chapter will show how our instrumentation system provides such feedback; the later discussion of the results will demonstrate how necessary it was.

In order to understand the pattern of effluent dispersion, we must see it in relation to the flow of the receiving waters; to gain this perspective, we make supporting measurements of the flow itself. Two quantities are of obvious and direct importance: density and current.

On its emergence into stratified salt water, the essentially fresh effluent,* undergoes turbulent mixing driven by its own buoyancy. That is, the buoyancy effects the flow dynamics; in this sense, the effluent is called an active constituent. During this phase, an anomaly in the density profile is observable, correlated with effluent concentration: where there's much effluent, the density is lower than it is at corresponding depths away from the effluent. A density measurement serves here as a gauge of activity, or buoyancy.

Under the influence of the buoyancy-induced mixing, the effluent comes to density equilibrium with its surroundings; its equilibrium depth is a function of the intensity of the mixing and the density profile into which it emerges. A strong pycnocline over the outfall will almost certainly contain

*Measurement of the effluents specific gravity yields a typical value of 1.002, or 2 sigma units.

the effluent below it. At this stage, the effluent, having the same density as its surroundings, no longer affects the flow and is merely carried with it; in this sense it is called a passive constituent. The relationship between effluent and density during this passive stage reflects the conditions which prevailed as equilibrium was attained, as well as any vertical (specifically, cross-isopycnal) mixing that may have occurred since.

The density thus provides important clues to the history of the effluent and the nature of mixing, so for this alone, its measurement is relevant to our work. Seasonal differences in the Sound are also reflected in the density profile, which thus acts as an index of both long and short-term changes. Once we understand the relationship between effluent mixing and the density field, then, when we are no longer tagging the effluent with dye, density measurements alone will suggest how the effluent is behaving.

Besides the density field, we would like to understand the current velocity field, including both its mean and fluctuating (turbulent) components, for this is the sole significant agent of dispersion once the effluent becomes passive. This is a difficult measurement. One should say "series of measurements," for we really need both the mean and fluctuating components as functions of both space and time. This would require a profusion of instruments and moorings quite beyond our means in the context of this experiment.

Fortunately for us, Ebbesmeyer and his associates (Ebbesmeyer and Okubo, 1974, Ebbesmeyer and Helseth, 1975) have found methods of extracting from drogue data a great deal of the information we need. See Chapter V.

Finally, one other supporting measurement seemed desirable, that of effluent reaching the beach at West Point. Because it is impractical for us to sample in our usual way in very shallow water (even where it's deep enough to bring the boat in, too much time is involved), we asked personnel from the University's College of Fisheries to collect bottle samples for us, once on each stage of the tide, at various of their standard West Point sampling stations. The collected samples were returned to the dye pumping station at West Point, transferred to our boat, and run through our fluorometer on deck, within a few hours of their being taken. The locations of their stations are included in Fig. 1.

B. Instrumentation and Techniques

1. Instrumentation

Our towed instrument package included sensors of dye concentration, temperature, conductivity, and depth. Of these, the first three were developed by this Laboratory's Ocean Physics Group for oceanic research; only the depth sensor is a commercial unit. The specifications for all of our instrumentations systems are given in Table I.

Our fluorometer is an *in situ* instrument capable of detecting Rhodamine dye in concentrations as dilute as 10^{-12} g/cm^3. It is unique in several respects. First, interference filters of 50 Å bandwidth provide extreme separation of the absorption and emission spectra, accounting largely for the high sensitivity of the instrument. Second, the circuitry is very stable with respect to temperature and needs no adjustment for changes in lamp intensity. Third, the instrument has a dynamic range of 10^3 on each of four overlapping

TABLE I - Instrument Characteristics

Measurement	Manufacturer/ Designer	Type/Description	Abs. Accuracy	Resolution
Dye Concentration	APL/UW	*In situ* fluorometer, maximum sensitivity 10^{-12} g/cm^3	±0.1 log units	0.1 log units
Temperature	APL/UW	Glass bead thermistor in Wien Bridge oscillator	±0.01°C	0.01°C [a]
Electrical Conductivity	APL/UW	3-electrode cell/Wien Bridge oscillator	±0.01 mmho/cm	0.01 mmho/cm [b]
Depth	United Control	Vibrotron	±0.1 m	1 m [c]
Position	Motorola	Mini-Ranger Mark III radar range-range system	±20 m	20 m [d]

Notes: a--sensor resolution is 0.007°C in this temperature range; present recording system digitizes only to stated resolution to save electronics, since no more precision is needed for this experiment.
b--see note a; inherent sensor resolution is 0.0005 mmho/cm.
c--see note a; inherent sensor resolution is 0.01 m or better.
d--see note a; system is good to about 1 m resolution.

ranges, so that this experiment could be conducted without changing ranges. An *in situ* instrument obviates the need for pumping samples to the surface, a procedure guaranteed to degrade spatial resolution at all but the shallowest depths.

The other sensors have been described in detail elsewhere. Temperature is sensed using a glass-bead thermistor incorporated into the bridge circuit of a Wien bridge oscillator, as described by Pederson (1969). These probes have proven dependable in countless experiments over the past ten years, but decided to make an exception in our case; during the second experiment, their repeated failure (by case leakage) was responsible for the loss of much density data. Electrical conductivity is sensed by a three-electrode resistance cell, incorporated, like the thermistors, into a Wien bridge oscillator, and likewise described by Pederson (1973). Depth is measured using a Vibrotron pressure sensor, in which varying pressure changes the tension on a vibrating wire, whose vibration frequency changes as a consequence.

The four devices just described are carried in an aluminum cylindrical housing, the "fish," shown in Fig. 2. The fish is streamlined for low drag, and contains a pump and plumbing system to distribute seawater to the sensors, electronics for digitizing and multiplexing the several sensor signals so they can be sent up the single-conductor towing cable, and a battery-operated pinger to aid in locating the fish in case of cable breakage. The nose of the fish is somewhat shock- absorbent, a desirable feature since an established pycnocline seems to collect deadheads as well as effluent.

The plumbing system comprises a dc-powered pump, three sensors (temperature, conductivity, dye) in parallel on its suction side, an intake screen at the nose of the fish, and control valves so that samples can be run through the fluorometer on deck (e.g., calibration samples or discrete bottle samples). The pumping rate of the system is nominally 500 ml/minute, but the rate showed an annoying variation during towing, possibly due to pressure effects at the intake whenever the fish's angle of attack was particularly high. Whatever the cause, the pumping system occasionally came close to stalling out, producing a long and variable time lag between the Vibrotron's pressure signal (which, of course, does not depend on the pumping system) and the signals from the other sensors. We have not found any algorithm for removing this lag from the data, so allowance must be made for the delay when viewing vertical sections of data. The effect is usually quite obvious in the contours.

2. Towing System

The towing system is our means of cycling the instrument package over a chosen depth range, so that it traces a sawtooth path in the vertical plane as it is pulled through the water. The system consists of winch, towing cable, winch control unit, and operator.

The winch is hydraulic, powered by a 14 h.p. gasoline engine mounted on the bow. In the hydraulic system is an accumulator which can provide about 50 hp output for short times; this allows for hauling in at emergency speeds, which is particularly valuable when working over rapidly varying terrain.

For towing, we used a single-conductor, 5/16 in. Amergraph cable. Although this cable has two layers of armor, wound in opposing directions, it is not completely torque-balanced. Rapid cycling, with the concomitant fluctuations in load, results in relative rotation of the two layers, forming what might be termed "torque waves." If the cable is constrained from rotating

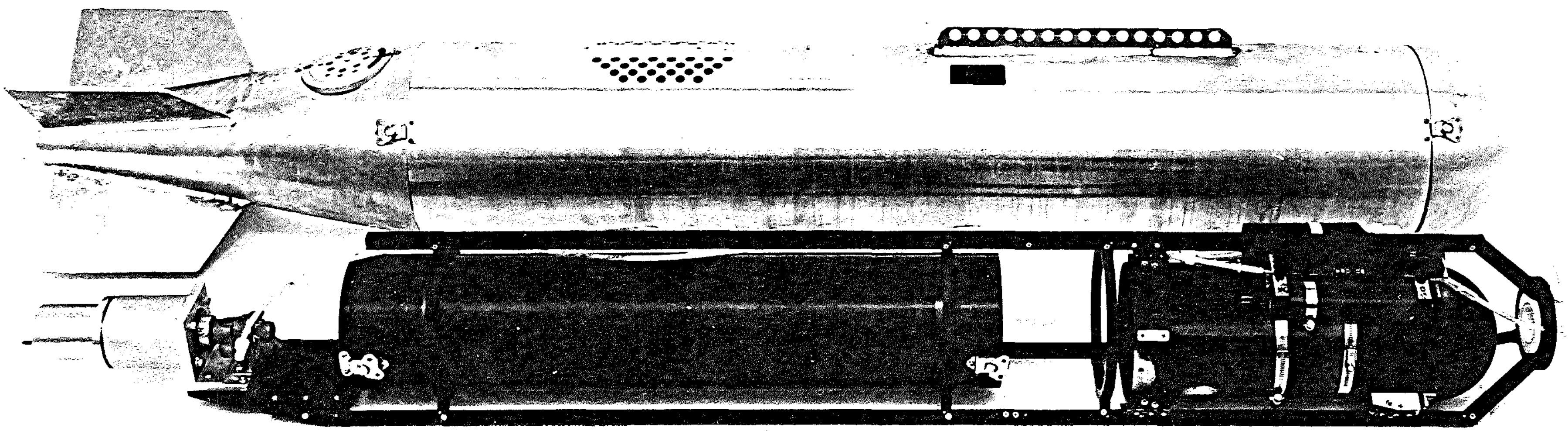


Figure 2.
The "fish," with its sensors and electronics package.

on the towing sheave as it's pulled in, the resulting waves in the armor are "milked" down toward the cable termination, where they build up until only one layer of armor is carrying the load. In some places, the inner layer, protruding through the outer, may be cut off. On the first cruise, using a rubber-coated wheel on which the cable apparently could not rotate, the cable lasted typically two or three days; the repeated failures were largely responsible for the early end of the experiment. Use of a steel block in the second experiment allowed the cable to last about two weeks, at the end of which time, the torque waves were just noticeable.

The winch control unit, facing the operator on the afterdeck, consisted of a fathometer to which had been added a channel for instrument depth, derived from the Vibrotron signal coming up the cable from the fish. The operator sees one trace for the bottom, one for the surface, and, between them, one for the fish; a sample of fathometer output is shown in Fig. 3. Thus aided, the operator can safely cycle the fish rapidly in a depth range specified by the scientist on watch on the basis of where dye is being detected. This system has now cycled without mishap some 16,000 times in the hands of Shoreline Community College marine technicians.

3. Navigation

Because the sampling could not be done on a fixed path surveyed in advance, and because our path was inevitably a complicated one, we needed a reliable and highly automated navigation system. In both experiments we used the Motorola Mark III Mini-Ranger, a radar system which continually provides the ranges from two fixed shore stations slaved to a master station on the

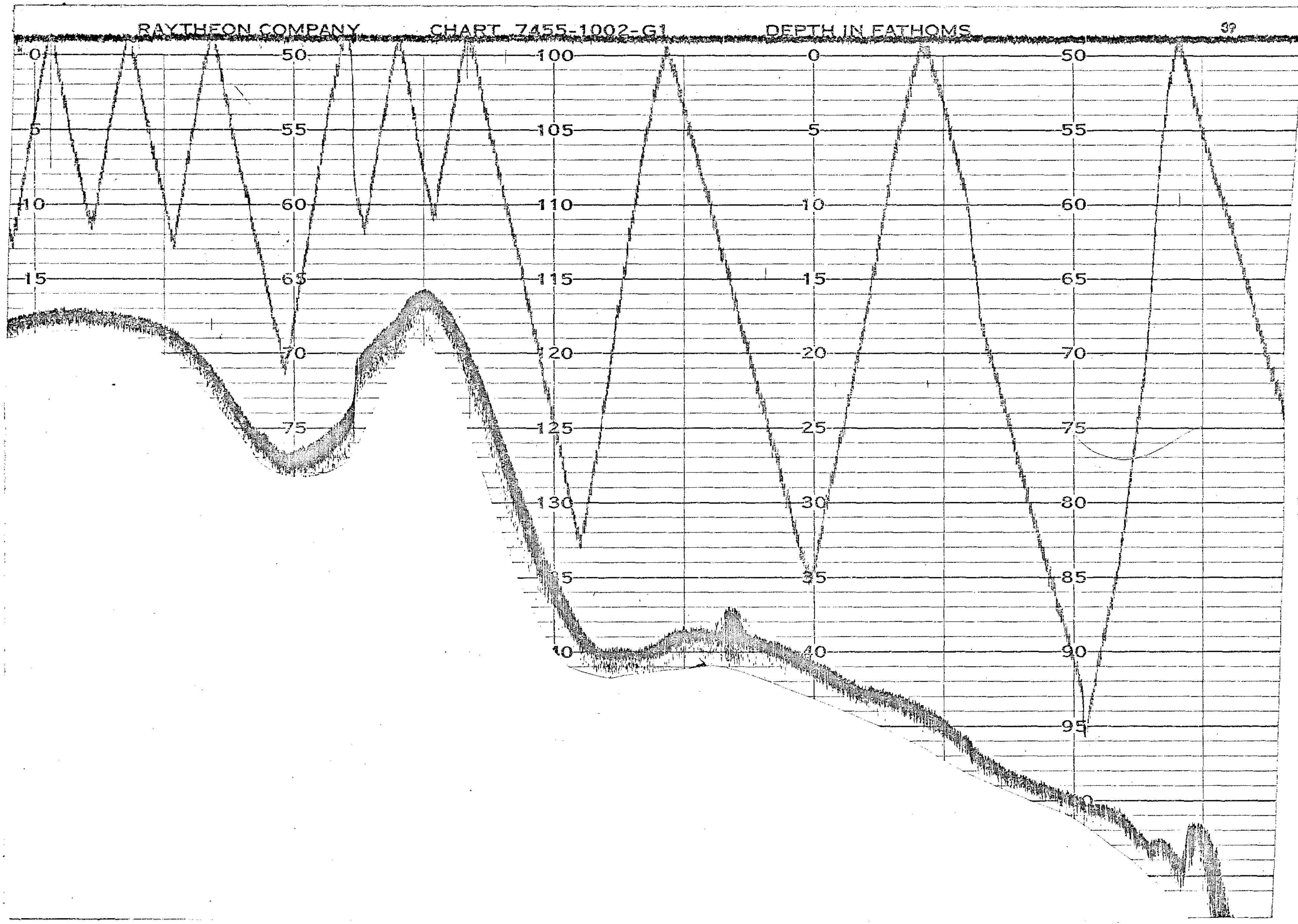


Figure 3.
Fathometer trace from winch control unit, showing bottom depth and depth of fish. The bump on the bottom at 38 f is the outfall pipe.

boat. Range resolution is about 10 m or less (depending on location and conditions), and maximum range, for our particular configuration, was about 13 km. The location of the shore stations was referred to the standard USGS grid, and the exact position of the outfall was supplied by METRO. From these data, a program was written for a Hewlett-Packard 65 programmable calculator which converted the two ranges into N-S and E-W coordinates, centered on the center of the outfall.* During the experiment these were plotted by hand, about one minute behind real time.

4. Data System

All measured data were recorded once per second on magnetic tape, in a format compatible with our CHI 2130 computer. The tape included the readings from the sensors in the fish, the two radar ranges, water depth, the length of cable played out, the time (derived from an oscillator in the data system), and a manually entered event number, used as a marker on the tape. In addition, the ranges, dye concentration, fish and water depths, and system time were all displayed immediately for use in conducting the experiment.

5. Dye Injection

We injected the Rhodamine B dye into the effluent flow just upstream of the west-side post-chlorinators. This location was chosen, first because it is an accessible point fairly far "downstream" in the plant's processing scheme, and second because the stirrers used to mix the chlorine also serve to

*See Karr (1975) for details.

mix the dye thoroughly into the effluent. We assume that the flows from the east and west halves of the plant mix well in the outfall.

Of the 1200 lbs of Rhodamine which we pumped, we wanted to leave as little as possible splattered around the plant; our dye system was so designed. The dye and equipment were contained in a covered trailer in the plant's parking lot. The dye discharge line, a seamless length of Tygon threaded inside a single length of garden hose (for chafe protection), ran directly from the trailer to the discahrge channel, where the weighted end of the hose was held several feet below the waterline. The dye was forced through the Tygon by a peristaltic "finger" pump, chosen because it has positive displacement but no seals to leak: the pump's metal fingers drum on the outside of the Tygon to push the dye through. To minimize the length of tubing containing concentrated (40%) dye, we injected the dye from the finger pump into a line from the plant's C3 water supply so that the dye mixture flowing back into the plant from the trailer was already diluted. We found that fluctuations in the plant's C3 pressure affected our dye injection rate, though, so for the second experiment we pumped the dye directly. The dye system was monitored and maintained continuously throughout both experiments.

The ideal dye injection system would maintain the concentration of dye in the effluent at a constant level; this would entail adjusting the dye injection rate to account for changes in the plant's pumping rate, which varies throughout the day. In the interest of keeping the procedures as simple as possible, we decided to forego this elaboration. We have compensated for the omission by referring the field measurements back to the concentration being pumped at the appropriate release time, which is arrived at by using the mean currents observed by Ebbesmeyer.

IV. RESULTS

A. Method of Handling Large Amounts of Data

With some two million measurements in hand,* it is hardly possible--or even desirable--to present all the data in a report. Instead, we have included some representative pictures, a few specific examples, and our conclusions after looking at all of the data. The complete data set has been submitted to METRO on magnetic tape.

Since each dive and climb of the instrument package produces a series of data which we can plot as a "vertical" profile (although the path of the fish tends to be more like a 45° sawtooth), all of the data have been examined in the form of plotted profiles of dye concentration and density. Some of these profiles taken along a straight track are combined into vertical sections and contoured. Figure 4 shows a typical set of profiles taken along a track; Fig. 5 is the contoured section produced from those dye profiles.

B. Results in the Immediate Vicinity of the Outfall

During each experiment, we tried, at various times, to sample as close as possible to the outfall in order to measure initial mixing rates. Several profiles taken at short range are shown in Fig. 6. If we compare the peak concentrations with the sumultaneous concentration of dye inside the outfall pipe (derived from the records of pumping rate and plant flow), we find that all but two of the near-outfall casts show the dye/effluent diluted by 100-to-1

---

*The result of 77.1 hours of actual data, with 8 channels recorded once per second each.

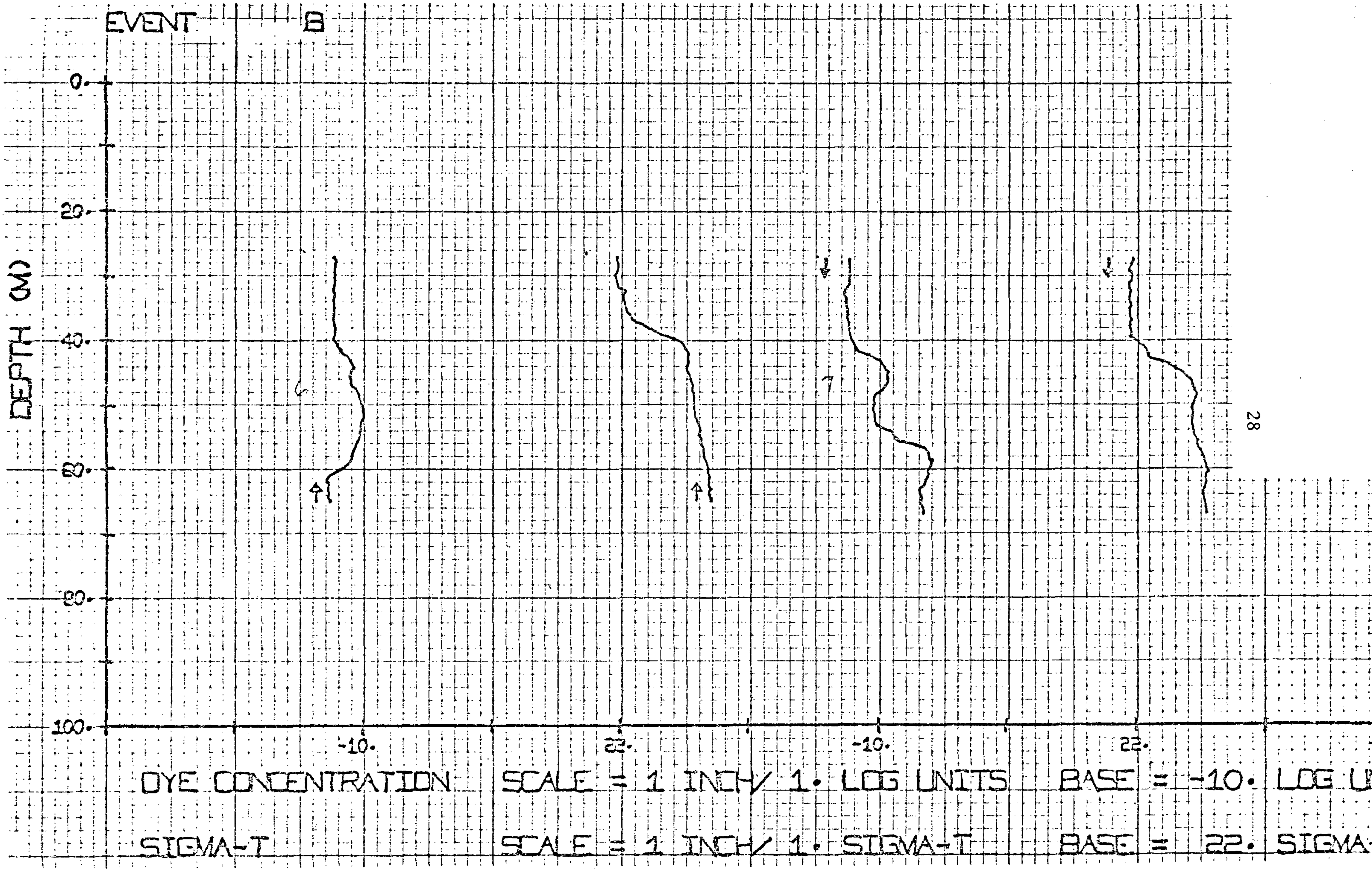
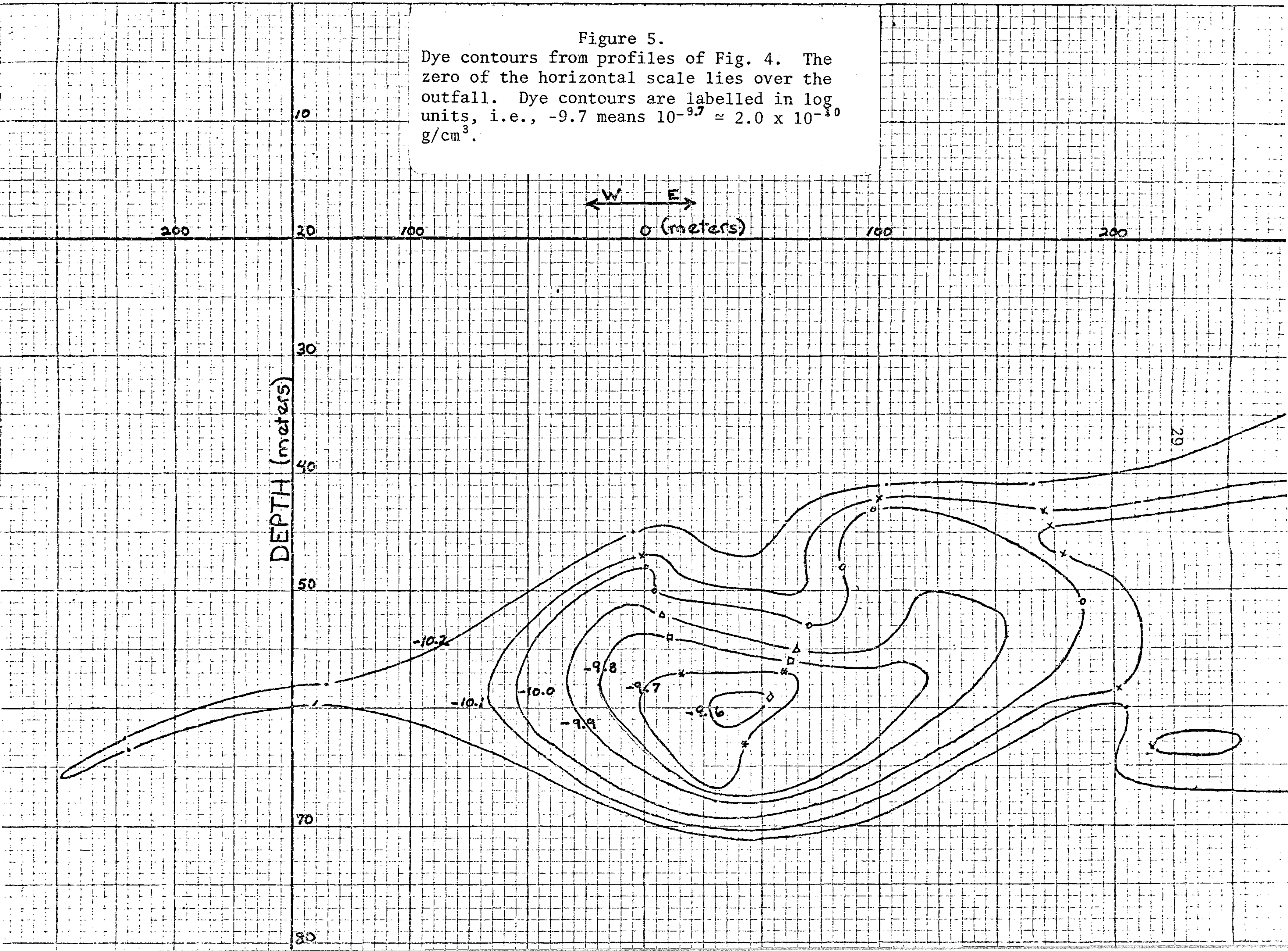


Figure 4.
Dye and density (σ_t) profiles used to generate contours for the figures which follow. Dye units are logarithmic, i.e., "-10.0" means $10^{-10.0}$ g/cm^3 of dye.

Figure 5.
Dye contours from profiles of Fig. 4. The zero of the horizontal scale lies over the outfall. Dye contours are labelled in log units, i.e., -9.7 means $10^{-9.7} \simeq 2.0 \times 10^{-10}$ g/cm^3.



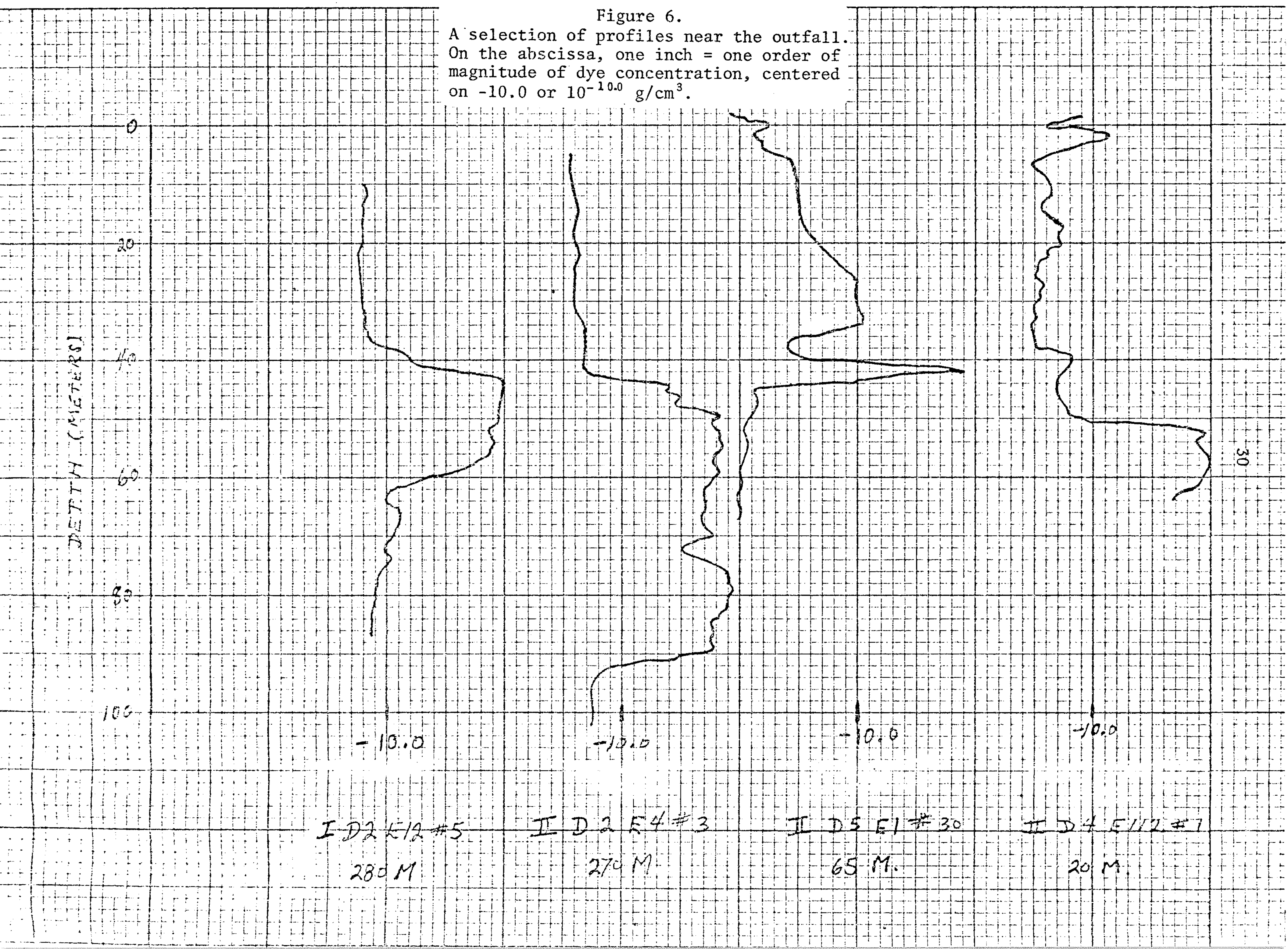


Figure 6.
A selection of profiles near the outfall. On the abscissa, one inch = one order of magnitude of dye concentration, centered on -10.0 or $10^{-10.0}$ g/cm^3.

or more; the two exceptions (II D4 Ev112 #1 and II D5 Ev1 #30)* were the closest samples, having been taken 20 m and 65 m, respectively, from the outfall ports. These profiles represent a wide variety of conditions of plant flow (from 70 to 325 mgd); it would appear that regardless of plant flow the effluent is diluted by at least 100-to-1 within the first 100 m or so by mixing which is driven not by the hydraulic pressure of the outfall, but by the buoyancy of the effluent itself.

C. The Vertical Distribution of Effluent

During the first four days of the summer experiment, we found the simplest kind of vertical distribution: the effluent was consistently bounded from above by a pronounced pycnocline at depths ranging from 35-60 m. An example from the first day is shown in Figs. 5 and 7, showing dye concentration and density respectively. These data (I D1 Ev6) were taken 1100 m south of the outfall on a flood tide.

On the other hand, a reversal of wind direction during the night between days 4 and 5 resulted in the breakdown of the pycnocline; the density profiles for the 5th day show shallow, weak steps near the surface in some profiles, and weak but fairly uniform stratification in others. A section of dye contour from that day (Fig. 8) shows much less horizontal orientation (note the similar orientation of isopycnals implied by the corresponding density profiles, which are shown in Fig. 9), and dye at much shallower depths, than on any of the

*Data are identified by experiment (I or II for summer or winter), day, event number (denoting a section of the search pattern), and profile number. For example, II D1 Ev 4 #8-13 refers to profiles 8 through 13 of event 4, on the first day of the second (winter) experiment. Day 1 refers to the first day on which dye was released; previously taken background data is labelled as "Day 0".

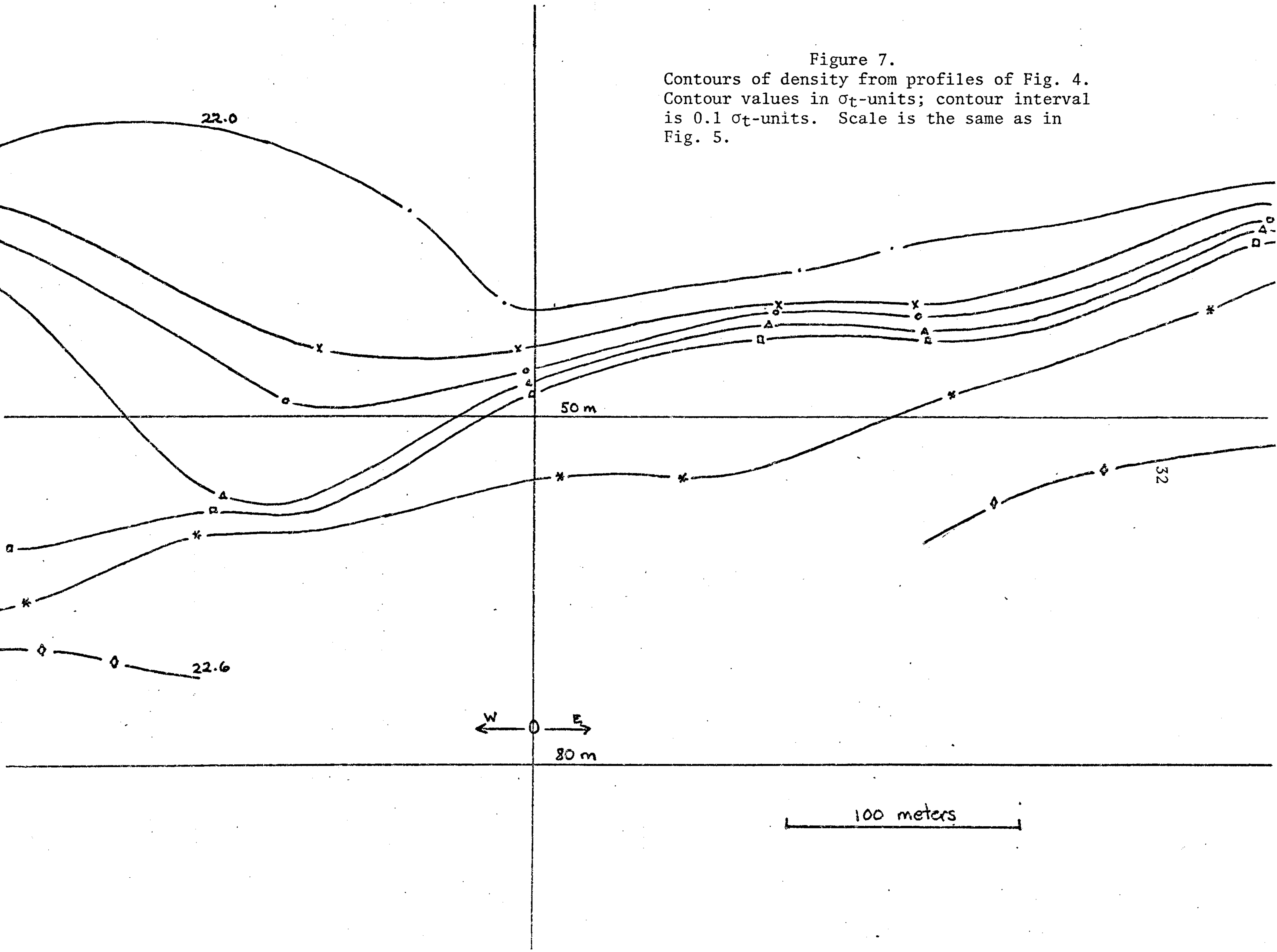


Figure 7.
Contours of density from profiles of Fig. 4. Contour values in σ_t-units; contour interval is 0.1 σ_t-units. Scale is the same as in Fig. 5.

Figure 8.
Dye contours from DAY 5, First Experiment
(I D5 EvO #23-31). Contour interval = 0.1 log units.

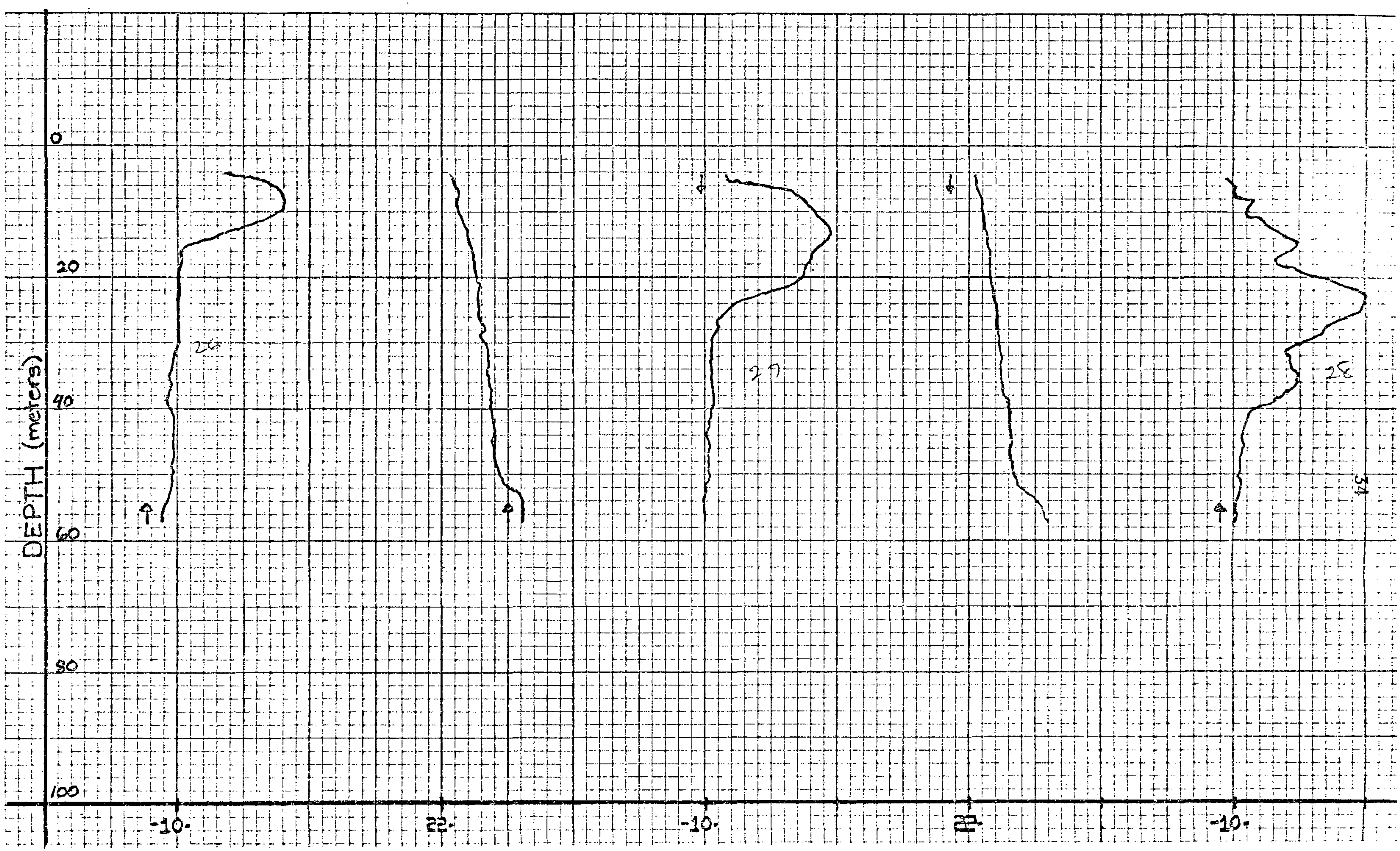


Figure 9.
Dye and density profiles associated with Fig. 8.
Baseline values are -10 (10^{-10} g/cm^3) and 22.0
σ_t-units for dye and density respectively.

previous days. This kind of inhomogeneous weak stratification is what we might expect under typically winter conditions--conditions that, in this case, occurred in early September.

In Figs. 10 and 11 we see dye and density sections from the winter experiment (II D1 Ev4 #8-13). In this case, the stratification is much weaker than in the first part of the summer experiment, but the dye contours do conform fairly well to those of density.

On the vertical sections taken transverse to the plume (i.e. roughly east-west), there is little tendency for contours of dye to cross those of density. However, on a long, longitudinal cut taken during the first experiment and covering from 7 km north of the outfall to 400 m south (I D2 Ev11), we find that the dye tends to lie in less dense water the further north (i.e., the further downstream) it is found; at 5 km north, the center (vertically) of the dye patch is 0.2 sigma units lighter than is the center at 3 km. Another longitudinal cut, this one from the second experiment (II D1 Ev10) shows the same trend, with a difference of about 0.2 sigma units over a distance of about 3700 m south of the outfall. (In this second case, the dye at the downstream end of the plume, although less dense, lies at greater depth: the isopycnals slope down to the south quite sharply.)

How are we to interpret this relationship between the effluent and density fields? There are at least two possibilities. First, it may be that under different current conditions the effluent comes to equilibrium, as a result of its initial buoyant mixing, at different densities. We have already described, in the previous chapter, the emergence of the buoyant effluent into the stratified water column; the density at which it comes to equilibrium will

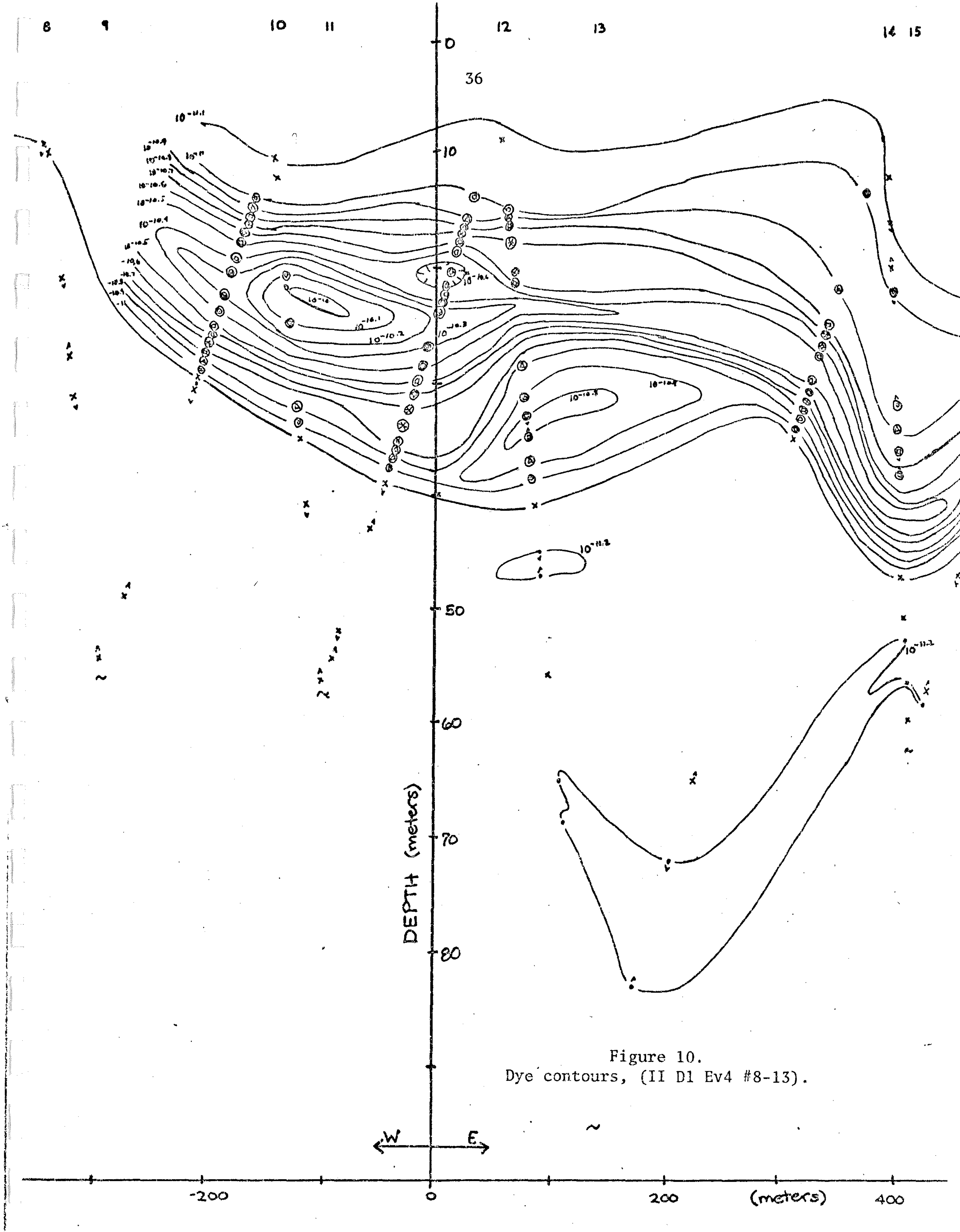


Figure 10.
Dye contours, (II D1 Ev4 #8-13).

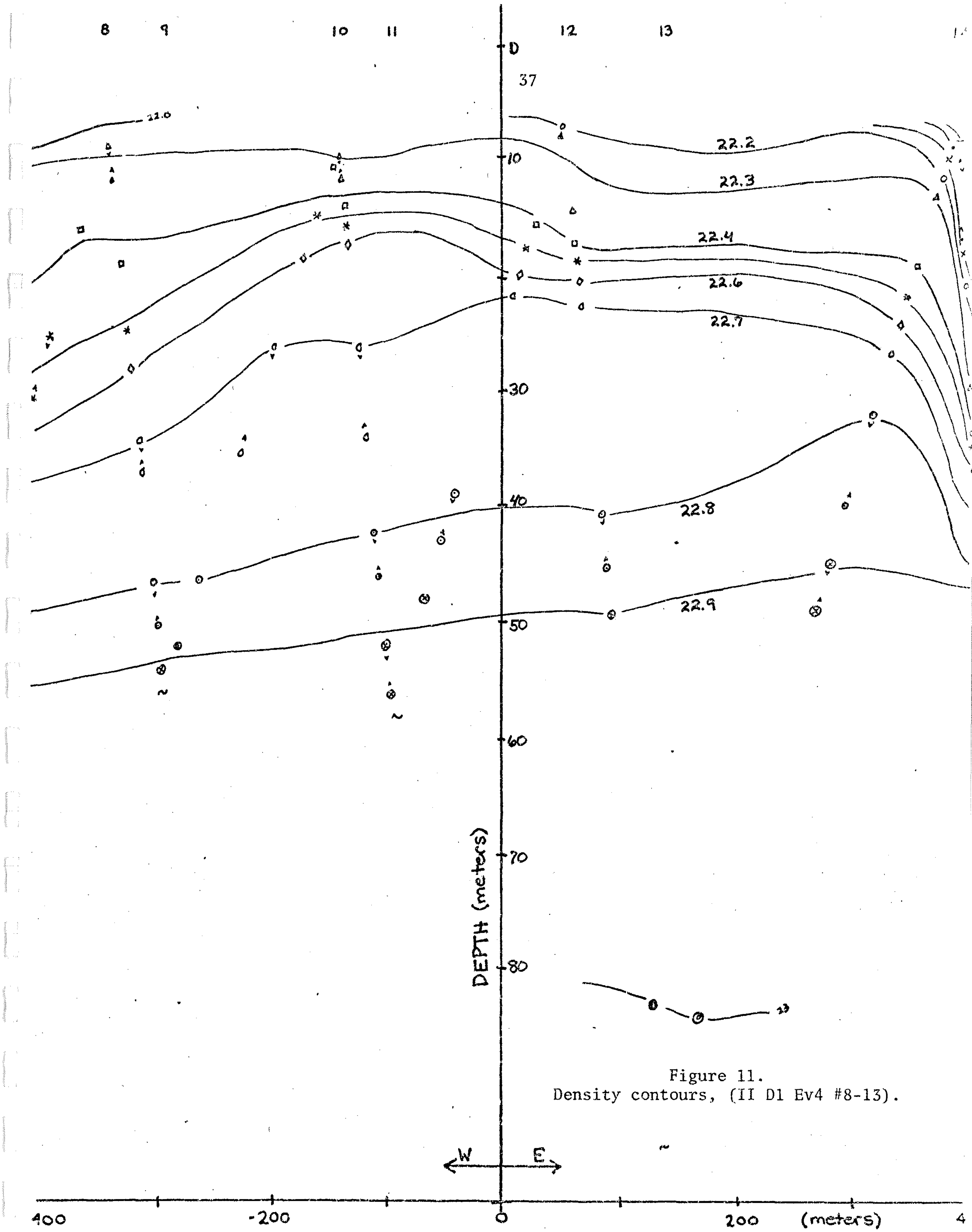


Figure 11.
Density contours, (II D1 Ev4 #8-13).

depend on the density profile and the mixing rate (the rate of entrainment of surrounding water by the rising effluent). The rate might well be incluenced the local mean current, which varies throughout the tidal cycle. However, if it is this variation which causes the observed "rise" of the effluent through the density field, it seems surprising that the rise would be as smooth and gradual as it is; one would expect a fairly sudden shift as the tidal flow developed, followed by a longer, more constant period.

The second possibility is that the effluent, after its initial dilution, is still somewhat buoyant and slowly mixes upward (in the density field) as it is carried along by the tide. This explanation is rendered more plausible by the observation of dye concentrations at considerable distances from the outfall that still show significant density anomalies, i.e., are still observably buoyant. In Fig. 12 (II D1 Ev2) we see a section taken 900 m north of the outfall, where the dye is obviously streaming vertically; the corresponding density is shown in the following figure. The peak concentration shown, $10^{-10.4}$, or 4×10^{-11} g/cm^3, is obviously buoyant (note the displacement of the isopycnals) although it has been diluted by a factor of about 650 from its concentration within the outfall pipe. On the other hand, if we look at Fig. 14, which is a part of the same section as Fig. 10, we see a filament, of the same peak concentration as in the previous figure, 4×10^{-11} g/cm^3. The corresponding density plot is found in Fig. 15. This second section is 1900 m north of the first, and was recorded about 30 minutes later, both on an ebb tide. The two peaks have the same density (22.8 sigma units), and show similar anomalies in the shape of the density contours. Clearly, in the half-hour (and 1000 m) between these observations, little mixing took place, but because of the remaining

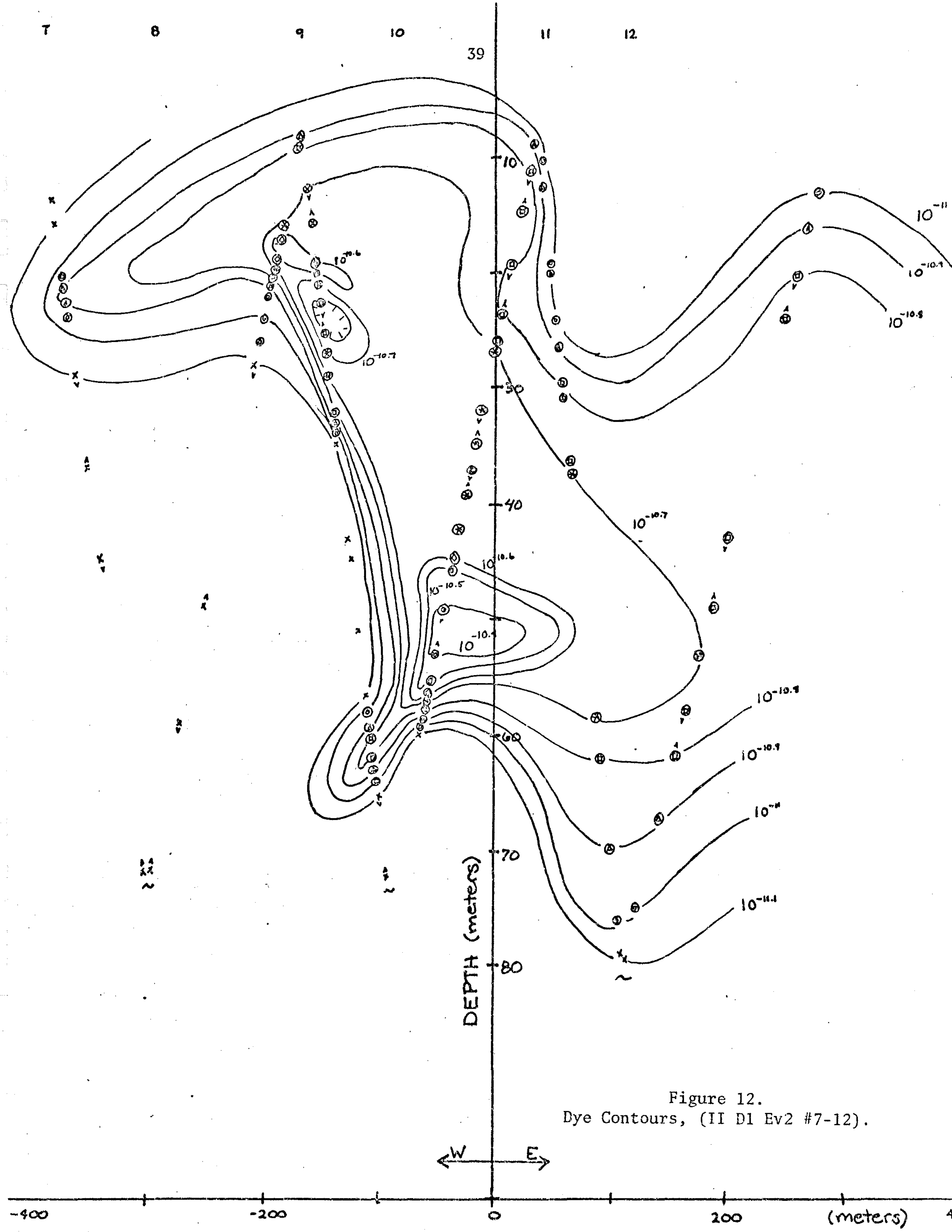


Figure 12.
Dye Contours, (II D1 Ev2 #7-12).

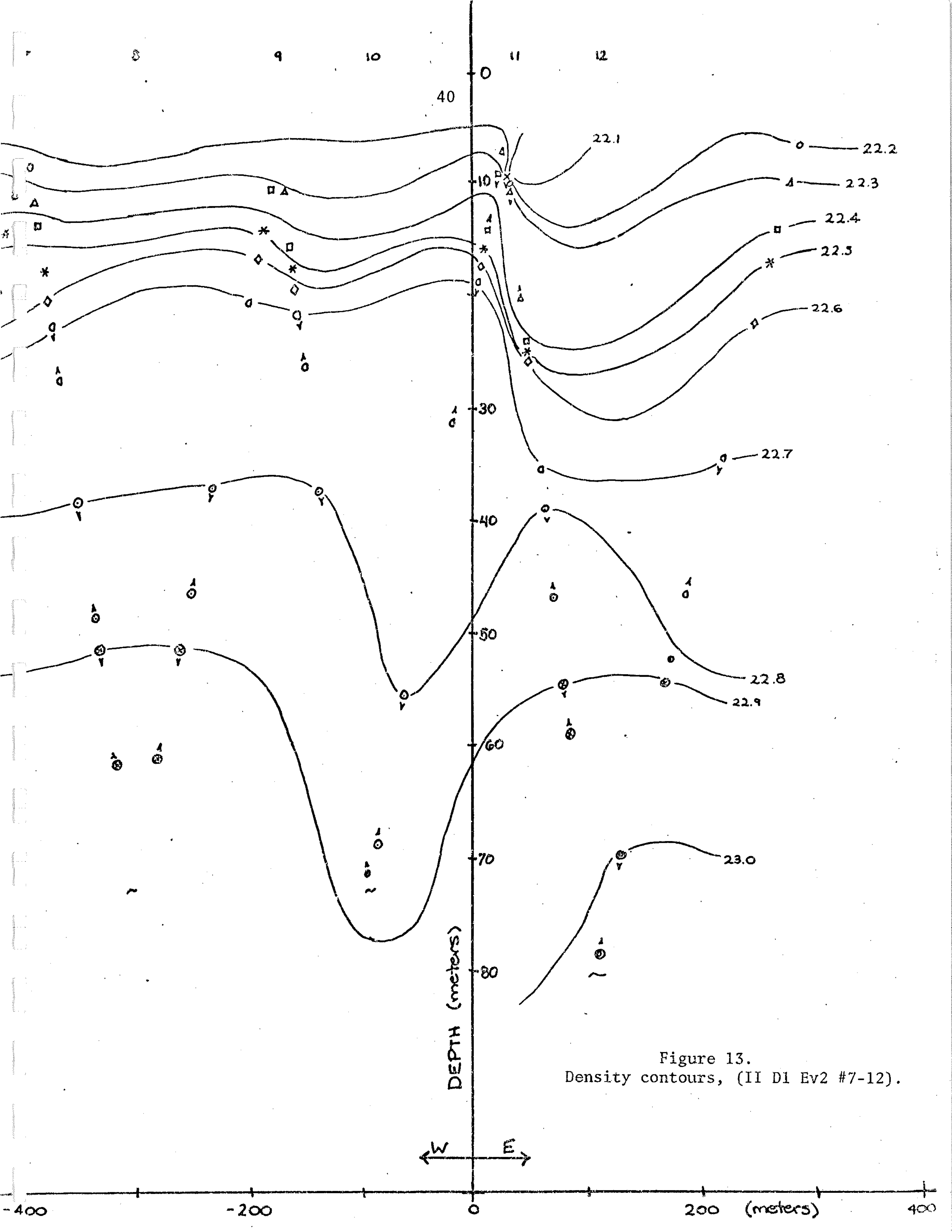


Figure 13.
Density contours, (II D1 Ev2 #7-12).

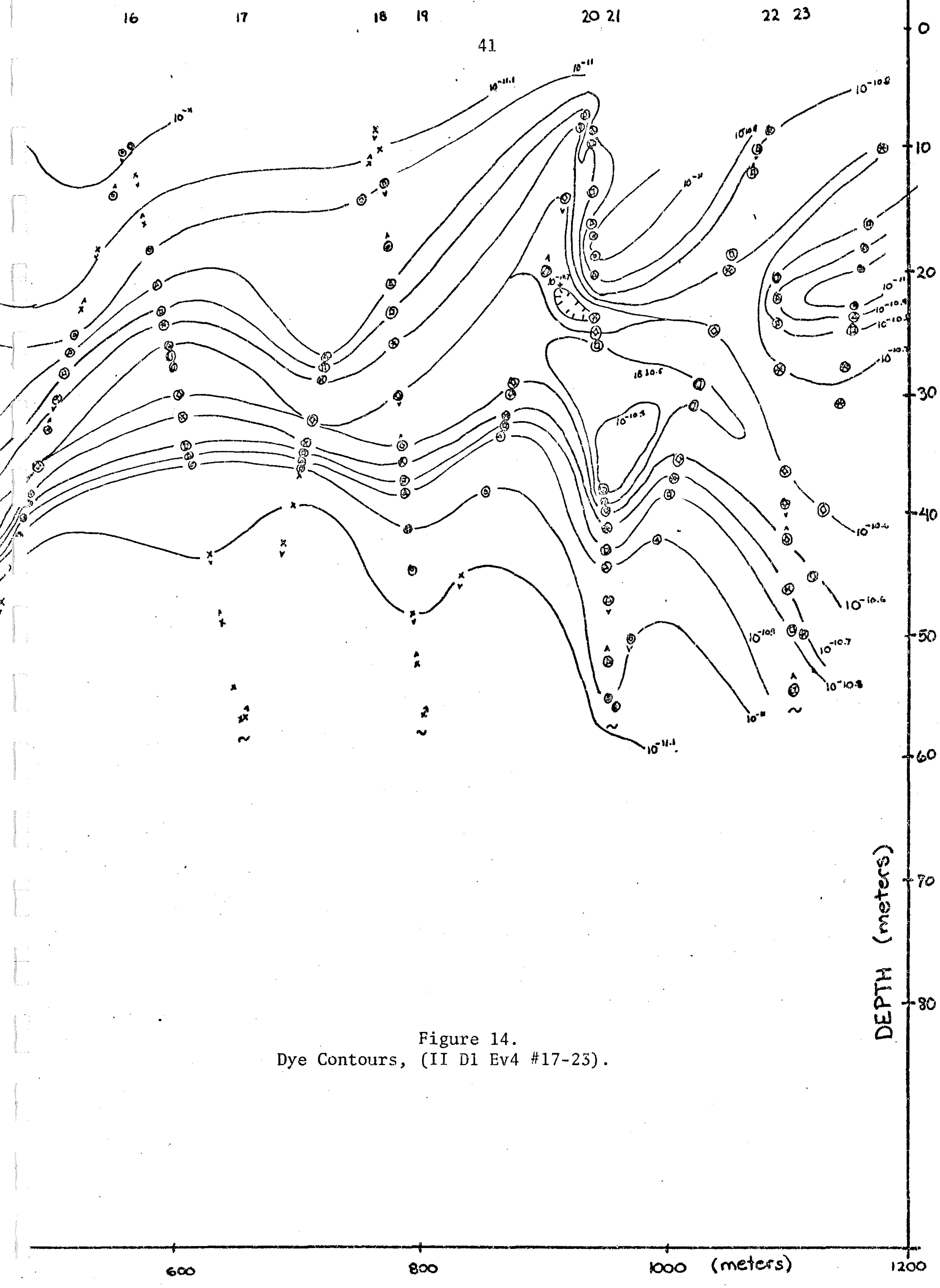


Figure 14.
Dye Contours, (II D1 Ev4 #17-23).

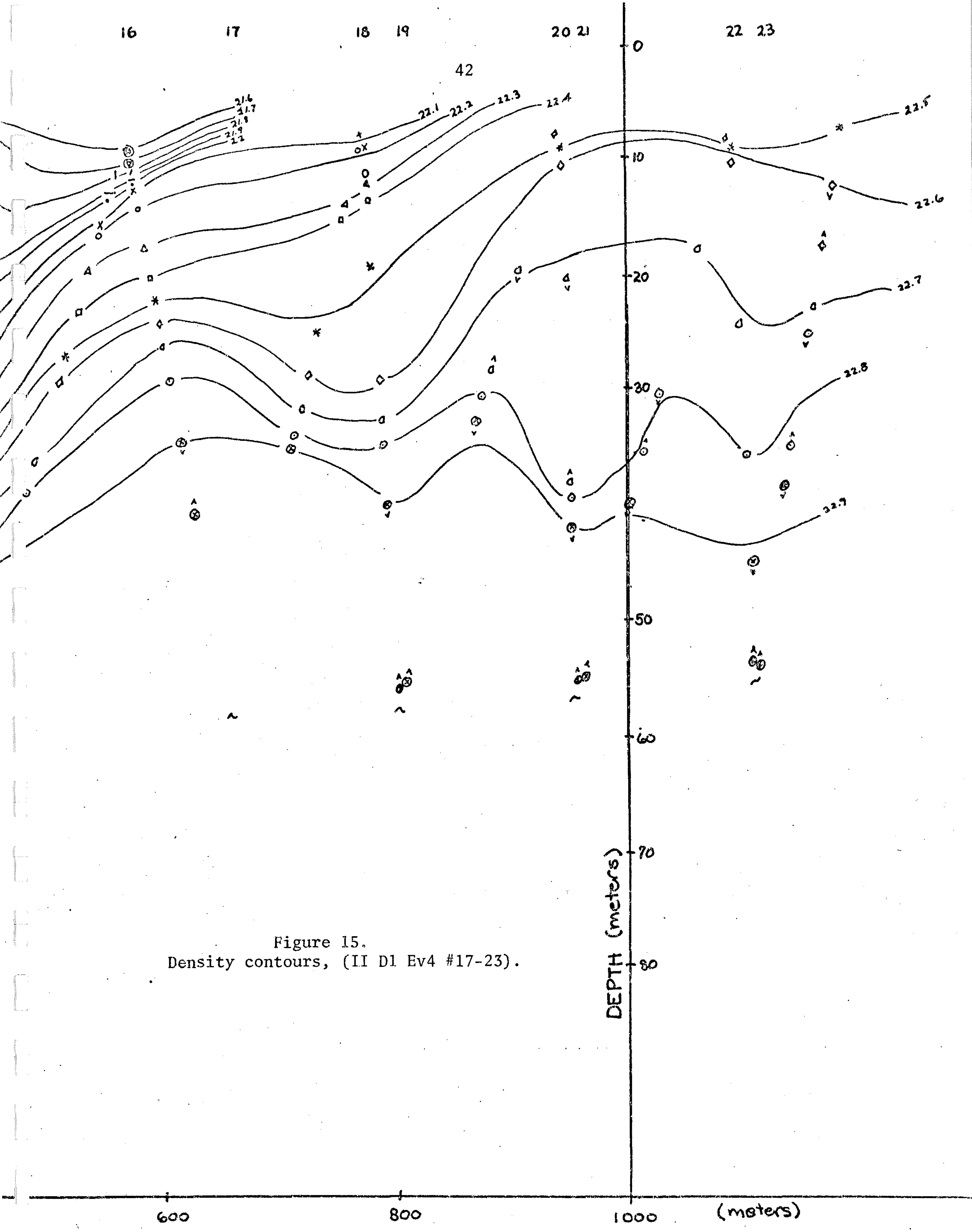


Figure 15.
Density contours, (II D1 Ev4 #17-23).

buoyancy, some very slow mixing must still occur even after several hours. The transition from an active to a passive contaminant appears to be a very gradual one.

Occasionally, effluent was observed below 70 m depth, the average depth of discharge. We did not always sample to that depth or below because an over-ambitious depth range sacrifices horizontal resolution. However, we did spot-check fairly often; the downward mixing of effluent is detectable but infrequent. Such downward mixing cannot, of course, be attributed to buoyancy, but must be due to the environmental turbulence.

To summarize what we have learned about the vertical distribution and mixing of effluent, we can say in general the effluent profile reflects the density profile which was over the outfall at the time of release; as the latter profile varies in time, so will the former (in the next section we will see just how variable the density can be). However, the initial adjustment of one profile to the other is incomplete and is followed by a longer period of upward mixing until the effluent is completely passive.

D. The Horizontal Distribution of Effluent

Because of the relationship between vertical variation of density and effluent, it is important to note the extreme horizontal variability of the density profile, especially in the winter. Figure 16 shows several adjacent profiles from II D1 Evl near the outfall.* From these examples it is evident that profiles taken within 100 m of each other are not necessarily similar. The effect of this variability was pointed out above.

*But out of the plume. Since no dye is present, we know these profiles are unaffected by the outfall.

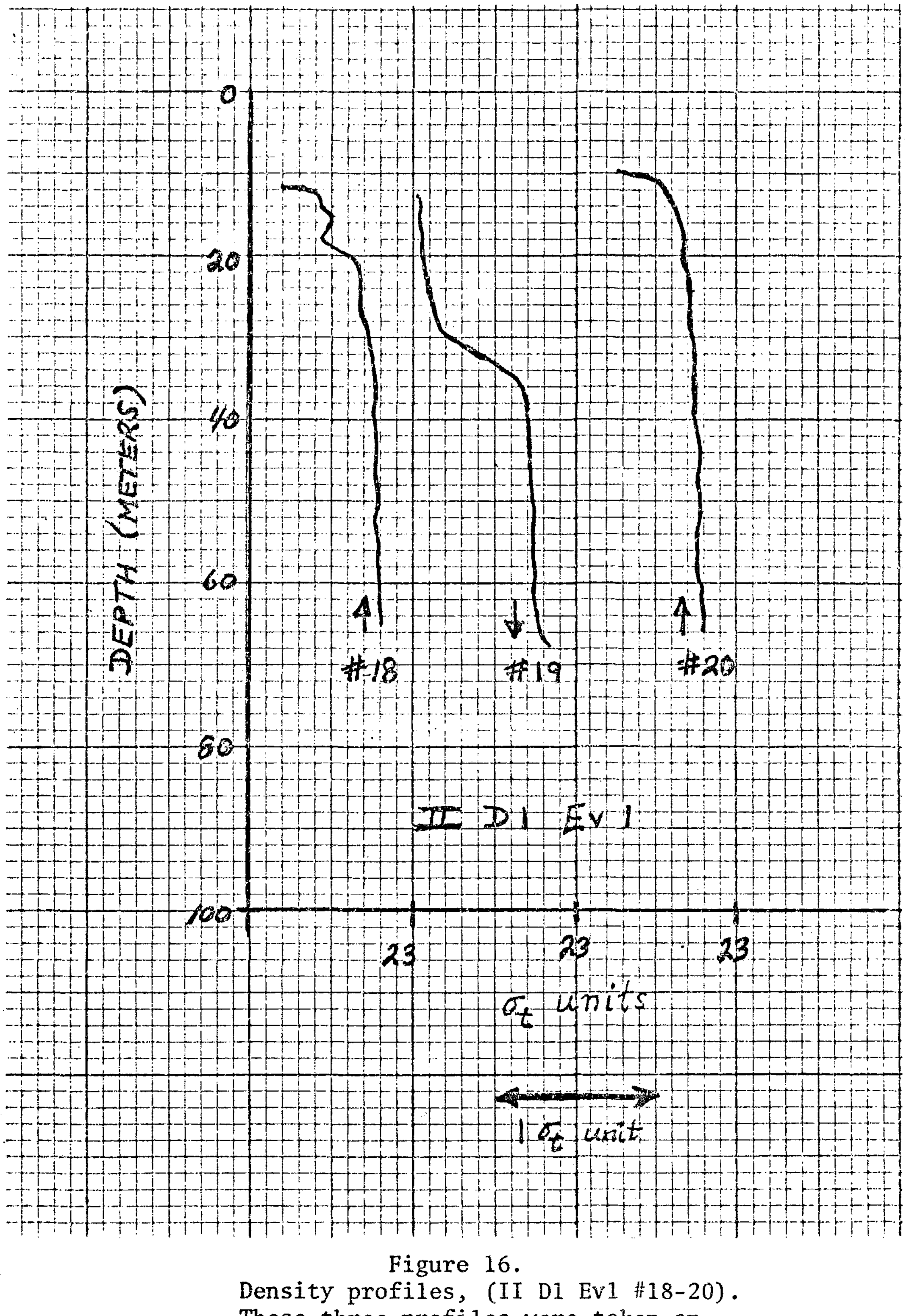


Figure 16.
Density profiles, (II Dl Evl #18-20).
These three profiles were taken an average of 75 m apart.

During the tidal flow, the effluent is swept downstream, forming a patchy and filamentous plume, terminated at its downstream end by a front that can be extremely sharp. An example, from the end of a flood tide, is shown in Fig. 17, from the first day of the winter experiment (II D1 Ev10 #70-75) about 4 km south of the outfall. At the front, the effluent concentration drops by nearly an order of magnitude in about 50 m horizontally. A second example is shown in Fig. 18, also south of the outfall, from Day 6 of the second experiment (II D6 Ev1002 #28-34). This front is not as sharp as the one in the previous example, but this is not surprising: this section was made three hours into an ebb tide, so this front, when observed, had suffered a reversal and was being carried back north. Although both the examples just cited were south of West Point, such fronts were observed north as well. However, the fronts on an ebb tide seem to be less sharp than those on the flood.

The plume formed by the effluent as it sweeps downstream is far from smooth, but is better characterized as a field of filaments and patches, similar to a cloud of smoke. In Figs. 10 and 14 (II D1 Ev4) we have two parts of the same vertical section, each with areas of peak concentration and occasional "holes." Successive transverse passes across the plume (at different distances downstream) suggest that the peak values are usually filaments, existing coherently for hundreds of meters or several kilometers, with characteristic widths and of 100 m and vertical thicknesses ranging from 1-10 m. Some, however, appear to be discrete patches. We also find larger patches, such as the ones mentioned by Karr (1975) from Day 2 of the first experiment. These two patches have longitudinal scales of several kilometers,

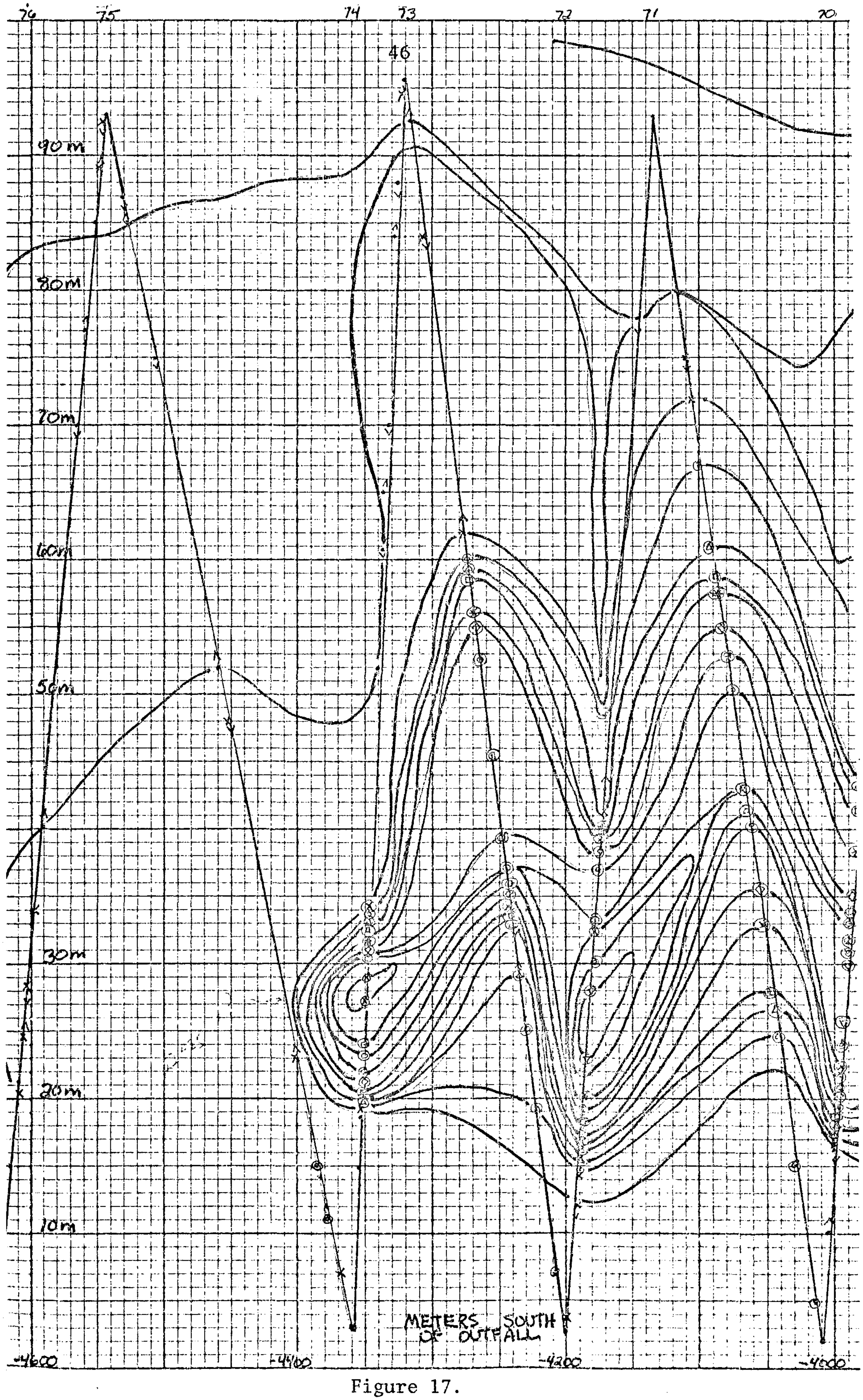


Figure 17.
Dye contours II D1 Ev10 #70-76 showing a sharp front. Time-delay referred to in the text is clearly evident in the wave-like undulations of the contours.

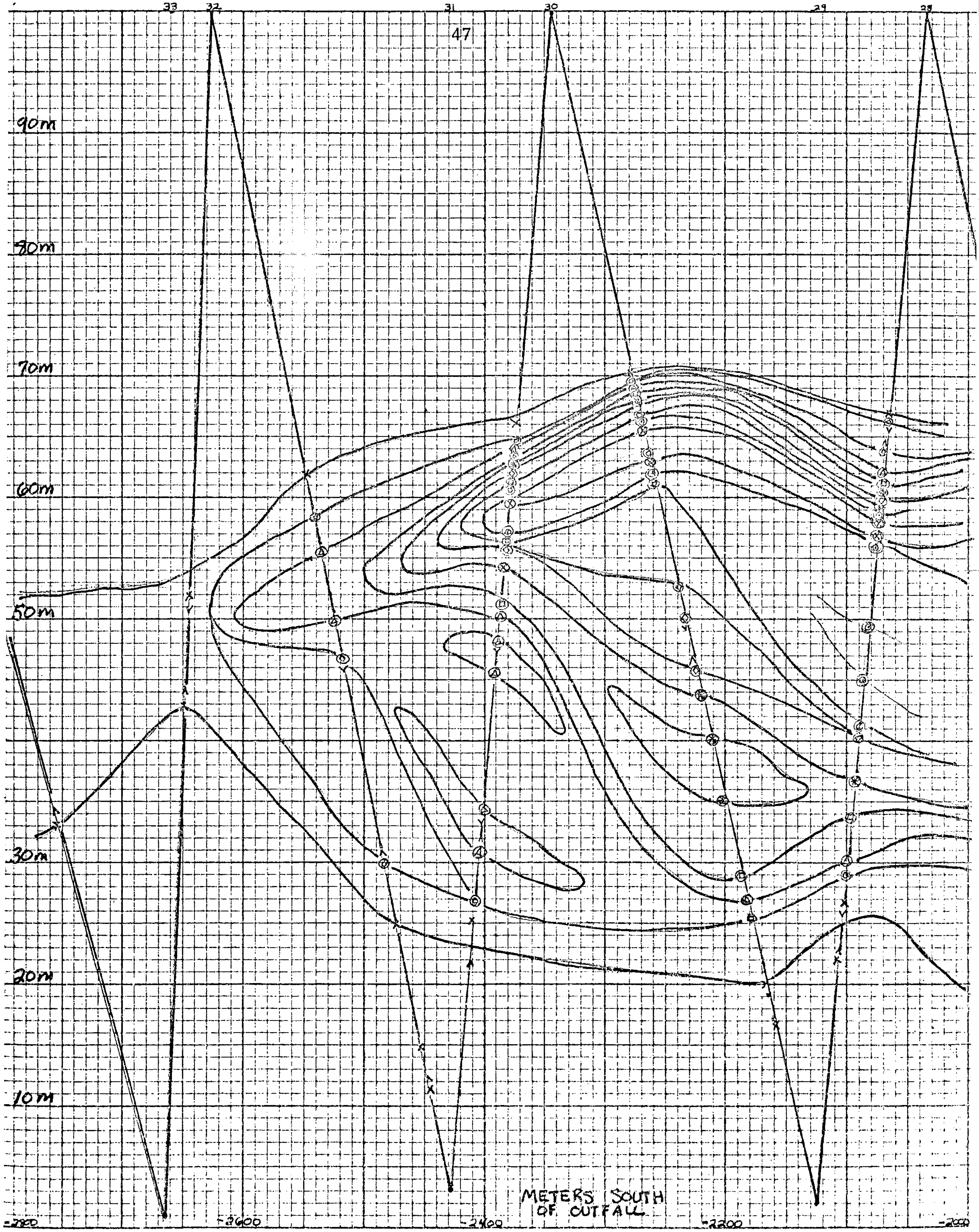


Figure 18.
II D6 Ev1002 #28-33 showing a front south of the outfall.

and neighboring patches may have different densities. It appears that the plume can "break" as the flow pattern changes during the buildup of tidal current; we will return to consider this possibility below.

If we consider the effluent distribution as a plume, that is, if we consider its smooth rather than its intermittent aspects, then we can examine its centerline concentration as a function of distance from the origin by picking off the maximum concentrations from successive transects (E-W sections). For each tidal cycle on which we made such measurements, we plot these values and examine the dilution of peak concentration and the shape of the curves. The result is shown in Fig. 19 where we have plotted relative concentration vs distance.* Many of the curves drop off sharply, reflecting the passage through the sharp fronts just described. On some days, however, the falloff is smoother; this is particularly true north of the outfall, where, as noted earlier, there is less tendency for sharp fronts to form. If we look at the dilutions just before they begin to drop off--that is, just behind the "front"--we find that they range from 1:200 to 1:1500; since the initial buoyant mixing is responsible for a 1:100 dilution within 100 m or so of the diffuser ports, the turbulent mixing during the tidal flow amounts to dilution by factors of only 2-15. In other words, peak concentrations are reduced rather slowly in the plume.

In order to check whether or not the plume as just described represented a significant percentage of the dye injected, Karr, in his examination of the data from the first experiment (Karr, 1975), estimated a mass balance from a

*Relative concentration is defined here as observed concentration divided by the concentration inside the outfall pipe. For reasons explained later, these values have been divided by 100. The solid and dashed lines are explained in Chapter V.

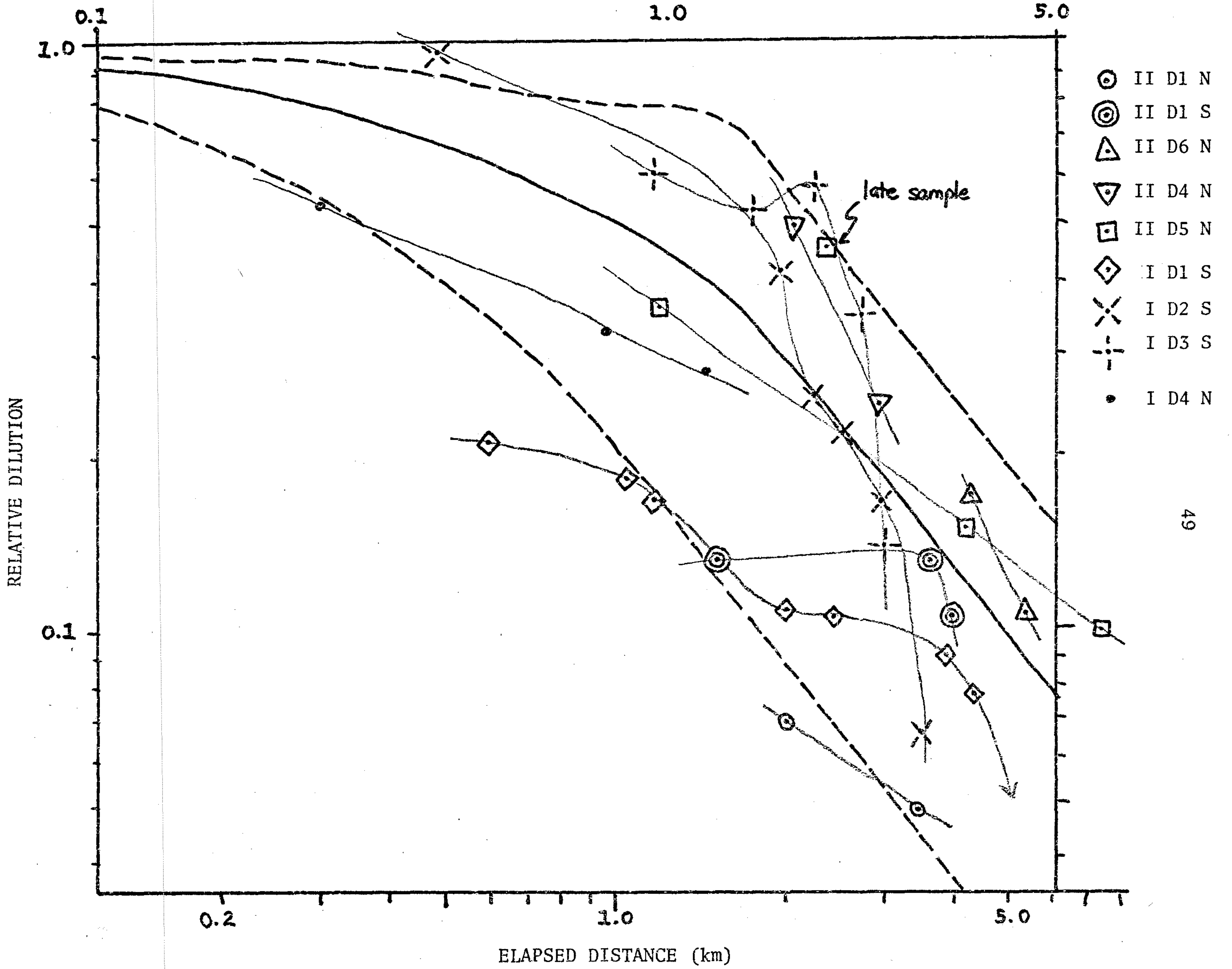


Figure 19.
Centerline concentrations, normalized as discussed in the text, from various transects as noted. The connecting lines are merely to aid in locating related points. The dashed lines are from Ebbesmeyer (1975).

part of the first day's results, when the plume happened to be particularly simple and there was not yet a background distribution of dye from previous cycles. He performed a simple numerical integration over several transects of the plume, arriving at a "linear concentration", 3.1×10^{-2} grams of dye per longitudinal centimeter along the plume axis. Using current data from Ebbesmeyer's drogue study (Ebbesmeyer and Okubo, 1974), he derived from this an injection rate, 2.1 kg/hr, compared with the actual injection rate of 1.7 kg/hr. This relatively good agreement suggests that our sampling covered a wide enough area to detect almost all of the plume.

What becomes of the plume when the tide reverses? In the first experiment, we were occupied with defining the plume to begin with, but in the second, we attempted to answer this question by circling the outfall during the turn of the tide and comparing the peak concentrations upstream with those downstream. Analysis of such data from Days 4, 6, and 7 shows that the peaks can be diluted by factors of 3-6 within 30 minutes to an hour at slack water. This is nearly the dilution suffered by these peaks during the entire previous 6-hour tidal excursion; clearly, dilution of peak values is accelerated at slack water. This is discussed further in the next chapter.

Having described the internal structure and evolution of the effluent field, we ask where the plume, and its background of "old" effluent (from previous tidal cycles) is to be found. That is, how wide an area does the effluent cover in the Puget Sound basin? As we mentioned under question 5 of Chapter I, we cannot give stable statistical estimates of where the dye is likely to be under any set of circumstances. Fig. 20 shows all the areas where dye was detected during the experiments, and thus gives a fair idea, at least,

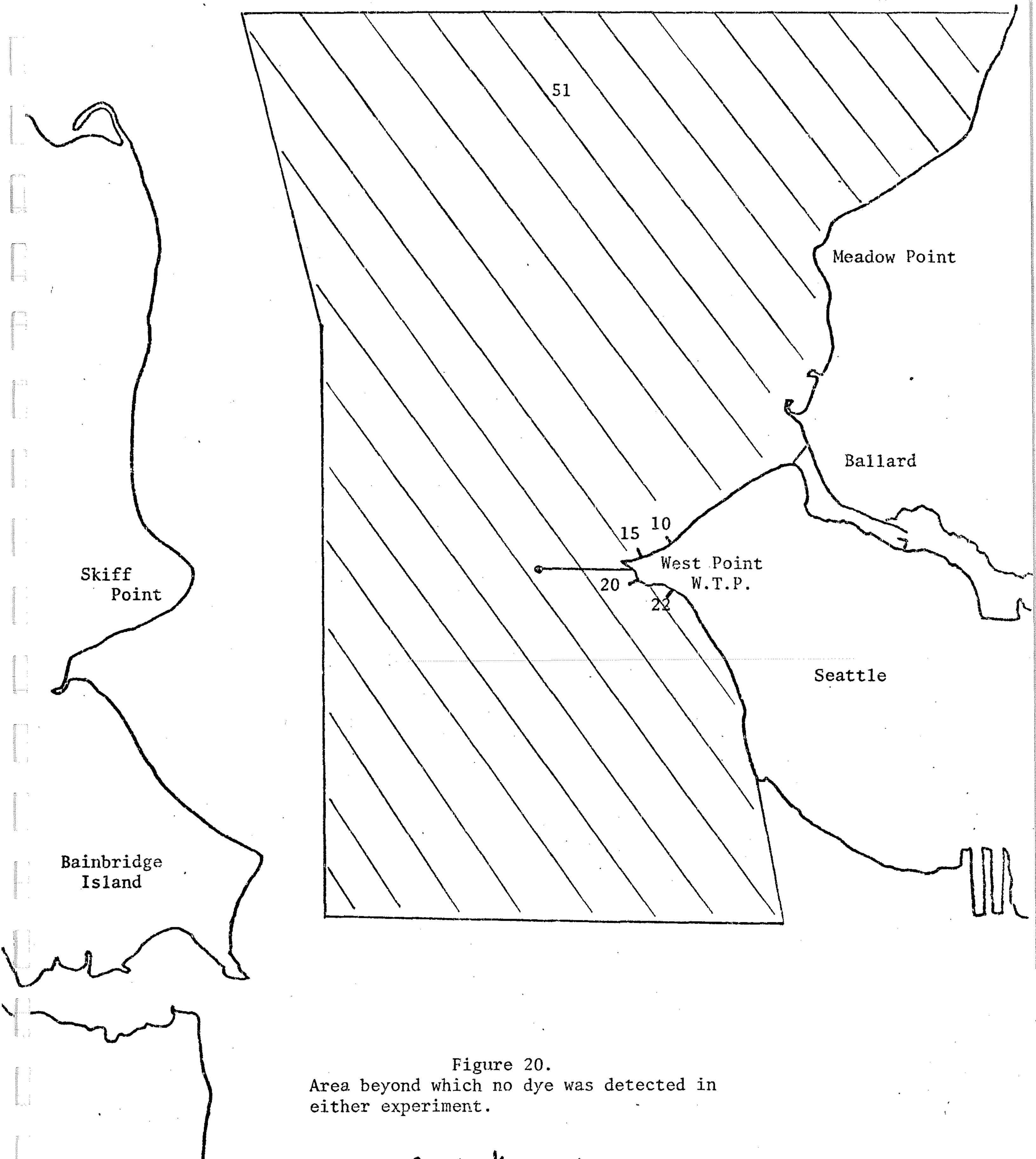


Figure 20.
Area beyond which no dye was detected in either experiment.

Scale in
Nautical Miles

of where effluent is not found in concentrations greater than our detection threshold. See Karr's (1975) report for some sample plumes, to give some idea of what a particular realization might look like. We refer the reader to Ebbesmeyer and Okubo (1974) and Ebbesmeyer and Helseth (1975); their drogue trajectories, while they can't show the full areal extent of the effluent, do give additional examples of newly-generated plumes. Taken together, all of these examples support the following generalizations:

1. Effluent is likely to be present in concentrations greater than 0.1 ppt (threshold for this experiment) from Pier 91 (4 km south) to Agate Pt. (8 km north), and from the beach on the east side of the basin to about 2.5 km west of the outfall (perhaps somewhat further west at the extreme north end of the range).

2. The newly-generated plume, and presumably all the older effluent around it as well, tends to swerve to the east, toward the beach, during established tidal flows. This is particularly true to the south, on the flood tide, although some of the same tendency is evident to the north as well. Observations of the Puget Sound hydraulic model at the U.W. Oceanography Department suggest that this is due to the formation of eddies downstream of West Point. The drogue trajectories from Ebbesmeyer's work confirm this hypothesis; some of his drogues were actually swept around and carried back north toward the point on a flood tide. Our own data are also consistent with this, for beside showing the general eastward tendency, we find on Day 1 of of the first experiment a pattern consistent with the existence of an eddy to the south, in the form of two filaments of dye, east of the

main stream, which stop about 2.5 km south of the outfall. These presumably represent the two sides of the eddy. They suggest a circulation loop several hundred meters wide and a kilometer or so long (again consistent with the other observations).

3. Photographs of the Puget Sound model cited by Ebbesmeyer (1975) suggest that at slack water, the eddies mentioned in the previous paragraph will detach from West Point and move westward, producing a westward "injection" of effluent. This seems to be particularly true at the start of an ebb. The newly-formed plume on an ebb tends at first to the north or northwest, later being pulled around to the northeast by the formation of an eddy north of the point. Our dye patterns are also consistent with this progression which, we think, explains the sudden change in flow pattern hypothesized earlier to explain the apparent large-scale breaks in the plume.

4. Bottle samples, taken at the stations indicated in Fig. 1, showed significant concentrations some of the time during the first experiment, but consistently negligible concentrations during the second. Table II shows the results from the first experiment. These are vaguely consistent with the idea of downstream eddies sweeping effluent back toward the beach, so that the effluent would show up on the downstream side of the Point. But there is also the suggestion that as the eddies collapse effluent is swept onto the point from the upstream side. Nothing is conclusive on this point. The real puzzlement is over the lack of effluent on the beach during the winter experiment.

TABLE II. Metro I Bottle Samples

Date and Time	North Side Station No. 15	North Side Station No. 10	South Side Station No. 20	South Side Station No. 22
<u>30 August</u>				
Flood				
1310			2.7×10^{-10} (1.8 ppt)	
1313	3.8×10^{-10} (2.5 ppt)			
1315				3.4×10^{-10} (2.3 ppt)
1330		5.2×10^{-11} (0.3 ppt)		
Ebb				
1940		5.2×10^{-11} (0.3 ppt)		
1947	2.2×10^{-10} (1.5 ppt)			
1954			5.5×10^{-10} (3.7 ppt)	
2000				2.0×10^{-10} (1.3 ppt)
<u>31 August</u>				
Flood				
0137	5.9×10^{-11} (0.4 ppt)			
0142			1.0×10^{-10} (0.7 ppt)	
0145		8.5×10^{-11} (0.6 ppt)		
0147				2.5×10^{-10} (1.7 ppt)
Ebb				
0717	5.1×10^{-10} (3.4 ppt)			
0721			2.9×10^{-10} (1.9 ppt)	
0729		5.0×10^{-11} (0.3 ppt)		
0731				1.4×10^{-10} (0.9 ppt)

Dye concentrations in g/cc.
Effluent concentrations in parts per thousand.

In the next chapter, we will advance an incomplete hypothesis to begin to explain this result, but that's the best we can do now.

V. DISCUSSION

This chapter we devote to an exploration of some of the theoretical ideas that we have previously touched on, and their relation to the observations already made. Some of the discussion is intended for those not already familiar with the basic ideas used to deal with turbulence and turbulent mixing.

A. Turbulent Mixing

We may approach the problem of turbulent mixing, rather gingerly, by considering a water parcel, or a patch of effluent (or any other identifiable entity), as it is affected by a turbulent flow around it. This turbulent flow--characterized as a random velocity field--is commonly analyzed by considering it to be made up of superimposed random motions each with some characteristic length scale: that is, as a superposition of eddies of different sizes. The total kinetic energy of the flow may be thought of as distributed among these motions of various sizes, and the physics of the flow is, therefore, partially described by specifying how energy is transferred from motions of one scale-size to those of another. We don't yet understand enough to predict from first principles the distribution of energy among scales (the spectrum) or its variation in time, but we will see that we can understand something about our observations in terms of these ideas.

Picture a patch of effluent embedded in a turbulent flow consisting of eddies of many characteristic length scales. If the eddies are predominently larger than the patch, what will happen to the patch? Intuition suggests: not much, except that it will be advected without deformation. On the other hand, a patch embedded in a field of eddies that are about the same size as the patch itself will undergo severe and rapid deformation, while one embedded in eddies much smaller than itself will find its edges being smeared out and will slowly diffuse, in a radially symmetric manner if the eddies are of the same intensity and size everywhere (i.e., if the eddies are homogeneous across the patch). Any time a patch is deformed, whether slowly around its edges or massively and rapidly by eddies of its own size, its surface area will be increased, yielding a much larger area over which molecular diffusion (a well-understood, but normally slow-acting physical process) can operate. Thus, turbulence enhances mixing by amplifying the effects of molecular diffusion (by increasing the area over which the latter process works). Clearly, the effectiveness of the amplification depends on the size of the patch relative to the sizes of the most energetic eddies--that is, relative to the spatial spectrum of the turbulent velocity field.

Because we don't know enough about turbulence and turbulent diffusion to be able to predict quantities such as the spectrum or the flux of a diffusing substance due to turbulent diffusion (molecular diffusion amplified by turbulence), we model such effects by analogy to molecular diffusion, or some other process, including in the model one or more parameters that we adjust empirically to make the model work as well as it can. The most common model used is the eddy coefficient or Fickian analogy to molecular diffusion. The flux due to molecular diffusion is rigorously described by the relation (in the case of one dimension)

$$Q = k \frac{dC}{dx} \quad ,$$

where Q is the flux of the diffusing quantity, C its concentration, k is a constant (the molecular diffusivity of the substance), and x the space coordinate. So we hypothesize that for turbulent diffusion,

$$Q = (k + K) \frac{dC}{dx}$$

where K is called the eddy coefficient and is assumed to be much larger than k. Note that while k, the molecular diffusivity, is a property of the diffusing substance, K depends not only on the substance, but also on the turbulent characteristics of the flow. For, as we've seen, the effectiveness of the turbulence in amplifying the effects of molecular diffusion depends on the relative sizes of the diffusing patch and the more energetic eddies in the turbulence. As the patch size increases, this size relationship changes, so that we can be confident that the eddy coefficient will be time-dependent--it should, in fact, increase in time.

Since turbulent eddies only act to disperse patches which are their own size or greater, then whenever we specify a value for an eddy coefficient, we also specify, usually implicitly, the size of the patch being dispersed. This characteristic scale divides the range of length scales present in the flow into two parts: those larger, which are not represented in the eddy coefficient, and those smaller, which are. An eddy coefficient not referred to some length scale is meaningless.

Let us consider, in these terms, the behavior of peak concentrations in our experimental effluent plumes. We observed the persistence, in the newly-generated plume, of peak concentrations with characteristic scales of

100 m. This must mean that the established tidal flow has little energy in scales of 100 m and smaller; the energy must lie predominantly in larger scales. Inspection of the Puget Sound model suggests that the smallest scales strongly represented in the flow have lengths characteristic of the variations in the shoreline, say on the order of 1 kilometer. The eddies formed downstream of West Point are an example. At slack water, however, the flow is observed, both in the model and in the field, to break up into much smaller motions. The energy of the larger motions (which comes, originally, from tidal motions on a still larger scale) is now transferred to smaller scales. These serve to dilute the peak patches at an accelerated rate during the period of slack water. As the current reverses and picks up again, the smaller motions die out, the topographic-scale motions receive a new energy input from the tidal driving forces, and what is left of a patch is advected back toward the outfall suffering as low a rate of mixing as it did originally. From the measured dilution rates, it appears that it takes several tidal cycles to reduce a typical patch to a concentration below the threshold of detection.

The eddy coefficient for patches about 100 m long thus varies in time, being low during the established flow periods, but comparatively large during slack water. Any model which hopes to account for turbulent diffusion on this (100 m) scale must include such a time dependence. To our knowledge, there is no such model in existence. Since the peak concentrations are an important consideration for both water quality studies and for biological studies (where, for example, feeding rates or other phenomena exhibiting threshold behavior are relevant), this would seem to be a worthwhile area of interest. Note, though, that a model concerned with larger scales, say 1 km or greater, would require eddy coefficients whose time dependence is just the opposite of that of the 100 m coefficients. A complete model would involve coupled time- and scale-dependencies.

B. Drogue Studies and Their Relationship to Dye Studies

In analyzing the trajectories of their drogues, Ebbesmeyer and his colleagues have chosen to consider the larger scales of the tidal flow as being characterized by a mean flow and four kinematic quantities, the horizontal divergence, the relative vorticity, and the stretching and shearing deformations (see Ebbesmeyer and Okubo, 1974). These five quantities, taken together, describe the flow field as it would be seen with all the smaller fluctuations averaged out, where, as before, the dividing line between "smaller" and "larger" is the "patch" size of the drifting array of drogues. Through what is basically a least-squares approach, the drogue trajectories yield values for the above large-scale parameters; the results of smaller-scale motions, the part not accounted for by the kinematic parameters, are represented by an eddy coefficient.

Conceptually, the large-scale parameters are functions of space and time (although the values obtained are averages over the time and space covered by the drifting drogue array). That is, we are working in an Eulerian framework, which is well suited to the description of a plume emanating from a fixed source; in this context, the drogues are visualized as a "random sampling" of the plume. But for the drogue results to correlate with the actual dye/effluent plume, the scales must match: the size of the drogue array at its release must correspond to some characteristic scale of the newly-formed effluent pattern, so that the same range of eddies in the background flow act equally on each.

Also, there is a further difference between the behavior of effluent and drogue: the effluent can move vertically with the three-dimensional flow, but the drogues are fixed in depth. Therefore, we should not even attempt to compare the two until some of the initial buoyancy of the effluent has been dissipated, after which the motion is more nearly two-dimensional. The relevant initial scale of the effluent is its width after the period of initial vertical mixing. Thereafter, any agreement between dye and drogue will indicate a low degree of vertical effluent motion or mixing. Karr (1975) has made such a comparison by calculating the standard deviations of the lateral dye distribution for the first day's data of the first experiment. These agree quite well with Ebbesmeyer's measured standard deviations of the drogue patch as it swept downstream that day.

Ebbesmeyer and Helseth (1975) have also cast the problem in Lagrangian terms, deriving, instead of the large-scale Eulerian parameters described above, Lagrangian parameters which pertain to properties of the flow seen following the drogue patch, wherever it goes. In this context the drogue array is considered, as a discrete drifting patch, not as a random sampling of a plume. Such calculations yield estimates of peak drogue concentrations as a function of time or (using the mean current as a characteristic velocity) distance downstream. These predicted concentrations can be compared to actual measured peak effluent concentrations, once the latter have been normalized to "start" at some point beyond which the comparison is a fair one--that is, beyond the stage of strong buoyant mixing, but where the plume width is still comparable to the initial size of the drogue array. We have chosen this "starting point" to be the point at which the effluent has been diluted by

1:100, so we divide this factor into our relative concentrations. Since this initial dilution is likely to proceed at somewhat different rates under different conditions of tide, the setting of the ratio is somewhat arbitrary, so that the normalized concentrations may be off by arbitrary factors (say, factors of 2-5); on a log plot, each of the curves may thus be arbitrarily shifted up or down, although the shapes of the relative peak concentration vs distance curves are unaffected by the shift. Fig. 19 shows such a comparison, between a number of cases from the dye experiment, and the mean and extreme concentrations calculated by Ebbesmeyer. The experimental points fall, for the most part, within the bounds. Ebbesmeyer and Helseth (1975) show curves for individual cases; agreement is reasonably good in most cases between the slopes, if not the magnitudes, of the individual curves. One should not expect extremely close agreement, since, besides the differences in vertical mixing, the Lagrangian technique considered drifting patches as independently entities, while the actual effluent distribution lies somewhere between being a smooth plume (an infinitely dense sequence of smoothly released patches diffusing into each other) and being a finite series of broken-off spots that are essentially independent of one another.*

C. The Effluent on the Beach

Effluent was present in the West Point bottle samples during summer, but not during winter conditions. The seasonal difference suggests that the strong and consistent stratification during the first four days of the summer

* The sharp dropoff of some curves is due to passage through a front. However, Ebbesmeyer's Lagrangian calculation does not include the existence of a front; the resemblance of the way the lines break is fortuitous.

experiment, which, we have seen, served to keep most of the effluent below 35-60 m, may be partly responsible for the presence of effluent on the beach. We hypothesize that the effluent which is collected below the pycnocline--and prevented by it from rising or mixing upward--may be able to work "around the edges" of the pycnocline where, as the pycnocline meets the bottom near shore, a turbulent bottom boundary layer forms and stratification breaks down locally. If there is onshore transport along the bottom, then significant amounts of effluent could be carried up within the boundary layer onto the beach without having to overcome a density gradient. (The source of such transport is not clear, however.) During the winter, the dye mixes more vertically and is not confined as much to the bottom. If this hypothesis has some truth to it, it implies that the benthos around West Point, from the depth of the pycnocline up, is exposed to considerable concentrations of effluent during summer conditions.

VI. REFERENCES

Carter, H. H. (1972). The Measurement of Rhodamine Tracers in Natural Systems by Fluorescence, Rapp. P.-v. Reun. Cons. int. Explor. Mer, 167: 193-200. December 1974.

Ebbesmeyer, C. C. and J. M. Helseth (1975). A Study of Current Properties and Mixing, Using Drogue Movements Observed Near West Point, Final Report to the Municipality of Metropolitan Seattle from Evans-Hamilton, Inc., Seattle, Wa.

Karr, K. R. (1975). Spatial and Temporal Behavior of the West Point Sewage Effluent in Puget Sound, MS Thesis, Department of Oceanography, University of Washington, Seattle, Wa.

Pederson, A. M. (1969). An Accurate, Low-Cost Temperature Sensor, Transactions of the Marine Technology Society Marine Temperature Measurements Symposium, June 1969.

Pederson, A. M. (1973). A Small In Situ Conductivity Instrument, Record of Ocean '73, the 1973 IEEE International Conference on Engineering in the Ocean Environment, IEEE Publication 73 CHO 774-0 OCC, pp. 68-75.

VII. APPENDIX - PARTICIPATING PERSONNEL

The following students from Shoreline Community College participated in this study.

Wayne Anderson
Mary Butler
John Carlson
Mark Childers
Wayne Gilbertson
Laurie Harazim
René Hernandez
Duane Ingham
Larry Iverson
Stephen Joyce
Daria Kling
Patrick McKeown
Carl Peterson
Maria Restrepo

Shoreline's Marine Technician program has proven itself on this and previous occasions by the quality of the people associated with it.