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ABSTRACT

Estuarine Oceanography is one in a series of single-topic problem modules intended for use in undergraduate and earth science courses. Designed for those interested in coastal oceanography or limnology, the module is structured as a laboratory supplement for undergraduate college classes but should be useful at all levels. The module has two distinct parts: a text covering general concepts and stressing the small-scale technology necessary to study small natural bodies of water, and a rather detailed exercise describing an ideal estuary. Emphasis throughout the module is on techniques that have evolved for low-budget studies of physical oceanographic phenomena, particularly water movements and mixing problems. Although estuaries are emphasized, most of the techniques discussed are equally applicable to lakes. Like other modules in the series, this module is inquiry- and problem-oriented, dealing with interdisciplinary, contemporary, and pragmatic aspects of the subject matter. It is designed to be open-ended so that ideas can be incorporated into higher level classwork. Supporting materials such as specifications of current drogues, bathymetric-survey data sheet, current measurement data sheets, drift-can data, and inshore T-S probe survey sheets are included in appendices. (Author/JN)

CEGS PROGRAMS PUBLICATION NUMBER 18

Estuarine Oceanography

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F. F. Wright measures salinity by hydrometer on the breakwater at Seward, Alaska. Date: April 20, 1973.
Air temperature: 10° C.
Water temperature: 3.6° C.
Salinity: 26.4 ‰.

CEGS Programs Publication Number 18

ESTUARINE OCEANOGRAPHY

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CONTENTS

FOREWORD

This publication is one of a series of single-topic problem modules intended for use in undergraduate geology and earth science courses. It was prepared under the direction of the Instructional Materials Program (IMP) panel of the Council on Education in the Geological Sciences (CEGS)–a project of the American Geological Institute (AGI) supported by the National Science Foundation and is presented through the cooperation of the McGraw-Hill Book Company.

Each module in this series serves as a model from which modern aspects of concepts basic to geology can be introduced. All modules are inquiry- and problem-oriented and deal with interdisciplinary, contemporary, and pragmatic aspects of their subject matter–matter difficult to treat in a more typical textbook fashion. They are designed to be open-ended so that ideas from them can be incorporated into higher level classwork. They should inspire teachers to develop similar materials in areas of their own interest and competence.

All modules should be usable alone or as a supplementary resource to other course materials. Therefore, they are designed to be self-contained, with written parts arranged so that they can be adapted to special local needs or conditions. Some are essentially a single laboratory exercise, others might occupy nearly an entire semester to complete satisfactorily. Their breadth is as variable as their depth.

Estuarine Oceanography is especially timely and treats aspects of one of the most fundamental problems of man–his adjustment to, and modification of, his environment. Where the land, sea, and air meet, man has concentrated his major cities and industrial sites. Yet few regions of the earth are subject to a more varied confluence of natural forces, ambient dynamic energy, or rapid change. The continuous rapid transformation of coastal areas demands scientific and political problem-solving with a sense of urgency. Students with varied backgrounds and future interests should find in coastal processes a natural laboratory where change is fast enough to measure easily and often hazardous enough to qualify as "relevant."

Thanks are due to all who contributed to the process of improving *Estuarine Oceanography* as an educational device. The author of the module, F. F. Wright, tested early versions in his classes, redrafted most of the figures, and reworked the educational aspects in response to class testing and editorial review. Raymond Pestrong of California State University, San Francisco, advised the author on procedural matters and reviewed an earlier version of the manuscript. Richard L. Bartels, Ingeborg Westfall, and Carol Moss, all of the University of Minnesota, were especially helpful to the editors in providing educational criticism and editorial advice. Martin A. Torre of the AGI staff reprocessed some of the author's photographs of equipment and field operations. The National Oceanic and Atmospheric Administration furnished pages from their *Tide Tables*, herein reproduced as Tables 1 and 2. Finally, to Jackson E. Lewis of the CEGS staff go the accolades rightfully his for carrying the major burden of bringing this module to the geological education profession.

Peter Fenner
Governors State University
George R. Rapp, Jr.
University of Minnesota

PREFACE

This module is for anyone seriously interested in coastal oceanography or limnology It is structured as a laboratory supplement for undergraduate college classes but should be useful at all levels The module has two very distinct parts. a text covering general concepts and stressing the small-scale technology necessary to study small natural bodies of water, and a rather detailed exercise describing a (somewhat) ideal estuary

Emphasis throughout the module is on techniques that have evolved for low-budget studies of physical oceanographic phenomena, particularly water movements and mixing problems These phenomena, and especially the analytic approaches necessary to extract useful information about them, are unique to oceanography and limnology and usually are not well understood by scientists or laymen outside the field. An appreciation for such phenomena is absolutely essential to the understanding of aquatic ecology, the transport and deposition of sediments, and problems of engineering construction and materials; often, however, they are ignored out of lack of knowledge and understanding or lack of analysts' confidence when they approach these matters.

In any study of a body of water, there will be specific local complications–biological, chemical, and geological–the full understanding of which requires the active and coordinated contributions of people having expertise in these corollary fields. Therefore, the results of a class survey of the sort described in this module will be far more meaningful if it is run in conjunction with classes in bacteriology, ecology, or chemistry.

Throughout the module, estuaries have been emphasized, and it is assumed that you will have one within easy reach. Of course, this will not always be the case, but you will find that most of the techniques discussed are equally applicable to lakes. Theoretical background is minimized throughout and should be obtained from standard oceanography or limnology texts. Considerable enthusiastic labor has been taken for granted, in effect, labor is substituted for hardware in this approach, and you will see what a tremendous amount of work can be involved in even a superficial study. Much specialized apparatus is needed too, so it may take some time to accumulate the capital equipment for a comprehensive study. In the meantime, you can still do useful work with whatever is at hand. An extensive collection of charts, tide tables, and local reference material will also have to be assembled.

One note about the gear described–it was created for me by a junior high school student. To simulate reality, I would simply sketch roughly what was needed, send him out to beg, borrow, or steal the wherewithal, and then have him build the gadget. Most of our "equipment budget" went for plastic electrical tape (needed by the kilometer), thermometers (very fragile, unfortunately), and such esoterica as plumber's helpers; everything else was "found." Needless to say, only the gadgets that actually worked are described here. Be prepared to improvise, and if you come up with a significant improvement, please send me a description.

The exercise on Hypothetical Bay was designed to be as close to reality as possible and is intended either for practice or as a substitute for a real estuary. I have included not merely a mass of raw data but have also tried to give some feeling for the context–technical, political, and sociologic–in which most such studies are actually conducted. The data are based on actual material collected by students. As in the original surveys, you will find that there are places where the ends just do not meet. Equipment malfunctions, people tire, and the weather (invariably) deteriorates. The result is anomalous or downright spurious information, and some of these data appear in the exercise. As you will discover when you get on the water, a continual trade-off operates between the information you believe in advance is absolutely necessary to do a minimal job and the data with which you must finally be content. Too often during a study it is really impossible to decide which data are superfluous, in the final synthesis coincidental information often proves to be highly significant. In the Hypo Bay material, you will find a good deal of information that is not strictly necessary for a first-approximation solution to the stated problems, but if (as is likely in such a situation) the case went to court, all the background data might prove important. This situation is really very much like the real world—there simply is no single, simple, obvious solution to the local problems. As you will see, the problems are not all oceanographic. . . .

Too often, people when confronted by oceanographic or limnological problems let themselves be intimidated by what they have read or seen on television. They assume you must have an unlimited budget and a sophisticated command of mathematics and physics to do realistic work. This is true enough for many deep-sea projects and for many of the basic research fields within oceanography. It is definitely not true for most small-scale inshore projects. All you need is a certain amount of carefully collected data and the confidence to manipulate these facts to produce useful estimates of the critical physical parameters. Intelligent amateurs can do as well as—or, because they can mobilize more observers, often better than professionals at the estuarine oceanographic game. If this module does nothing else, I will be content if it convinces a few bodies to get out in a boat and do some real oceanography.

As a final and quite personal note, *Estuarine Oceanography* is based on more than 10 years' experience doing oceanographic work without a budget. Nothing herein is strictly original or, for that matter, identical to earlier operations. The equipment is based on the many curious expedients that I used as a student or that were dreamed up by friends or students of my own. My thanks to all these friends, professors, students, and technicians. My particular thanks go to Kirk Randall, who actually built most of the gear mentioned, and to Dave Burbank, who improved on much of it. The material for most of the Hypo Bay exercise was generated by a series of class studies; to those students involved, my thanks and appreciation. If any of them encounter this module, they will recall the frustrations and excitement of our surveys. Finally, I must also mention the CEGS people who have been uniformly cooperative, constructive, and very, very tolerant throughout the evolution of the module!

Best of luck!

F. F. Wright

ESTUARINE OCEANOGRAPHY

INTRODUCTION

Oceans cover over 70 percent of our planet's surface, but the exposed land areas profoundly influence the meteorology, geology, and biology of the entire system. The transition zone at the coast, where land, sea, and atmosphere meet, is thus critical to all the natural sciences. This module is concerned with the oceanography of particularly important features of the coastal zone—estuaries.

Estuaries are usually bays where rivers flow into the sea, but there are many geomorphic variations. They are strictly defined as semienclosed coastal bodies of water having a free connection with the open sea and a certain amount of dilution from land drainage. The estuarine environment is critical because it is through estuaries that virtually all physical and chemical products of the land are transferred into the ocean. The first contact between sediments and the sea occurs here, and many important physical and chemical processes are initiated here.

Geologists are especially concerned with the estuarine environment because more than 50 percent of all ancient sedimentary rocks were deposited in the sea close to the continents. These ancient sediments reflect their individual histories of erosion, transportation, and deposition, and thus are necessary guides in the reconstruction of the history of the earth. As a consequence of their efforts to understand earth history, geologists must carefully study the chemistry, physics, and biology of this zone of transition—in effect, they must become estuarine oceanographers.

Today, there is another reason the study of estuaries is important. Pollutants, the wastes of all sorts produced by our society, enter the sea primarily through estuaries. Most pollutants, in fact, may be regarded as specialized forms of sediment, for they are influenced by precisely the same processes as natural products of the land. Thus, as we study the geologic processes in estuaries, we can attain a better understanding of the interaction of man with his environment.

In this part of the module, you will study first the general characteristics of the estuarine zone and the physical processes, both natural and artificial, that are found in estuaries. Then, you will be exposed to some basic techniques necessary for the scientific study of estuaries—techniques that can be used by any interested group. In the second part of the module, a study program for a typical estuary will be described, especially in the context of potential pollution problems. As a practical matter, if the techniques discussed here are integrated with a biological survey of an estuary in your local area, you can—with a few weeks of field and laboratory work—accomplish a study that can be very important in planning the conservation or development of your home area.

Study Suggestions

1 In your state, what is the legal seaward (or lakeward) limit of private property? (This is usually an average high-tide mark, but precise definitions vary.)

2 List all the local, state, and federal authorities who have jurisdiction over estuaries (or lakes) in your area. Try to define precisely their responsibilities.
3 What are the uses to which estuaries (or lakes) in your region are put? Commercial fishing? Recreation? Waste disposal? List all the uses, and rank them by relative importance to private citizens, to governmental authorities, and to industry.

THE ESTUARINE ENVIRONMENT

Geomorphology and Geology

Estuaries are geologically temporary features of a shoreline. As sheltered embayments that can trap materials from either hinterland or the open continental shelf, they inevitably fill and disappear in time. Because sea level has recently risen owing to the melting of the last great continental glaciers, many estuaries exist at the present time. Many of these represent the drowned valleys of rivers adjusted to lower sea level earlier in the Quatemary Period. Other large estuaries have developed as lagoons behind beach ridges or barrier beaches that were produced when sea level was lower than at present. Virtually any coastal map shows estuaries of many forms and sizes. Remember that to qualify as an estuary an embayment must have relatively free access to the sea and a certain amount of fresh-water dilution from the land, even if the runoff is largely seasonal.

In detail, the physical form of estuaries is the result of the interaction of marine and terrestrial agencies. Waves, wind, and tidal and river currents all contribute to the erosion, transportation, and deposition of sediments in estuaries, also very significant are the type and quantity of available sediments. Human influence on many estuaries has often been drastic. Deforestation, agricultural practices, or hydraulic mining have strongly altered the fluvial input of water or sediment to estuaries, and dredging or construction projects have often completely changed estuaries' geometric forms. (The two review papers by Schubel and Pritchard, published in 1972, describe in more detail the origin, development, classification, and pollution of estuaries.)

Study Suggestions

1 Obtain nautical charts and topographic maps of your local estuaries.
2 What geomorphic types of estuaries are there in your locality?
3 What geologic agencies are responsible for their forms?
4 What are the obvious (or subtle) effects of civilization upon the forms of your local estuaries?
5 If maps over a significant time span are available, estimate rates of change, erosion, sedimentation, sand-spit migration, etc.

Biology

Paradoxically, the estuarine environment is one of the most exacting environments for life but also one of the most productive. Runoff from the land and wave and tidal mixing tend to keep the nutrient levels in the shallow waters very high, so plants, both planktonic and benthic, tend to grow very well. Of course, marine plants, like terrestrial plants, are at the base of the trophic pyramid, and where plants thrive, animals rapidly appear to exploit them.

Three factors make life in estuaries difficult for organisms. tides, waves, and the influx of fresh water. The tidal rise and fall of sea level are extremely variable in different parts of the world or even between neighboring bays. Much of the local effect of tides depends on the specific geometry of the embayment. The tides are critical to many benthic organisms because they expose part of the sea floor to the atmosphere several times each day, intertidal creatures are likely to be desiccated at low tide, and they are subjected to much wider ranges of temperature than is deeper living marine life. Wave attack is also highly variable, depending on local weather patterns and on the configuration of the shoreline. Waves assist in the mixing processes necessary for high productivity in estuaries, they may also move sediments that choke life or may physically detach organisms from the substrate. The fresh water which is always present to some degree in estuaries is critical to the stratification of the waters, and because it tends to lie above the denser saline water, it has a profound influence on the intertidal biota. In fact, because the intertidal creatures are so profoundly influenced by the local water characteristics, the normal proportion of fresh water can be gauged very closely in most localities by the character of the population.

The ecology of estuaries is a very precisely balanced thing. In any locality, it represents a slowly developed system that optimizes the utilization of the local resources. Natural catastrophes are not uncommon in this rigorous environment, but we are now observing large-scale artificial disruption by humans in a great many estuarine systems. Where the interference by humans has been "natural" (such as alterations in the local hydrologic cycle, introduction of excess sediment, or simply overexploitation of some estuarine organism), the environment, given time, can compensate and reestablish its balance Unfortunately, many of the things humans now introduce into estuaries are either quite unnatural (such as detergents, pesticides, or industrial waste waters), or if natural (such as oil spills), they are introduced in such large volumes that the environment simply cannot cope. The ecological results of pollution may be either the direct killing or stunting of populations or, more subtly, estuarine products made poisonous to creatures outside the immediate environment, those affected by the latter may include even humans

Study Suggestions

1 From field trips and reference books, work out the local intertidal zonation of plants and animals on an open shoreline (without fresh-water influence).
2 Compare the zonation in nonestuarine areas exposed to and protected from wave attack
3 Compare the intertidal communities in local estuaries with those of the open coast, especially from the points of view of species diversity and absolute numbers
4 Tabulate what is known of the tolerance of your local biota to temperature and salinity variations.
5 Tabulate any obvious local sources of coastal pollution and their consequences on the biota

Oceanography

The oceanography of estuaries is exceedingly complex and involves primarily studies of water mixing and circulation patterns and the physical or chemical transport of numerous substances transport often influenced profoundly by organisms of many sorts. These studies can be greatly simplified by accepting the assumption that we are dealing with an approximate *steady state* in a thermodynamic sense If we assume a balance between the input and output of energy and matter in an estuary, as is implied by a steady state, we can then create a relatively uncomplicated model which can be analyzed by determining a limited number of energy and material budgets, and which may be used to predict probable changes in the system. Natural estuaries are so complex that such an approach is necessary even though we are aware that our simplified model is not a very close approximation of nature.

Our model of estuarine circulation assumes the presence of two "active" layers of water (Fig. 1*a*). At the surface, there is a mixed layer containing less dense fresh water from runoff and some admixed sea water. At depth, there is a denser layer of virtually pure sea water. Between the two layers is the *pycnocline*—a zone of very rapid vertical change in water density caused primarily by the difference in salt content between the layers, but often also strengthened by temperature differences. The pycnocline is actually the summation of the influence of steep vertical gradients in the salinity (the *halocline*) and in the temperature (the *thermocline*). This pycnocline serves as a barrier to mixing between the two layers. Much of our attention in estuarine oceanography focuses on the volumes of water and the currents in the two layers. These determine mixing and flushing rates within the estuary - the critical factors in most coastal-pollution problems.

In a horizontal view (Fig. 1*b*), we see that surface currents tend to have a rotational motion with incoming and outgoing currents stronger, on the average, on opposite sides of the estuary. This condition is due to the Coriolis effect, the apparent deflection of moving particles on the surface of the rotating earth.

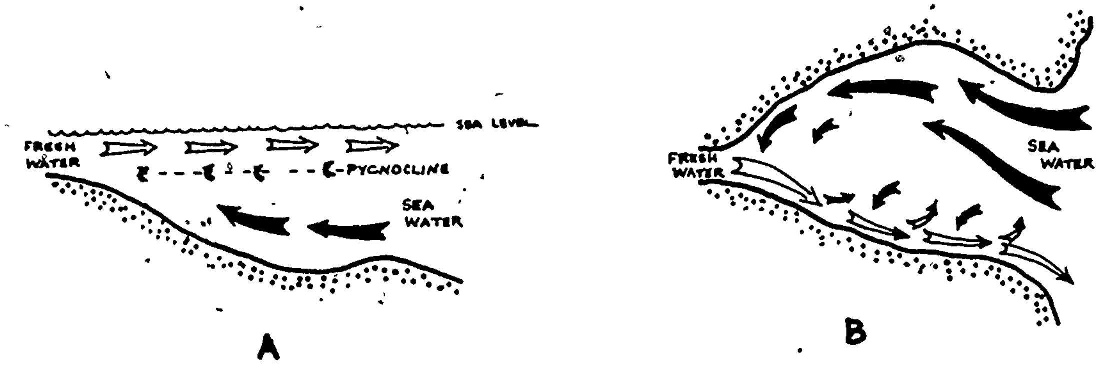

FIG. 1 Circulation in Northern Hemisphere estuaries. (A) Longitudinal cross section, (B) horizontal view.

Water in the currents tends to move toward the right in the Northern Hemisphere, toward the left in the Southern; thus, in the Northern Hemisphere an almost permanent counterclockwise circulation may be established in a tidal basin.

The remainder of this part of the module deals with techniques necessary to study the circulation and mixing in estuaries, especially as they can be applied in reconnaissance studies. None of these techniques is particularly refined, but if intelligently applied, conclusions based on information they provide can be very important in planning the use of our estuaries.

Study Suggestions

1. Contact the local office of the Weather Bureau, and obtain copies of the National Oceanic and Atmospheric Administration's "Annual Summary of Local Climatologic Data" for your region. Study these, and then prepare a graph showing average precipitation over an annual cycle.
2. Obtain any available local river- and stream-flow information (from the U.S. Army Corps of Engineers or a state agency), and correlate this with the precipitation data.
3. From the precipitation and stream-flow graphs, try to assess the importance of seasonal influences in estuarine circulation.
4. Check with the local office of the Coast Guard for any available information on local currents and any significant changes in the shoreline or location of landmarks that postdate your charts.

The magnitude of Coriolis force per unit mass C can be calculated for any latitude from the equation

$$C = 2\,\Omega\,\nu \sin\phi$$

where Ω is the angular speed of the earth's rotation (1.458×10^{-4} second^{-1}), ν is the speed of the moving body, and ϕ is the latitude. The direction of the Coriolis vector is always normal to the original direction of acceleration.

Calculate the Coriolis force on a water particle moving in a 2-knot (50 cm/sec) tidal current in your latitude.

Calculate Coriolis influence on unit masses of water for each 15° of latitude between the equator and the pole. Plot these on a graph, and then explain the variation in intensity with latitude.

Why do we observe right deflection due to Coriolis force in the Northern Hemisphere and left in the Southern?

ESTUARINE OCEANOGRAPHIC TECHNIQUES

Study-Site Selection

Many factors should be considered in the selection of a study estuary. its accessibility, the availability of boats, docks, or bridges from which to sample, the availability of adequate charts, the time and money that can be allocated to the study, and, of course, the need for the study. Perhaps the most important early considerations should be those of geographic simplicity and size, the area must be small enough and sufficiently uncomplicated that a small group with limited time and funds can conduct a fairly comprehensive survey. A good estuary for class study might be approximately triangular, 3 or 4 miles long, and no more than 1 mile wide, it should have only one major source of fresh water and depths no greater than 50 feet. A reasonable model of such an estuary can be worked out with 2 or 3 days of intensive study and a few weeks of occasional observations.

Working Boats

A powerboat of some sort is really essential for a comprehensive estuarine survey. This can be of any convenient size, shape, or power, but preferably it should be relatively small and have a shallow draft and wide beam to make a stable working platform. The boat need not be fast, much of the work will be done at slow speeds or while anchored or drifting. If a powerboat is not available, a good-sized rowboat or even a small sailboat can be used, but mobility will be proportionately reduced. You must be able to anchor the vessel for some operations. In some built-up estuarine areas, enough docks and bridges may be available to permit reasonable sampling, and little boat work will be necessary. Needless to say, Coast Guard regulations on life preservers and other basic safety gear should be followed whenever working on the water.

Bathymetric Survey

The basic requirement for an estuarine study is an adequate map. In most coastal areas of the United States, excellent charts are available from agents of the Coast and Geodetic Survey. Many ship chandlers and harbor masters stock them. These maps should be used with care for research purposes, however, because their quality is usually in direct relation to the importance of local shipping; therefore, if your study area is not in a busy port, the charts will often be out-of-date. Also, silting can be quite rapid in estuaries, and this too may invalidate the available charts. Thus, it is wise to check the available charts, and it is often necessary to remake or revise them in part. Assuming that a good base topographic map and a small powerboat are available, running a simple bathymetric survey is relatively simple and rapid.

Sources for some of the equipment necessary for a small-scale bathymetric survey are listed in Appendix A. Specialized gear includes a simple sextant or a compass which can be used to take bearings, a three-arm protractor to plot positions, and some sort of sounding device. This can be either a small fathometer (if available) or an adaptation of the traditional sounding line – a weighted, graduated line used to measure water depth directly If you are using a compass, be sure to take your bearings far enough away from the engine or other large metal structure to avoid local magnetic aberrations. An enlarged working copy of the base topographic map should be carefully mounted on a plywood frame and covered with an acetate film to protect it from spray or rain. Before starting the survey, be sure that all the prominent local landmarks are clearly marked on your base map. It may prove necessary to install temporary landmarks to permit adequate triangulation within the estuary, a tall flagpole with a bright banner is usually quite satisfactory.

A sextant for inshore surveys should be simple and sturdy but need not have an optical system. It consists of a sighting frame through which a landmark can be seen and an adjustable mirror system with which some other landmark can be aligned with the first. A graduated arc is provided to measure precisely the angle between the two landmarks. To make this kind of sight, hold the sextant flat in your left hand, sight directly at the first landmark, and pivot the arm controlling the mirror system until the reflection of the right landmark is in line, then read the angle. For an accurate position, repeat the process using one of the original landmarks and a new one. With a protractor and tracing paper, draw these three lines separated by the appropriate angles, then move the tracing over the map until the lines intersect their respective landmarks. The origin, then, is your position on the chart A three-arm protractor is designed specifically to plot positions by this method and is a great convenience Practice this entire technique ashore before your survey. It is simple enough, but the field of view in the mirrors is limited, and a bobbing small boat is no place to make your first sextant sight.

Location with a hand-bearing compass is less accurate than with sextant angles, but it is much easier to accomplish in a small boat. Any good compass graduated to at least 5° increments can be used, but those designed specifically for yachtsmen (such as the inexpensive model produced by Davis Instruments–see Appendix A) are much easier to use on a boat than a Brunton or similar survey-style compass Simply align the compass with landmarks that appear on your chart, and read the magnetic bearings. These lines of position are then transferred to your chart (correcting for declination, if necessary), and your position is defined by their intersection. You must use at least two bearings with this technique, it is much more accurate to use three or more, which will then define a triangle or polygon within which your true position lies. Again, practice and speed in taking correct bearings are essential.

The simplest way to operate the survey is to run your boat at a slow constant speed on predetermined lines evenly spaced within the estuary. As a general rule in small-boat surveys, it is wise to run as slowly as possible and still stay on course, remember that at 2 knots you travel about 200 feet every minute. Your initial survey lines should be laid out in advance, heading, as much as possible, directly for obvious landmarks so that the helmsman will have a straightforward job. A hypothetical survey is illustrated in Figure 2. At regular time intervals (perhaps 30 seconds if you are using a fathometer, longer if you are using a sounding lead), the depth should be measured and recorded. If you are sounding with a lead, practice a good bit before you attempt to run your survey lines. In this techinque, a 1- or 2-pound weight is tied to the end of a line graduated at appropriate intervals (1-meter spacing is adequate). As the boat proceeds along its track, the leadsman heaves the lead underhand ahead of the boat, pulls the line taut, and reads it as it comes vertical; he then recovers the line and coils it for the next cast. In water less than about 5 meters deep, it may be convenient to use a graduated bamboo *sounding pole* instead of a line. Once a good rhythm is established, highly precise depths can be obtained very rapidly in shallow water by this technique. In deeper water, lead-line sounding becomes slow and very tedious. Periodically, perhaps every 5 minutes during a run, you should take a series of sights with the sextant or take compass bearings to determine your true position. If enough hands and space are available during the survey, plot your locations immediately; this will provide a good check on your speed and general accuracy.

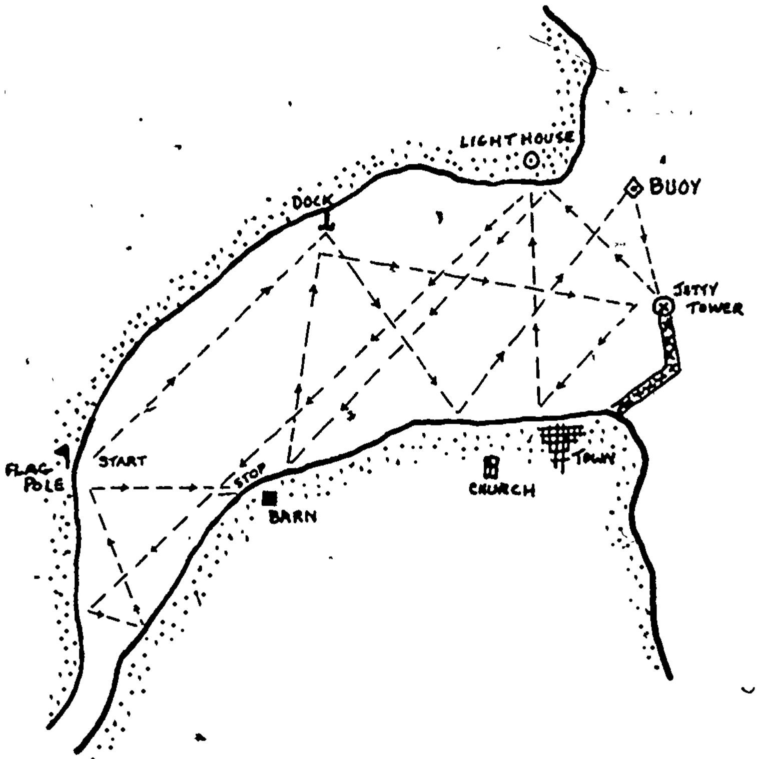

FIG 2 A possible estuarine bathymetric-survey grid. Most tracks head toward obvious landmarks to simplify navigation.

If a survey could be run entirely at low- or high-tide slack water, charting would be considerably simplified. Since this is never possible, the soundings obtained must be corrected for the stage of the tide. To do this, a tide-height curve should be drawn (see the section on tides), and the correction necessary to bring the observed soundings to the reference datum (usually average low tide) must be applied. Normally, survey lines are short enough and boat speed high enough so that tidal-current corrections can be ignored. With currents greater than 1 or 2 knots, it is wise to suspend operations during peak flood and ebb periods.

Back at the laboratory, the sounding tracks should be transferred to an enlarged version of your base map A convenient scale for this map might be 1 inch to 200 feet, or 1 centimeter to 50 meters. When all the tracks have been marked, transfer in your soundings (corrected for tidal height as necessary). Normally, coastal charts will use Mean Low Water as the datum plane. Once all the soundings have been recorded, the map should be contoured at an appropriate interval and then reduced to a convenient size for field use. A 2-meter (approximately 1-fathom) interval is excellent, but often a larger contour interval will prove more convenient and realistic.

Tides and Tidal Observations

Tides are a special form of wave produced by the attraction of the moon and sun. Ideally, there are two tidal bulges, one facing the moon and one opposed to the moon, traveling constantly around the earth. The crest facing the moon is caused by direct attraction, the other by the slightly off-center centrifugal force of the rotation of the earth-moon system. These ideal tides are very small—less than 1 meter high in the open sea, but observed tides can be much greater owing to the interaction of these waves with the geometry of the solid earth.

Every body of water has a natural period of oscillation depending on its dimensions. These dimensions are so influential that tides in different basins geographically close to one another may differ greatly, and corrections must be made for both amplitude and timing for every inlet of any size. To evaluate the potential for large tidal effects in an open-mouthed estuary, the natural period of oscillation T of the basin can be calculated from

$$T = \frac{4L}{\sqrt{gd}}$$

where L is the length of the basin, d is its average depth, and g is the acceleration of gravity; these parameters must be in metric terms. The period of an enclosed bay or lake can be calculated in a similar way from

$$T = \frac{2L}{\sqrt{gd}}$$

If the period of oscillation is approximately 1 lunar day (24 hours, 50 minutes) or a simple fraction thereof, reinforcement is possible, and great-amplitude tides and strong tidal currents may result. For the derivation of these expressions, see such standard oceanographic texts as Gross (1972) or Sverdrup, Johnson, and Fleming (1942).

Tides are also influenced by the sun. The familiar fortnightly cycle of spring and neap tides is the result of the interaction of lunar and solar forces. When the moon and sun are aligned at full and new moon, we encounter the high-amplitude spring tides. At the quarter moons, when the sun and moon are opposed, there is some cancellation of forces, and the lesser amplitude neap tides occur. The resultant tide, influenced by sun, moon, and basin shape, is a complex wave form. Tidal heights over a month-long period in different parts of the world are shown in Figure 3. Soundings on nautical charts are usually referred to the average lowest tide level (MLWS–Mean Low Water Springs, or MLLW–Mean Lowest Low Water) as their datum plane. This is a safety factor; the depths shown are thus minimum values.

Tides along the coasts of North America are of three general types: diurnal, semidiurnal, and mixed (Fig. 4). The simplest–diumal tides with only one high and one low each day–occur in parts of the Gulf of Mexico. The semidiurnal tides of the East Coast have two highs and two lows each day. The mixed tides of the West Coast exhibit diurnal and semidiurnal components; they too have two highs and two lows each day, but successive similar tides reach different levels. For an interesting computer-assisted study of the three types of tides, see the paper by Fox (1969).

In estuarine work, we are concerned with both the vertical and horizontal water movements of the tides. In this section, we will discuss primarily the rise and fall of tides (the vertical component); tidal currents (the horizontal movements) will be discussed with other currents. Tide tables prepared by the Coast and Geodetic Survey are available for most of the coastal areas of the United States. These tables give, for critical coastal points, the times of high and low tide and either the tide height or maximum current velocity associated with the flood and ebb tides. (See the sample page reproduced in Table 1.) They also list correction factors for localities near these critical points (see Table 2). For any estuarine study, be sure to use the *Tide Tables*, not the very similar *Tidal Current Tables*. Local tide tables, sometimes giving both tide height and current predictions, are often available from local businessmen. With any tide table, be sure to read very carefully the instructions for application. The corrections are often rather confusing, and you will need to prepare tide curves to correct your bathymetric survey and to calculate water volumes. In a large estuary, the tide may have a somewhat different height at various points on the shore; such an estuary and the water volume represented by the tidal effect (*tidal prism*) are shown in Figure 5.

Figure 6 shows a typical tide curve for 1 day–13 August 1970–for a small bay in southeastern Alaska. The data are taken from Tables 1 and 2; using these tables, continue the curve in Figure 6 for the following three days–14, 15, and 16 August.

Most tide gauges are automated and are designed to record tides (and sometimes waves as well) for long periods of time. They operate either with a float or a step-resistance bridge coupled to recording devices. Such gauges are too expensive for classwork, but adequate observations can be made with a simple graduated staff and patience. The staff should be carefully marked off in tenths of meters over a vertical range somewhat greater than the anticipated tides; then it should be securely mounted on a dock piling or a stake where it can be easily observed. All that is necessary is a record of the average high- and low-water levels at slack tide over the period of your survey. Naturally, you must disregard the swash of waves to obtain a true tide figure. A variation uses a long, clear plastic cylinder with a float; the response time of the cylinder may be adjusted by the size and spacing of water-escape ports to filter out small waves (Fig. 7). Wave observations may be obtained at the same time.

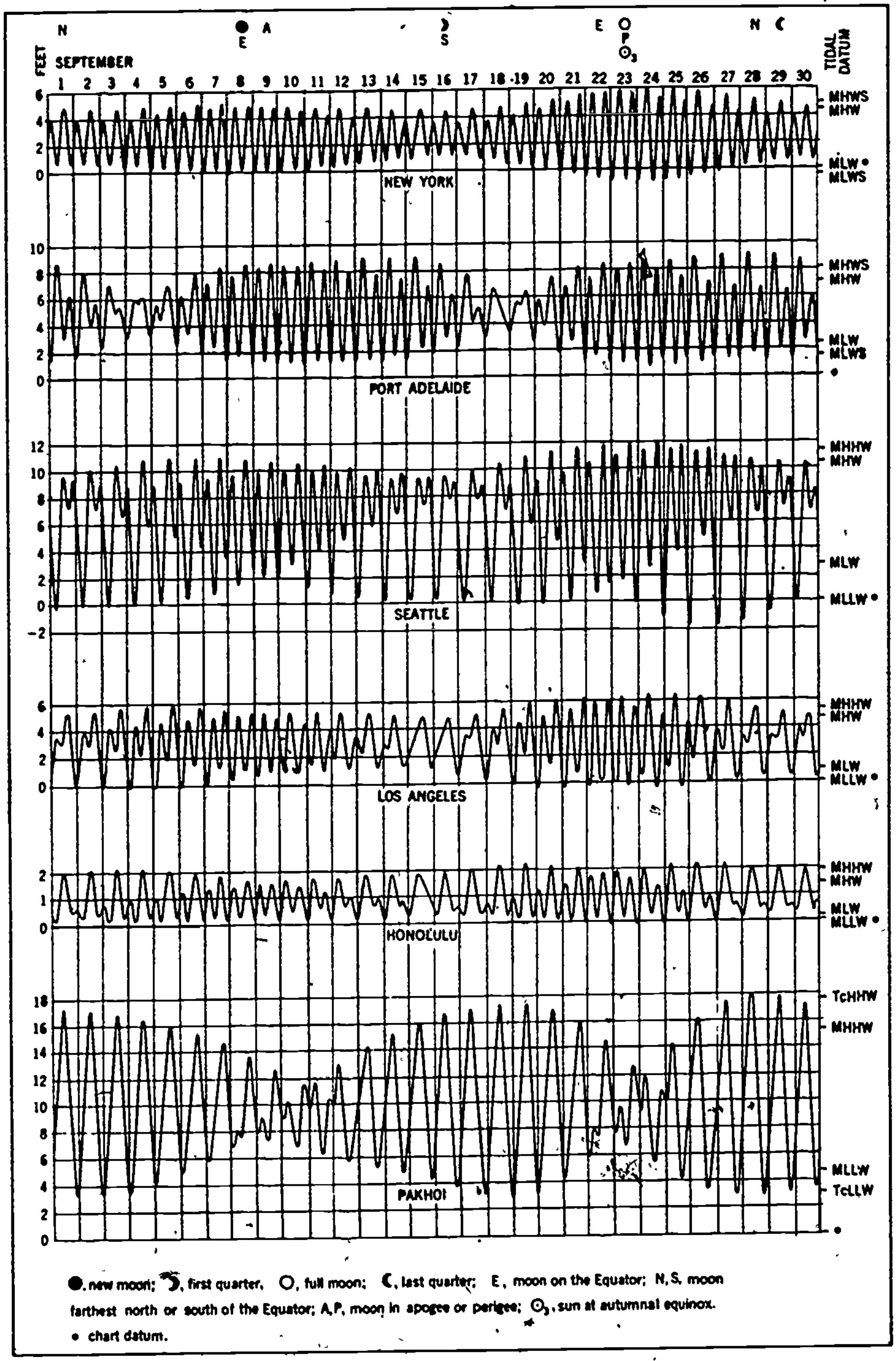

FIG. 3 Tidal variations at various localities during a month (*From U.S. Naval Oceanographic Office, American Practical Navigator, Bowditch, H.O. Publ.* 9, 1966).

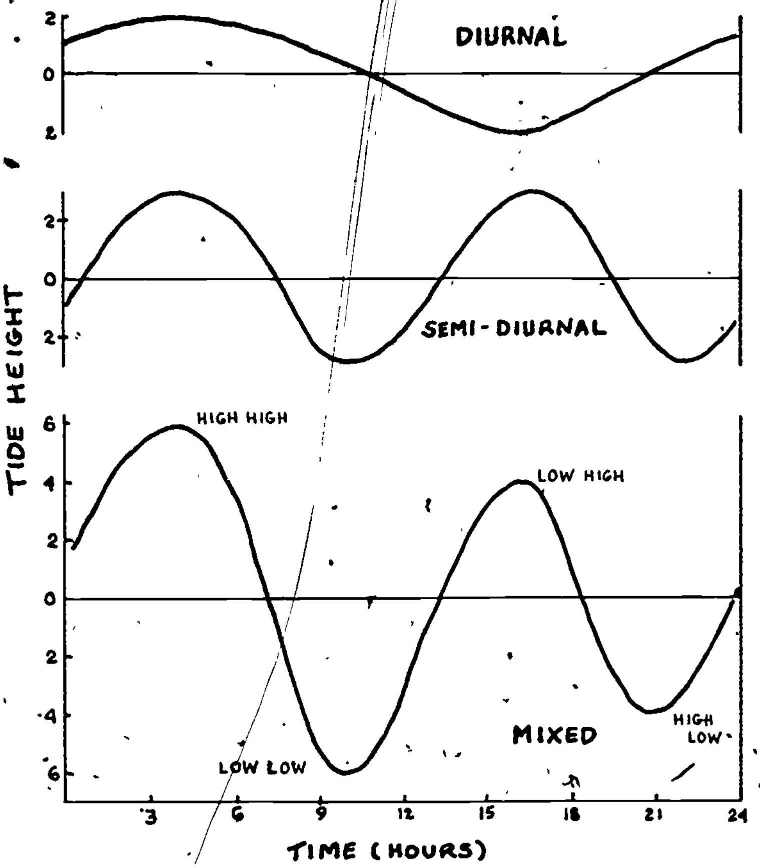

FIG. 4 Types of estuarine tides.

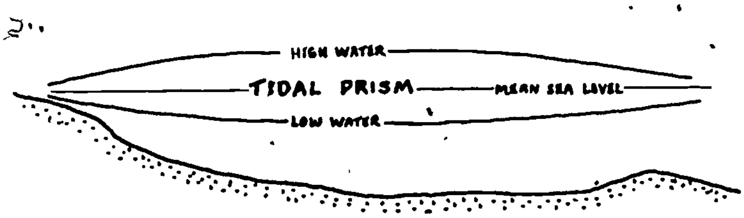

FIG. 5 Tidal variations in the volume of an estuary.

TABLE 1 Tide Table for Juneau, Alaska, for Period July to September, 1970. From *Tide Tables, High and Low Water Predictions, 1970, West Coast of North and South America,* U.S. Department of Commerce, Environmental Science Services Administration, Coast and Geodetic Survey, 1969.

Times and Heights of High and Low Waters

JULY

DAY	TIME H.M.	HT. FT.	DAY	TIME H.M.	HT. FT.
1	0630	−1.2	16	0600	−0.8
W	1306	13.7	TH	1236	13.1
	1830	4.5		1754	4.6
				2354	17.1
2	0036	16.7	17	0648	−2.3
TH	0712	−1.7	F	1324	14.4
	1348	14.1		1848	3.6
	1912	4.3			
3	0118	16.8	18	0048	18.1
F	0754	−2.0	SA	0730	−3.4
	1430	14.5		1406	15.6
	1954	4.0		1936	2.5
4	0200	16.8	19	0142	18.8
SA	0830	−2.0	SU	0818	−4.1
	1506	14.7		1448	16.6
	2030	3.8		2024	1.5
5	0236	16.6	20	0230	19.1
SU	0906	−1.8	M	0900	−4.3
	1536	14.8		1530	17.4
	2112	3.7		2112	0.8
6	0312	16.3	21	0318	18.8
M	0942	−1.4	TU	0942	−3.8
	1612	14.8		1612	17.8
	2148	3.7		2200	0.4
7	0348	15.7	22	0406	17.9
TU	1012	−0.8	W	1024	−2.6
	1642	14.8		1654	17.8
	2224	3.8		2254	0.4
8	0424	14.9	23	0500	16.5
W	1048	0.1	TH	1106	−1.0
	1718	14.7		1736	17.5
	2306	3.9		2348	0.7
9	0500	13.9	24	0554	14.8
TH	1124	1.1	F	1154	0.9
	1748	14.5		1824	16.9
	2348	3.9			
10	0548	12.9	25	0048	1.1
F	1200	2.3	SA	0654	13.2
	1824	14.4		1248	2.8
				1918	16.1
11	0042	3.9	26	0200	1.4
SA	0642	11.8	SU	0812	11.9
	1242	3.6		1348	4.5
	1906	14.2		2018	15.4
12	0148	3.7	27	0312	1.5
SU	0742	11.0	M	0942	11.4
	1330	4.7		1506	5.7
	1954	14.3		2130	14.9
13	0254	3.1	28	0424	1.1
M	0906	10.7	TU	1106	11.7
	1436	5.5		1624	5.9
	2054	14.5		2236	15.0
14	0400	2.0	29	0530	0.4
TU	1030	11.0	W	1212	12.5
	1548	5.8		1730	5.6
	2200	15.1		2336	15.4
15	0506	0.7	30	0618	−0.3
W	1142	11.9	TH	1300	13.3
	1700	5.4		1818	4.9
	2300	16.0			
			31	0030	15.9
			F	0700	−0.9
				1336	14.1
				1906	4.2

AUGUST

DAY	TIME H.M.	HT. FT.	DAY	TIME H.M.	HT. FT.
1	0112	16.3	16	0042	18.2
SA	0736	−1.4	SU	0712	−3.3
	1412	14.7		1342	16.7
	1942	3.5		1924	1.0
2	0148	16.6	17	0130	19.1
SU	0812	−1.7	M	0754	−3.9
	1442	15.2		1424	17.9
	2018	2.9		2012	−0.4
3	0218	16.7	18	0218	19.4
M	0842	−1.7	TU	0836	−3.9
	1506	15.6		1500	18.8
	2048	2.5		2054	−1.3
4	0254	16.5	19	0306	19.0
TU	0912	−1.4	W	0918	−3.2
	1536	15.8		1536	19.1
	2124	2.2		2142	−1.7
5	0324	16.0	20	0354	18.0
W	0942	−0.8	TH	0954	−1.8
	1600	15.8		1618	18.9
	2154	2.1		2230	−1.4
6	0400	15.3	21	0442	16.5
TH	1012	0.1	F	1036	0.0
	1630	15.7		1700	18.1
	2230	2.1		2318	−0.6
7	0430	14.4	22	0530	14.7
F	1042	1.3	SA	1118	2.0
	1654	15.4		1742	16.9
	2312	2.3			
8	0512	13.3	23	0012	0.5
SA	1112	2.6	SU	0630	12.9
	1730	15.1		1206	4.0
	2354	2.6		1836	15.6
9	0600	12.1	24	0124	1.6
SU	1148	3.9	M	0748	11.5
	1806	14.7		1312	5.8
				1942	14.4
10	0048	2.9	25	0242	2.2
M	0700	11.0	TU	0924	11.0
	1236	5.2		1442	6.8
	1900	14.4		2100	13.8
11	0206	2.9	26	0406	2.1
TU	0824	10.3	W	1100	11.5
	1348	6.3		1618	6.6
	2006	14.2		2224	13.9
12	0330	2.3	27	0512	1.4
W	1006	10.6	TH	1200	12.5
	1518	6.5		1718	5.8
	2124	14.6		2324	14.6
13	0442	1.0	28	0600	0.6
TH	1124	11.8	F	1236	13.6
	1636	5.8		1812	4.6
	2242	15.6			
14	0542	−0.6	29	0012	15.4
F	1218	13.4	SA	0642	−0.1
	1742	4.3		1312	14.5
	2348	16.9		1848	3.5
15	0630	−2.1	30	0054	16.1
SA	1300	15.1	SU	0712	−0.7
	1836	2.7		1342	15.4
				1924	2.5
			31	0130	16.5
			M	0742	−1.0
				1406	16.0
				1954	1.7

SEPTEMBER

DAY	TIME H.M.	HT. FT.	DAY	TIME H.M.	HT. FT.
1	0200	16.7	16	0206	19.1
TU	0812	−1.0	W	0812	2.4
	1430	16.5		1424	19.9
	2024	1.0		2036	−3.0
2	0230	16.6	17	0248	18.7
W	0836	−0.7	TH	0848	1.6
	1454	16.8		1506	19.9
	2054	0.6		2118	−3.1
3	0300	16.2	18	0336	17.7
TH	0906	0.0	F	0930	−0.2
	1518	16.8		1542	19.3
	2124	0.5		2206	−2.4
4	0336	15.6	19	0418	16.3
F	0936	0.9	SA	1006	1.6
	1542	16.6		1618	18.2
	2200	0.6		2248	−1.2
5	0406	14.7	20	0512	14.6
SA	1000	2.1	SU	1048	3.4
	1612	16.3		1706	16.7
	2236	0.9		2342	0.4
6	0442	13.6	21	0612	12.9
SU	1036	3.3	M	1136	5.2
	1642	15.8		1754	15.1
	2318	1.5			
7	0530	12.4	22	0048	1.9
M	1112	4.6	TU	0724	11.6
	1718	15.2		1242	6.7
				1900	13.7
8	0012	2.3	23	0206	2.9
TU	0630	11.2	W	0900	11.2
	1200	5.9		1418	7.4
	1818	14.4		2036	13.0
9	0130	2.8	24	0336	3.0
W	0806	10.6	TH	1030	11.9
	1318	6.9		1600	6.9
	1936	14.0		2206	13.2
10	0300	2.5	25	0442	2.4
TH	0948	11.1	F	1124	13.0
	1506	6.8		1706	5.6
	2112	14.2		2306	14.0
11	0418	1.3	26	0530	1.7
F	1100	12.7	SA	1200	14.1
	1630	5.5		1748	4.3
	2230	15.3		2354	14.9
12	0518	−0.2	27	0606	1.0
SA	1154	14.5	SU	1230	15.2
	1736	3.5		1824	[illegible]
	2336	16.8			
13	0606	−1.5	28	0030	15.6
SU	1236	16.4	M	0636	0.6
	1824	1.3		1300	16.1
				1854	1.7
14	0030	18.1	29	0106	16.2
M	0648	−2.4	TU	0706	0.3
	1312	18.0		1324	16.8
	1912	−0.6		1930	0.6
15	0118	18.9	30	0136	16.5
TU	0730	−2.7	W	0736	0.4
	1348	19.2		1348	17.3
	1954	−2.1		2000	−0.2

TIME MERIDIAN 120° W. 0000 IS MIDNIGHT. 1200 IS NOON.
HEIGHTS ARE RECKONED FROM THE DATUM OF SOUNDINGS ON CHARTS OF THE LOCALITY WHICH IS MEAN LOWER LOW WATER.

TABLE 2 Tidal Corrections, Juneau Area, Alaska. From *Tide Tables, High and Low Water Predictions, 1970, West Coast of North and South America,* U.S. Department of Commerce, Environmental Science Services Administration, Coast and Geodetic Survey, 1969.

No.	PLACE	POSITION Lat.	POSITION Long.	DIFFERENCES Time High water	DIFFERENCES Time Low water	DIFFERENCES Height High water	DIFFERENCES Height Low water	RANGES Mean	RANGES Diurnal	Mean Tide Level
		° ′ N.	° ′ W.	h. m.	h. m.	feet	feet	feet	feet	feet
	ALASKA–Continued			on SITKA, p. 118						
	Sumner Strait–Continued									
				Time meridian, 120° W.						
1421	Port Beauclerc, Kuiu Island	56 17	133 57	–0 08	–0 10	+1.9	–0.1	9.7	11.9	6.2
1422	Port Protection, Prince of Wales I	56 19	133 36	–0 07	–0 09	+2.4	0.0	10.1	12.4	6.4
1423	Reid Bay	56 23	133 53	–0 05	–0 17	+2.5	0.0	10.2	12.4	6.5
1424	Sumner Island	56 25	133 48	–0 13	–0 10	+2.6	0.0	10.3	12.6	6.6
				on KETCHIKAN, p. 110						
1425	Red Bay, Prince of Wales Island	56 18	133 19	+0 05	+0 08	–0.8	0.0	12.2	14.6	7.6
1427	Level Islands	56 28	133 06	+0 05	+0 05	–0.4	0.0	12.6	15.0	7.8
1429	Duncan Canal, Kupreanof Island	56 34	133 04	+0 17	+0 17	–0.2	–0.1	12.9	15.2	7.8
1431	St. John Harbor, Zarembo Island	56 26	132 57	+0 11	+0 06	–0.7	–0.2	12.5	14.6	7.0
1432	Greys Island	56 31	132 33	+0 08	+0 05	+0.2	0.0	13.2	15.6	8.1
	Wrangell Narrows									
1433	Point Lockwood, Woewodski Island	56 33	132 58	+0 22	+0 16	+0.2	+0.1	13.1	15.7	8.1
1435	Finger Point, Lindenberg Pen	56 41	132 57	+0 31	+0 42	+1.2	0.1	14.2	16.7	8.6
1436	Anchor Point	56 38	132 56	+0 22	+0 36	+0.6	0.0	13.6	16.0	8.3
1437	Petersburg	56 49	132 57	+0 11	+0 27	+0.3	–0.1	13.4	15.7	8.1
	Keku Strait									
1439	Monte Carlo Island	56 32	133 46	+0 04	+0 04	–2.8	–0.1	10.3	12.5	6.6
1441	Seclusion Harbor, Kuiu Island	56 33	133 52	+0 07	+0 03	–3.0	–0.2	10.2	12.3	6.4
1443	Beck Island	56 39	133 43	+0 10	+0 32	–1.6	0.1	11.5	13.8	7.1
1445	The Summit	56 41	133 44	+0 33	+0 38	+0.3	+0.1	13.2	15.7	8.2
1447	Entrance Island	56 49	133 47	+0 24	+0 32	–0.7	0.0	12.3	14.7	7.6
1449	Port Camden, Kuiu Island	56 44	133 55	+0 05	+0 05	–1.5	0.0	11.5	13.9	7.2
1450	Hamilton Bay, Kupreanof Island	56 55	133 50	+0 05	+0 05	–1.6	0.0	11.4	13.8	7.2
1451	Kake	56 58	133 56	+0 07	+0 13	–1.4	–0.1	11.7	14.0	7.3
	Frederick Sound			on JUNEAU, p. 114						
1452	Dry Strait	56 37	132 34	–0 19	–0 04	–0.3	0.0	13.5	16.1	8.3
1453	Cosmos Point	56 40	132 37	–0 20	–0 15	–0.7	0.0	13.1	15.6	8.1
1454	Ideal Cove, Mitkof Island	56 40	132 38	–0 10	–0 06	–0.3	0.0	13.5	16.1	8.3
1455	Brown Cove	56 53	132 48	–0 15	–0 11	–0.4	–0.1	13.5	15.8	8.2
1457	Thomas Bay	57 00	132 47	+0 06	+0 06	–0.9	–0.1	13.0	15.4	8.0
1459	Portage Bay, Kupreanof Island	57 00	133 19	–0 20	–0 16	–0.8	0.0	13.0	15.5	8.1
1461	Cleveland Passage, Whitney Island	57 13	133 30	–0 02	+0 02	–1.3	–0.1	12.6	15.0	7.8
1463	Pybus Bay, Admiralty Island	57 18	134 08	+0 02	–0 02	–2.0	–0.1	11.9	14.3	7.4
1465	Eliza Harbor, Liesnoi Island	57 10	134 17	–0 20	–0 20	–2.0	–0.1	11.9	14.3	7.4
1467	Saginaw Bay, Kuiu Island	56 54	134 18	–0 25	–0 22	–2.3	–0.1	11.6	14.0	7.3
	Stephens Passage									
1469	Port Haughton, Robert Islands	57 18	133 28	–0 22	–0 18	–0.9	–0.1	13.0	15.4	8.0
1471	Hobart Bay	57 24	133 25	–0 07	+0 02	–1.2	–0.1	12.7	15.1	7.8
1473	Good Island, Gambier Bay	57 29	133 54	–0 04	+0 03	–1.5	–0.1	12.4	14.8	7.7
1475	Windham Bay	57 33	133 30	–0 01	–0 01	–1.2	–0.1	12.7	15.1	7.8
1477	Rasp Ledge, Seymour Canal	57 41	134 02	+0 05	+0 04	–0.8	+0.1	12.9	15.6	8.2
1479	Windfall Harbor, Seymour Canal	57 52	134 16	+0 13	+0 17	–0.3	0.0	13.5	16.0	8.3
1481	Holkham Bay, Wood Spit	57 43	133 35	+0 02	+0 05	–0.9	–0.1	13.0	15.4	8.0
1483	Port Snettisham, Point Styleman	57 58	133 53	–0 13	–0 07	–0.5	–0.1	13.4	15.8	8.2
1485	Taku Harbor	58 04	134 01	+0 05	+0 02	–0.8	–0.1	13.1	15.5	8.0
1486	Greely Point, Taku Inlet	58 13	134 04	–0 02	–0 05	–0.7	–0.1	13.2	15.7	8.1
1487	Taku Point, Taku Inlet	58 24	134 01	+0 13	+0 12	+0.3	0.0	14.1	16.7	8.6
1489	JUNEAU	58 18	134 25	Daily predictions				13.8	16.4	8.5
1491	Fritz Cove, Douglas Island	58 19	134 36	–0 02	+0 04	–0.4	–0.1	13.5	15.9	8.2
1492	Auke Bay	58 23	134 39	–0 07	–0 04	–0.5	0.0	13.3	15.9	8.2
	Lynn Canal									
1493	Funter, Funter Bay	58 15	134 54	–0 01	0 00	–1.2	0.0	12.6	15.1	7.9
1495	Barlow Cove, Mansfield Peninsula	58 20	134 53	–0 14	–0 07	–1.2	–0.3	12.9	15.0	7.8
1497	William Henry Bay	58 43	135 14	+0 01	+0 08	–0.6	0.0	13.2	15.7	8.2
1499	Pyramid Harbor, Chilkat Inlet	59 11	135 28	–0 14	–0 13	–0.1	–0.2	13.9	16.3	8.3
1501	Haines, Chilkoot Inlet	59 14	135 26	–0 10	–0 07	+0.4	0.0	14.2	16.8	8.7
1503	Skagway, Taiya Inlet‡	59 27	135 19	0 00	+0 02	+0.3	0.0	14.1	16.7	8.7

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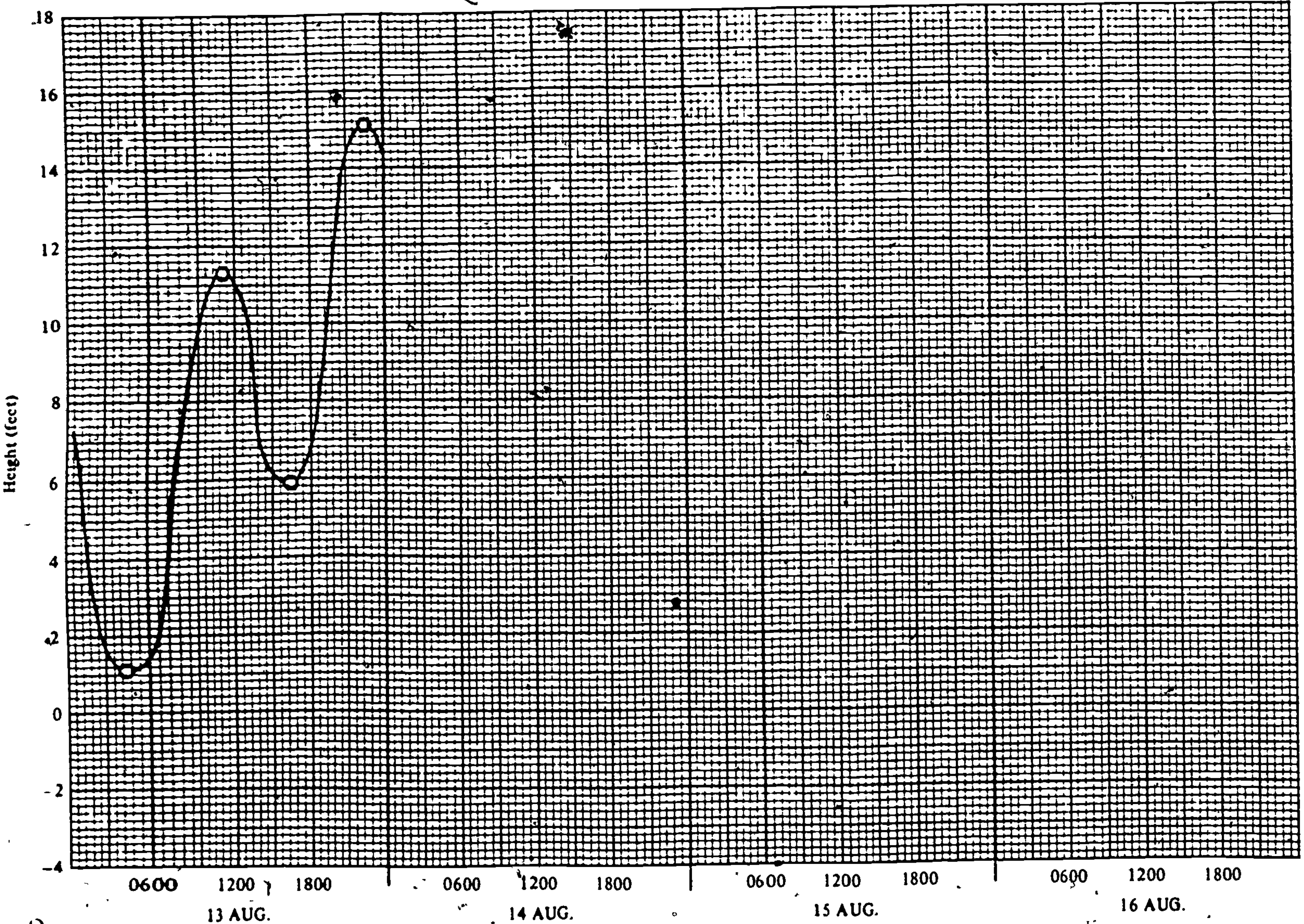


FIG 6 Sample tide curve for Auke Bay, Alaska, 13 to 16 August 1970 Complete, using data from Tables 1 and 2

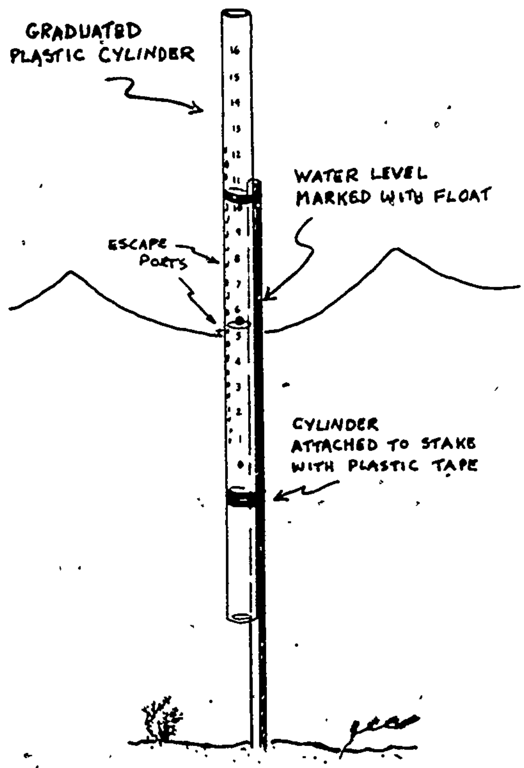


FIG. 7 Plastic-cylinder wave gauge. Escape ports are adjusted from experience to filter out noise response.

Study Suggestions

1. If you have not already done so, complete the curve in Figure 6.
2. Obtain local tide tables, and with them prepare tide-height curves similar to those in Figure 6 for three or four points in your general area. Compare these, and explain any significant differences.
3. Determine what types of tide predominate in your area, and identify the influence of the fortnightly cycle and, if convenient, the longer period tidal cycles. You can identify these by consulting Defant (1958).
4. What influence would extensive landfill operations within an estuary have upon the local tides?

Wave Determination and Analysis

Wave effects within sheltered estuaries are usually of minor importance. To develop waves of any real size, the wind must have the opportunity to work on the water surface for a considerable time and over a considerable distance. The only estuarine areas, then, where waves are likely to be significant are places exposed to waves coming in from the open sea. In these areas, there are likely to be considerable mixing of surface waters and longshore currents developing in the shallow water. Also, the energy of breaking waves is such that finer sediments are carried away and sand or gravel is left behind to form a beach.

One of the most important effects on waves in estuaries is refraction—the bending of wave crests in shallow water until they approximately parallel the shore. Sea-surface waves are a wave-form mechanism of energy transfer, like radio and light waves. As such, their behavior is governed by the medium in which they travel. In the case of sea-surface waves entering shallow water, the critical factor controlling their velocity is water depth. At depths less than one-half the wavelength L, the group velocity of a wave train C is related only to the water depth d and the acceleration of gravity g, according to the equation

$C = \sqrt{gd}$

At greater depths, the wave velocity can be calculated from

$$C = \sqrt{\frac{gL}{2\pi}}$$

where L is the crest-to-crest wavelength (see Fig. 8). These velocity relations are critical to wave refraction, for they account for the "bending" of wave fronts in shallow water. In effect, the waves are slowed in the shallower water and continue at normal speed in the deeper portions, causing the wave fronts to encircle points and to be bowed out where a submarine canyon heads near the shore (Fig. 9). When the waves come in at an angle on a straight coastline, this refraction effect causes them to actually come to shore nearly

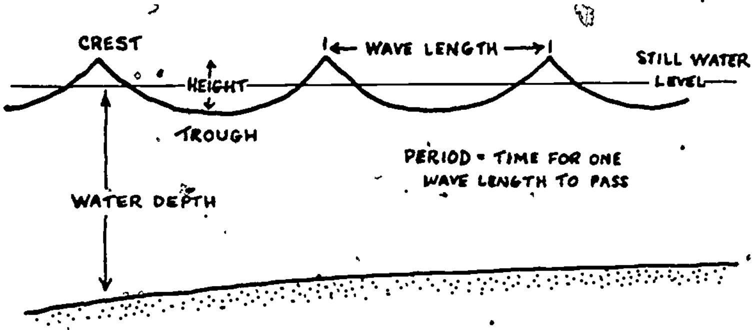


FIG. 8 Wave terminology.

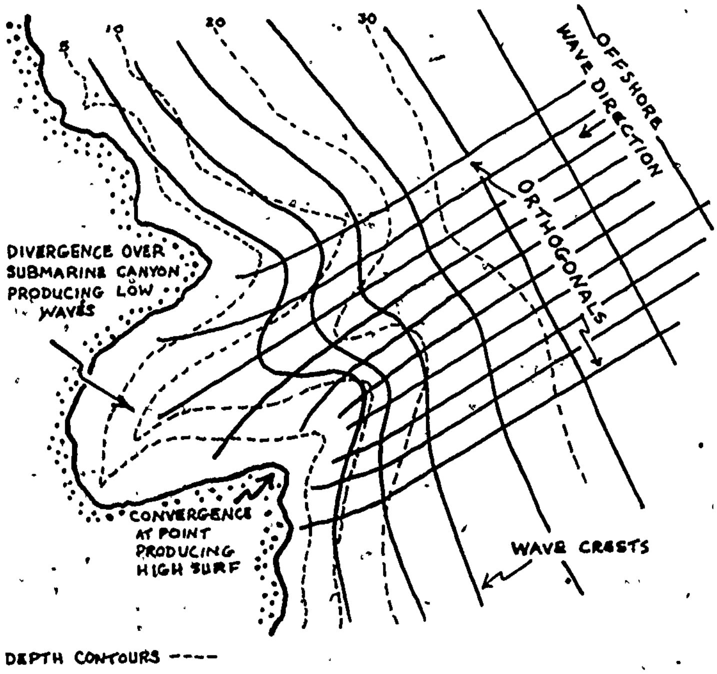


FIG. 9 Wave-refraction diagram showing the bending of wave crests due to sea-floor topography.

parallel to the beach, although they always have a slight residual component which will tend to move sediment along the shore. The actual amount of bending can be determined by applying Snell's law

$$\frac{\sin\alpha_2}{\sin\alpha_1} = \frac{C_2}{C_1}$$

where α_1 and α_2 are angles between wave-front positions and the adjacent bottom contours (see Fig 10).

On a chart showing wave-refraction patterns, it is often useful to construct *orthogonals* - lines normal to the wave crests (Fig. 9), which are analogous to light rays in the theory of geometrical optics The orthogonals can be taken to represent the direction in which wave energy is transmitted, and their spacing is proportional to the wave energy available. Thus, in places where orthogonals converge, there is greater energy (resulting in higher waves), while where they diverge, less energy reaches the shore.

Experienced surfers learn intuitively to take full advantage of the phenomenon of wave refraction, and oceanographers can use their understanding to predict the areas of maximum or minimum wave attack. Also, the influence of proposed interruptions in the sea-bottom topography due to dredging, breakwater construction, or landfill can be assessed. In practice, you must draw a separate refraction diagram for each major direction of wave attack, using appropriate-sized waves. The absolute magnitude of the wave influence on shore, then, is a function of the magnitude and frequency of a given sort of wave train.

The wave parameters of particular importance to us are their period, their length, and the angle of incidence of the wave fronts on the shore. Field observations are complicated by the fact that we rarely see only a single set of waves. Normally, several major wave trains with different characteristics interfere with or reinforce one another. This is why surf-riding tradition holds that every seventh or ninth wave is larger. There is nothing magic about the number, of course. In effect, that "larger" wave represents the cumulative effect of the various wave trains present. When graphed, the data in Figure 11 reveal two sets of waves with very different periods. To distinguish the various components of the waves at a study site, one must record every significant wave crest and trough over an appreciable time period - at least 3 to 5 minutes. In Figure 11, it is left to you to plot the water-level data and then connect the points with a smooth curve; this should enable you to distinguish the two sets of waves.

As with tides, there are many automated and expensive devices for recording waves of various sorts, but a simple graduated staff is adequate, and tide and wave observations can often be made simultaneously from the same staff. For wave measurements, the staff should be installed in water somewhat deeper than the extreme low-tide level. This position should definitely be seaward of any regularly breaking waves. At convenient intervals during the time of an estuarine study, a team should occupy the wave-observation station and record the height and time of 100 consecutive waves. If possible, it is also good to record the

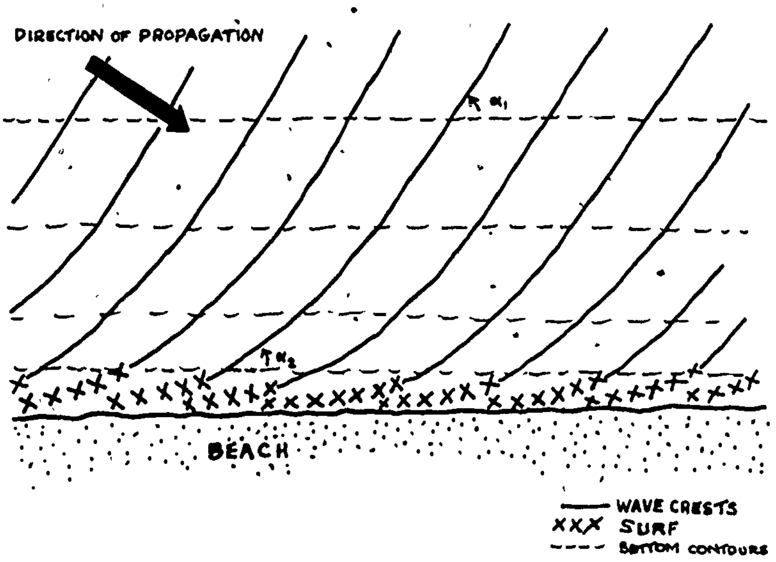
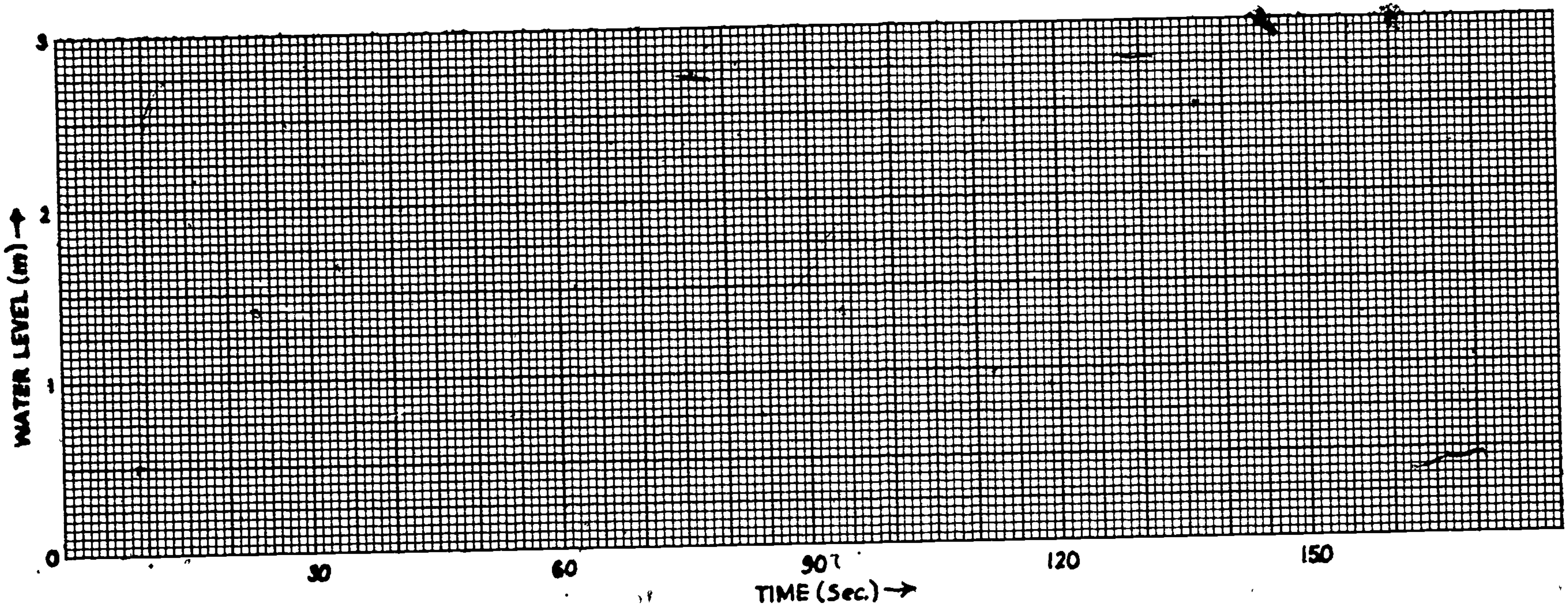


FIG. 10 Wave refraction on a straight shoreline.



OBSERVATIONS:

TIME (Sec.)	HEIGHT (m)
05	1.9
13	1.6
22	2.2
30	1.6
37	1.9
45	1.2
52	1.5
~~02~~ 62	0.9
~~11~~ 71	2.0
~~19~~ 79	1.2
~~28~~ 88	1.9
~~35~~ 95	1.5
~~46~~ 106	2.2
~~57~~ 117	1.4

T	H
~~04~~ 124	1.7
~~14~~ 134	0.9
~~25~~ 143	1.2
~~30~~ 150	1.0
~~40~~ 160	1.6
~~47~~ 167	1.4
~~58~~ 178	2.3

WATER DEPTH AT OBSERVATION POINT = 5 m

FIG. 11 Unplotted wave record. Plot the water-level data; then connect the points with a smooth curve. You should be able to distinguish two sets of waves.

angle of incidence of the wave fronts as they approach the shore. These must be observed some distance offshore because of the refraction they may undergo in shallow nearshore waters.

A team of at least three is required to make wave observations by this technique. One person, with binoculars if necessary, must watch the wave staff and call out water levels to the nearest tenth of a meter. At the same time, another observer with a good, sweep-second-hand watch or a stopwatch must report the time of each observation in seconds. The recorder must note the data carefully and keep track of the count. It will take some practice before useful data can be obtained with this technique, and in particular you must learn to ignore the *noise* produced by the small waves. These are usually of local origin and rather chaotic, they contribute little to mixing or transport phenomena in the estuary, but they can make observation difficult.

When the data have been collected for a station, graph the results as water level against time, and select the more important wave trains. From the graph, you can determine the period T in seconds for the waves and then calculate the wavelength L from the relationship

$$L = \frac{C}{T}$$

where C, the velocity of the wave train, is given by

$$C = \sqrt{gd}$$

Average water depth at the observation point is d, and g is the acceleration of gravity. The wavelength may then be used to determine the depth to which water mixing due to wave motion is an important factor in the estuarine or oceanic circulation. This thickness of water is approximately equal to L/2.

Direction and intensity of longshore water drift due to waves can be most easily observed by using a neutrally buoyant float that can be tracked along the shore. One of the most satisfactory floats of this sort is an overripe orange or grapefruit. It is easily seen and followed from the shore, and its density is very close to that of sea water. Routinely, if there is longshore movement, the drift of such a float should be timed for a measured distance along the beach—ideally at least 50 meters. If the float is rapidly washed ashore and stranded or remains at one place, the longshore wave-induced current can be regarded as negligible.

Study Suggestions

1. If you have not done so, plot the wave record on Figure 11. Identify the two principal wave sets by their periods, and calculate the wavelength and the depth at which these waves would begin to be refracted. These waves are already in "shallow" water.
2. On charts of your own area, identify the sections of shoreline most likely to be subject to wave attack.
3. For one section of your coastline, construct a wave-refraction diagram either using local data or assuming a direction of propagation from the most open side and a period of 10 seconds. Identify areas of erosion or deposition of sediment.
4. On the same section of shoreline, introduce a mile-long breakwater normal to the shore, and construct a new refraction diagram. Where will the sites of erosion and deposition now lie?

Current Measurement

Currents are certainly the most important physical processes at work in estuaries. They exist in three dimensions throughout the entire system and are produced by several factors. The flood and ebb of the tides usually produce the greatest currents, but there is often a residual gravity-driven flow of river or stream water, and wave- or wind-driven currents may have considerable local influence. Currents often change both velocity and direction with depth, and it is by no means uncommon to find surface water flowing out of the estuary while deep-sea water flows in.

Of the two basic approaches to current measurement, one is passive (measuring the current flowing past your point of observation), while the other is active (putting something into the water and following its trajectory). Often, both approaches must be used to gain a comprehensive view of estuarine circulation.

A trajectory study of water circulation is mechanically very simple to conduct. All that is necessary is something distinctive that will travel with the current and can be observed along its route or at its final destination (Fig 12) A familiar example of this approach is the traditional note in a bottle produced by shipwrecked (or bored) sailors For an integrated record of average surface currents away from a given location, the drift-bottle or drift-card technique is quite useful. This is fundamentally the technique suggested earlier for observing currents in the alongshore drift area of beaches The greatest problem with the technique is the uncertainty of recovery. To get any information you must use many bottles and must trust to casual fishermen or beachcombers for their return. Since the technique depends on recovery at the shore, it can only be used for surface currents

In practice, a considerable number of bottles must be obtained and should be rather distinctive--perhaps painted brightly so that people will notice them. Inside the bottle, place a return questionnaire postcard (Fig 13) and enough sand or other weight so that the bottle floats with only its top above water. Cork or seal the bottle securely. A modern variation of this technique employs plastic bags or envelopes instead of bottles. These have the advantages of light weight and portability, and they eliminate broken glass on the shore Experiment with freezer bags to develop a good weighting and sealing technique The heavier polyethylene bags used for freezer storage usually prove most satisfactory. The cards should float at the surface but should expose as little area as possible to catch the wind. A few small washers usually provide enough weight, and sealing with a moderately hot household iron is usually satisfactory Each card in such a drift survey should be numbered, and the numbers and locality recorded when you release them. On recovery, map time and place of release and recovery to show an average surface drift pattern and rate

A somewhat different approach may be used in the trajectory system. Instead of leaving recovery entirely to chance, you may choose to follow directly the movements of a float of some sort Such a float is called a *drogue* and may be used to study either surface circulation or currents at depth For surface-water movements, you can use any sort of convenient float, weighted like the drift bottles to float at the surface The drift can illustrated in Figure 12 is a sealed 1-gallon gasoline tin. To mark the drogue, attach a mast and an easily spotted flag Since you want to minimize wind effects, one of the most practical marking systems is a wire mast, made from a straightened coat hanger or wire of similar gauge, with a flag of light-weight material painted with a bright UV fluorescent paint such as Day-glo orange or red To measure currents at depth by this technique. build a simple current cross of plywood, weight it with an old sash weight or a similar object, and suspend it from a small float at the depth you wish to monitor A typical current cross might be a half meter square. The float and suspending line should be as small and streamlined as possible to reduce drag. Since the surface area of the cross is much greater than that of the suspension system, this sort of drogue will move with the deep currents. Normally, drogues are released at slack water at critical points within the estuary and their movements checked periodically by sextant angles or compass bearings Routinely, several floats will be set from one site to trace currents at various depths simultaneously The drogues should be numbered so that you can identify individual paths.

To gauge currents directly, there are two techniques that do not require expensive equipment Both must be used from a fixed platform–either a pier or an anchored vessel. The current-pole method is an adaptation of the old chip-log system of measuring ships' speed, and it is still used by the Coast and

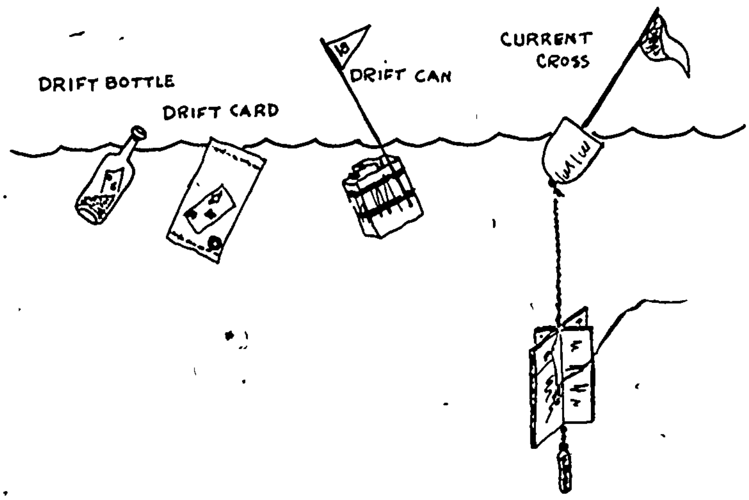


FIG. 12 ' Types of free-trajectory current-measuring devices.

ATTENTION! No.__________

This drift card has been released as a part of a study of water circulation. Please answer the questions and drop this card in the mail. If you provide a return address (on the other side) you will be sent the time and place of release.

THANK YOU!

DATE AND TIME FOUND__________

PLACE FOUND (be specific)__________

ANY SPECIAL CIRCUMSTANCES?__________

Name:

Address:

STAMP

Environmental Science Study Group
Department of Geological Sciences
Kenai Peninsula Community College
P. O. Box 3961
Soldatna, Alaska 99426 U.S.A.

FIG. 13 Sample drift card.

Geodetic Survey. The other technique, developed recently by John Foerster, measures the amount of deflection of a biplane drogue similar to the current cross.

The standard current pole used by the Coast and Geodetic Survey is about 15 feet long and is weighted to float upright with only a foot showing above the surface. It is attached to several hundred feet of light buoyant line of the type that is readily available from marine-hardware stores. In practice, the pole is released and allowed to drift far enough to be beyond the effects of any local turbulence caused by the boat or pier. Then the line is marked, and the pole is permitted to drift freely for a convenient time interval. When the pole is recovered, the amount of line carried out is measured. For a 1-minute interval, a distance of 6080/60, or 101.3, feet represents a current velocity of 1 knot. If you are working in the metric system, the calculation is even simpler; usual units are meters per second. Subsurface currents may be measured using this device like the drogue and float of the current-cross system. The direction of the current is determined by taking a compass bearing on the current pole at the end of its movement.

The Foerster technique eliminates the need for handling masses of line and is particularly well-adapted for use from a small anchored boat. Like the current cross, this technique also employs a biplane, but it is weighted and suspended from a measuring board equipped with a level bubble (such as a plumber's level) and graduated in a protractorlike arc (Figs. 15 and 16). The biplane is lowered to the appropriate depth for the measurement, the board is carefully leveled, and the angle of deflection produced by the current is read (Fig. 16). However, you must be sure your boat is not swinging at anchor when you measure the deflection angle.

The angle of deflection θ of the biplane drogue is related to the current velocity V, expressed in English units (feet per second), by the expression

$$V = 0.92\sqrt{\frac{W \tan\theta}{A}}$$

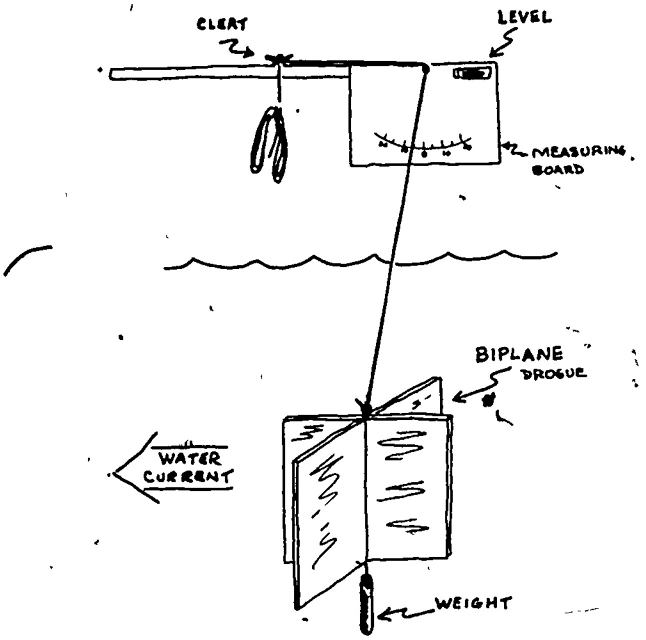


FIG. 14 Biplane current meter.

FIG. 15 Deploying a biplane current drogue from an anchored ship. The sash weight attached below the biplane keeps the unit vertical.

FIG. 16 Taking current measurements with a biplane drogue. A carpenter's level is mounted on the handle next to the measuring board. A water-sampling bottle and extra biplane are stowed in the bows.

where W is the weight in water of the biplane (in pounds) and A is the exposed area of one "wing" of the biplane (in square feet). Values of V can be converted to knots by multiplying by 0.59, or to meters per second by multiplying by 0.305. For a given size and mass of biplane, tables or graphs of current speed as a function of deflection angle can be prepared for use in the field. Weight in water is most easily measured with a fisherman's scale when the apparatus is in the field. The biplane drogue has proved remarkably effective in use, and it permits rapid, inexpensive determination of current profiles. A convenient version can be made from two sheets of plywood each roughly 10 X 20 centimeters, weighted with steel angle iron. The size and weight of the biplane can be varied to suit the study, larger surface areas will produce a device more sensitive to gentle currents but more awkward to handle on a small boat.

Water Sampling

Adequate water samples for analysis are not easy to obtain. At the surface, a clean bucket will serve, but the collection of uncontaminated samples from known depths can be quite difficult. Even sending a diver down with sterile bottles is not ideal, for his presence may disturb the waters, or his technique may produce contamination. Ideally, for estuarine work we need samples of water from the surface, the bottom, and a number of points between. Usually, 1 or 2 liters is an adequate volume for simple chemical or biological analyses and for determining the physical characteristics of the water column. Although perhaps obvious, it bears repeating. It is very important to know the precise depth of sampling and to be sure that your sample is being recovered unmixed with waters from above or below, for oceanographic studies in particular we must determine the temperature and salinity of the water at known depths.

In standard oceanographic work at sea, the *Nansen bottle* is used. This is actually a precision instrument machined of brass and designed to be lowered open to a predetermined depth, where it is closed by a messenger weight sliding down the wire. Special thermometers attached to the bottles register the temperature at sampling depth. The salinity is measured by chemical or electrical techniques on the water sample recovered These instruments are expensive to use in terms of both money and time, and they tend as well to be very clumsy for small-boat operations in estuaries.

A simple water sampler that is cheap to build and perfectly adequate for shallow-water operations is shown in Figures 17 and 18. This water bottle is made from a section of 3-inch internal-diameter tubing (preferably clear, as shown, but opaque PVC can be used) and two rubber balls or the ends of plumber's helpers that are large enough to serve as plugs. In the example figured, the cups from plumber's helpers have small steel eyes screwed into their tops and bottoms, and they are rigged as shown. A piece of rubber surgical tubing, obtainable from any pharmacy, or shock cord is attached to the handle side of the plugs, and loops of light, sturdy line are attached to the eyes on the cup side. The length of surgical tubing, which is run through the plastic tube, is adjusted so that the plugs are firmly seated in each end of the cylinder. Then the lengths of the loops are arranged to hold the bottle open held, as shown in the figure, by a light toggle When sampling, the bottle is attached to a piece of line (nylon parachute cord is convenient) above a weight. The cocked bottle is lowered to the predetermined depth, and the trigger line is jerked sharply to withdraw the toggle and collect the sample. A certain amount of experimentation is necessary to develop a reliable toggle, we use a smoothly sanded wooden peg. Usually, you can feel a bump on the line when the bottle samples successfully. The bottle is attached to the sampling line with several turns of black plastic electrical tape—one of the true necessities of modern oceanography.

With the water sampler, you can collect reliably to depths as great as 100 feet, but with increased depth, there is more opportunity for malfunction. Fortunately, in most estuarine work you are concerned largely with the shallow waters. Ideally, one should take a number of samples simultaneously, but this has not proved convenient with this apparatus. A number of bottles can be lowered serially, but triggering these is very awkward if you use individual trigger lines and almost impossible if you try to use one trigger line. Instead, it is usually easier and quicker to anchor and take a number of samples successively at the station, using a single bottle and set of line.

An improved model of the basic water sampler can be triggered remotely by a messenger weight, eliminating the need for multiple lines from the surface (Figs. 19 and 20) The messenger is a shackle or carabiner weighted with a lead sinker that can be slipped down the main line when the bottle is at sampling depth. The messenger pulls the trigger line taut, extracting the cotter pin and thereby activating the sampler. Simultaneous multiple water samples can be collected using this version of the bottle. Messengers are looped on the main line beneath each sample bottle and are attached to the lower plumber's helper with light string in such a way that they come free when the bottle is triggered. Each messenger then triggers the bottle beneath it Usually, you feel the thumps of the successive bottles functioning and tell if there is a malfunction When this occurs, a violent jerk on the line often releases the messengers, and sampling proceeds.

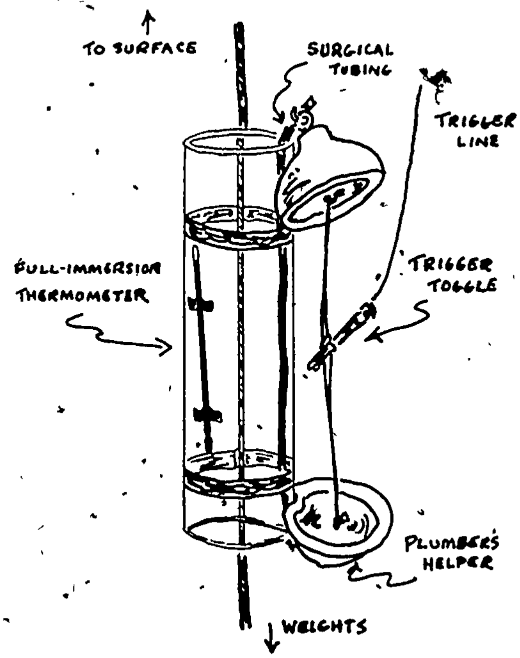


FIG. 17 Surface-actuated water-sampling bottle.

FIG. 18 Close-up of a water sampler. A full-immersion thermometer is taped to the inside of the tube.

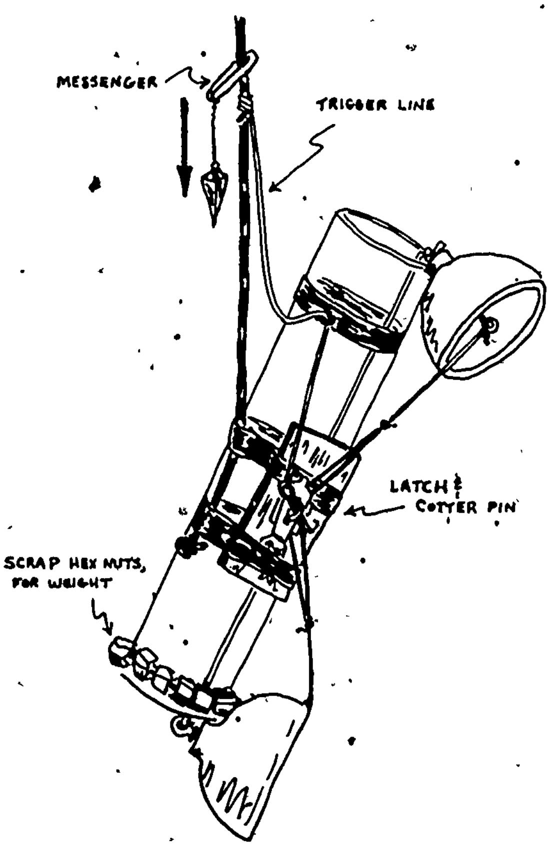


FIG. 19 Remotely triggered water bottle.

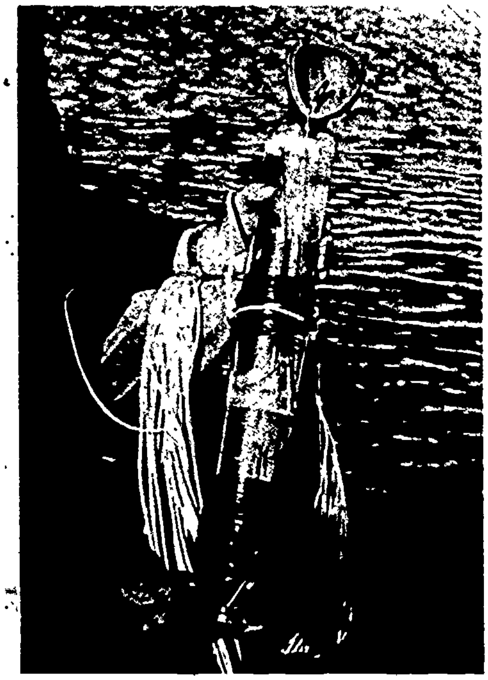


FIG. 20 Rigged water-sampling bottle—messenger-triggered model.

A very simple but often satisfactory water sampler for shallow depths is the *Meyer bottle*. Take a half- or quarter-liter bottle with a ground-glass stopper, and attach it with plastic tape to your sampling line just above a moderately heavy weight. Above the bottle, leave a slack loop of sampling line, then half hitch the line to the stopper. In use, the Meyer bottle is lowered empty with its stopper in place to the desired sampling depth, then the line is jerked to unseat the stopper. The bottle fills with water and is raised to the surface. There should be little exchange of water during rapid recovery, and the sample will be representative of the desired depth. Such bottles are particularly useful where a rapid succession of samples in very shallow water is desired. At depths greater than 10 to 15 meters, it becomes difficult to be certain that the bottle has functioned correctly.

Samples of water close to the bottom are often desirable, and a variation of the basic water bottle has been developed to collect them (Figs. 21 to 23). A small rectangle of plywood is firmly attached to the bottle with plastic tape. On this plywood frame are two guides for the trigger and a metal trigger rod with a hook on one end, a shoe to contact the bottom on the other. The loops from the bottle plugs are secured as shown in the sketch, retained by the hook that bears on a small shelf attached to the frame. A piece of old pipe on the trigger rod adds enough weight to prevent accidental activation. In practice, this apparatus is quick and easy to use, and the sampling depth above the bottom can be adjusted by the length of the trigger rod. A large plywood or metal plate mounted as a shoe on the trigger is often useful to ensure proper operation on soft bottoms; it should be perforated to reduce drag in the water.

Water Analysis

The most critical water data in estuarine studies are temperature and salinity, but tests for other attributes such as dissolved oxygen, bacteria, and nutrients may also be desirable. Many complex techniques have been developed to determine these parameters, but in estuaries where water characteristics change drastically, relatively unsophisticated and inexpensive procedures can be followed.

For temperature, a full-immersion thermometer is attached (with the ubiquitous vinyl tape) to the inside of the sampling cylinder as shown in Figure 18. Before triggering the sampler, allow a moment for the thermometer to equilibrate. Then bring up the bottle, and immediately read the thermometer. Ideally, it should read in tenths of degrees from +20 to −5°C. Some error is introduced because hydrostatic

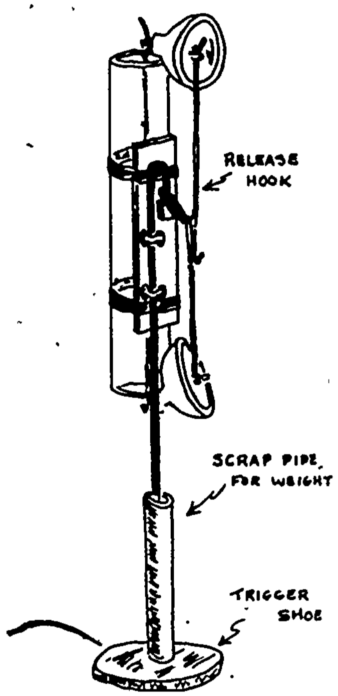


FIG. 21 Bottom-water sampler.

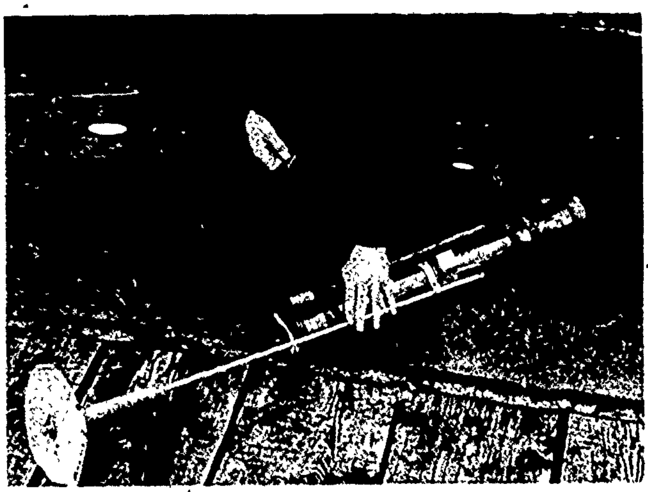


FIG. 22 Rigging the bottom-water sampler. The round shoe hitting the bottom triggers the apparatus. Pieces of scrap pipe are attached to increase the reliability of operation in currents.

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FIG. 23 Lowering the bottom-water sampler from a small boat. (Kneeling on the rail is not a recommended technique when working in rough waters.)

compression of the glass of the thermometer produces a slightly high reading, in estuarine work this can be neglected. Salinity – dissolved salts in the water – is most conveniently measured by its influence on density. Inexpensive sets of hydrometers, calibrated to measure salinity, are available from most scientific supply houses. They may be used in the field (see frontispiece), or with more precision in the laboratory if the samples can be stored and carried back.

The dissolved-oxygen (DO) content of the water is also important, particularly in studies related to pollution. If you are going to run DOs, the subsample for the DO should be drawn from the bottle first, being careful to avoid bubbling through the water. For this purpose, it is useful to pierce the sampler and attach a small plastic stopcock or a drain tube to which surgical rubber tubing can be fitted. (Note the base of the bottle in Figure 20.) To draw DO samples, put the end of the tubing in the bottom of the sample bottle, release the drain valve, and gently ease up the upper seal on the water sampler, permitting water to drain gradually, without turbulence, into the subsample bottle. Measurement of DO is by the relatively straightforward Winkler procedure, which is described in standard water-analysis manuals, such as Renn (1970) or Strickland and Parsons (1965).

Once temperature and salinity have been determined, water samples are available for further analysis. In a study of sewage pollution, for example, a fraction of each water sample should be plated and cultured for colon bacteria. The quantities of dissolved oxygen and various nutrient compounds (phosphate, nitrates, and the like) can also be determined if facilities are available. Be sure to conduct any additional testing quickly, though, for the character of stored water changes rapidly as the inevitably included bacteria flourish.

Tracer and Diffusion Studies

A very flexible technique for evaluating currents and mixing effects in a limited area, such as a bay or lake, utilizes a tracer dye. The dye is released at the particular point of interest, and its direction and rate of dispersal are monitored. One of the best tracer substances is the organic dye rhodamine-B—a nontoxic, extremely water-soluble, purple material that is very strongly fluorescent under ultraviolet light. From the visible light produced under UV excitation, highly diluted rhodamine-B can be readily detected in fresh or salt water; it is still recognizable even at concentrations in the parts-per-billion range. Other dyes available include those in surplus air-sea-rescue dye-marker packets which comprise various substances – including rhodamine-B. If such dyes are available, experiment with them.

Equipment required for a tracer survey is quite simple. Besides the small workboat, charts, and navigation gear, you need only a supply of dye, a small battery-powered ultraviolet lamp (the prospector's type in long-wave UV is preferred), a set of reference standards for different dye concentrations, and a small lightproof working space, such as a large photographic film-changing bag. Before your survey, make up a series of standard-concentration bottles of the tracer dye in natural water from the working area. A convenient dilution scale is logarithmic, with a series of bottles running from one part per hundred to one part per billion, by weight. Use small, easily sealed bottles such as plastic pill vials, but make certain the vials are not already UV-fluorescent. Mount the standards in a frame small enough to fit (together with your head and hands) into your improvised darkroom.

To conduct a tracer survey, first carefully select the point in the estuary or lake from which you want to measure dispersal, and then select appropriate tide and weather conditions. Mix several kilograms of dye with water—preferably water of the same temperature and salinity as that of the effluent or other feature in which you are interested. Then introduce the dye, either at the surface directly from your skiff or at depth by a diver if you are studying deep circulation. Next, start to cruise a regular grid around the dispersal point, trying not to artificially spread the dye with your own wake, and carefully record the time and position for each sample you collect. Surface samples can be taken with a bucket, subsurface most rapidly with a simple sampler such as the Meyer bottle. As samples are collected, a fraction of each should be put in a vial similar to those in your reference-standard set, and with his head in the "darkroom" the observer can immediately estimate the order-of-magnitude dye concentration in the sample. Mark this information on your working chart together with position and time. As the survey continues, extend your sampling grid progressively farther and farther in the direction of dispersal as shown by the higher fluorescence, until you reach such low levels of concentration that reasonable estimates cannot be made.

Back in the laboratory, the data from the tracer survey should be posted as a time series of charts, showing direction and rate of dispersal at some convenient interval. Ideally, current measurements will be made at the same time by drogue or current cross; this information should also appear on your charts. The time series of charts showing the movements of your dye plume should now provide an excellent semiquantitative picture of water or effluent movement under the ambient conditions. To do a comprehensive job, the survey should be repeated under the various weather and tide conditions most typical of your study area. These studies are particularly useful in predicting the areas likely to be influenced by discharge from a projected sewage or industrial outfall.

MIXING AND FLUSHING IN ESTUARIES

General Considerations

A most critical and poorly understood aspect of estuarine oceanography is the problem of mixing and flushing rates. Clearly, understanding the residence time of the water and any introduced sediment or pollutant is essential to any serious consideration of the circulation. The variables that may be considered in estuarine mixing are formidable—basin geometry, tidal volumes and periodicity, runoff volumes, the relative physical and chemical characteristics of the fresh water and sea water in the system, the behavior of the pollutant, and many others. Also, the physical mechanisms of mass-transport diffusion and mixing in such fluid systems are really not well understood. Two basic approaches to mixing and flushing studies have been tried, one depending on theoretical considerations and model studies, the other derived empirically from field observations. Neither approach has proved completely satisfactory. The theoretical studies suffer from the diversity of variables and the scale-factor problem—a true-scale laboratory-model estuary simply will not run properly if for no other reason than that you cannot alter the viscosity of the medium to match the size reduction; therefore, models are like a light post to a drunken man—more for support than illumination. On the other hand, the empirical studies are always hampered by the scarcity of observation points, both geographic and temporal; often in such studies you cannot observe the situation long enough to evaluate completely even the noise level of your measurements, to say nothing of such critical estuarine influences as the occasional but catastrophic storms that hit most coasts. The consequences of these problems in the evaluation of estuarine mixing processes are widespread confusion and frustration, particularly among those who must make serious economic and sociologic decisions about pollution problems. Essentially, they demand to know—at least by order of magnitude (hours, days, weeks, and so forth)—the fundamental housekeeping datum: "How long does it take to sweep the refuse under the carpet?" Oceanographers and engineers have rarely been able to answer this question.

Throughout our discussions of estuarine processes, we have generally avoided considering seriously anything but the simple physical processes of water movement. We have scrupulously omitted the many biological and chemical complications simply because they add so to the complexity of problems that we already find overpowering. In this section, we will continue this approach and limit our considerations to the simplest and most direct techniques, knowing full well that we can only produce crude approximations of reality. Technologically and mathematically more sophisticated procedures are available for reaching similar conclusions, but at the present state-of-the-art, the simple procedures are as likely to produce satisfactory results as the most refined techniques.

Estuary-Volume Estimation

In all considerations of estuarine mixing and flushing, an essential bit of input data is the volume of water involved. In effect, this is the volume of a very irregular geometric figure—the estuary itself—and to obtain a value you must determine and then sum the volumes of the basin segments enclosed within the bathymetric contours on the best available chart of the estuary. These contours (*isobaths*) represent the intersection of the bottom topography with plane surfaces parallel to some arbitrary datum, and because they are often extremely irregular, it may be difficult to compute the areas of the segments they circumscribe. Routinely, an expensive precision instrument known as a *planimeter* is used to mechanically integrate these areas, but simple techniques can provide useful approximations.

The simplest system for estimating the area of an irregular plane figure is counting squares. The figure is ruled off into a convenient-sized grid or traced onto graph paper, and the complete squares and fractions of squares are summed and then converted to true area using the map scale. The figure can also be traced onto top-grade heavy paper, which is then carefully cut out and weighed on a precision balance. Its weight, compared with the weight of a known area cut from the same paper, also provides a quick approximation of area.

The most accurate inexpensive technique for measuring irregular areas uses a simple tool known as a *hatchet planimeter*, which can be made from a length of heavy, stiff wire, such as a coat hanger, reformed as shown in Figure 24. The legs *AB* and *CD* should be identical in length—from 5 to 10 centimeters. However, the arm *BC* can be any convenient length, for most map work an overall length of 30 to 50 centimeters is adequate. End *A* should be sharpened to a fairly fine but rounded point. The other end *D* must be hammered flat and filed to a sharp blade which should be oriented parallel to *BC*, as shown in the sketch. End *D* is the "hatchet" of the tool's name. When fabrication is completed, be sure that *AB* and *CD* are still the same length.

To measure an irregular area with the hatchet planimeter, draw a line tangent to the figure at any convenient point—a line long enough so that the planimeter can be positioned with point *A* at the point of tangency and blade *D* lying on the line. Then, holding end *A* like a pen, trace lightly around the figure, letting the hatchet blade slide freely around the paper. The hatchet should either move freely only parallel

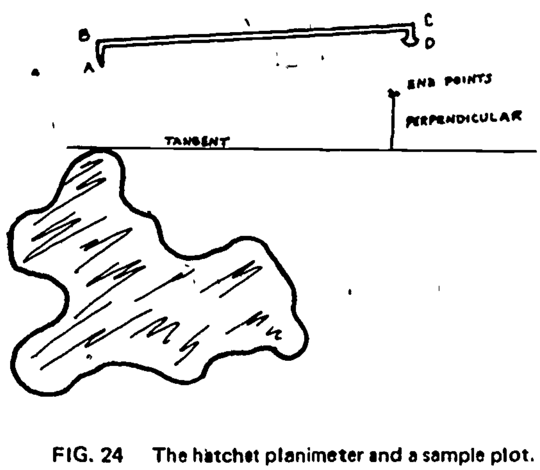

FIG. 24 The hatchet planimeter and a sample plot.

to its edge or act as a pivot, if it drags sideways, there is usually an odd noise, and the results are spurious After you have traced all the way around the figure to your starting point, mark the final position of the center of the hatchet blade. Repeat the process two or three times until you have a tight grouping of endpoint marks. Erect a perpendicular to the original line of tangency through the averaged endpoint position, and measure the length of this perpendicular at map scale. This value multiplied by the length of BC, also at map scale, provides a close approximation of the area of the irregular figure. The technique is limited by the length of BC, for areas larger than $(BC)^2$ cannot be handled. Larger areas can be determined either by making and using a planimeter with a longer arm or by subdividing. The proof of this procedure is quite esoteric, but you can satisfy yourself of its utility by measuring and calculating the area of a figure whose true area is already known.

To determine the volume of an estuary, you may follow the simple procedure of guessing its average depth and multiplying that figure by its area, or you may calculate the volume more precisely, as follows

1 With your bathymetric chart and planimeter, measure the areas enclosed by each isobath
2 For each depth zone (the vertical distance between isobaths), add the areas enclosed by adjacent isobaths, and divide by 2 to determine the average area enclosed in that zone.
3 Multiply the average area of each depth zone by the isobath interval to determine the volume of the zone.
4 Sum the volumes thus derived, making appropriate corrections for tidal complications and the incomplete deepest interval.

Calculation of Estuarine Flushing

A very simple crude approximation of estuarine flushing time can be made if you assume that there is complete mixing and that all water entering with a rising tide mixes with the water already present and exits completely on the next falling tide. In units of tidal cycles, the expression for flushing time F is

$$F = \frac{L + H}{H}$$

where L is the low-tide basin volume and H is the volume at high tide. The value for flushing time thus determined is a minimum figure; actual times are likely to be many times greater. The U.S. Navy Hydrographic Office has developed a considerably more rational procedure to estimate flushing time in estuaries. Based on the assumption that the net mass transport of estuarine waters is controlled by tidal fluctuations and river input, this procedure is designed specifically to estimate the rate at which an inert pollutant would be dispersed from a estuary. It requires an understanding of the thermohaline stratification in the estuary and knowledge of the runoff entering at its head. The technique can be adapted also to accommodate the often, seasonal condition of reduced or absent river runoff. The remainder of this discussion is based on the Hydrographic Office technique, for detailed discussion and derivation of terms you must go to the original reference (Gibson, 1959).

The first step in this procedure is to examine the thermohaline stratification of the estuary. In most estuaries, there are two active layers, as illustrated in Figure 25: a surface layer of mixed river water and sea water A and a deeper layer of unmixed sea water B. (If a sill is present, a third layer of relatively stagnant water may exist which this procedure ignores.) As discussed earlier, net circulation is such that there tends to be an overall inflow from the sea into the estuary at depth and an outflow at the surface. This procedure proceeds from the fundamental assumption that any pollutant introduced into an estuary will rapidly mix with the deeper waters, will be mixed upward gradually, and will exit with the surface waters. Such behavior is typical of salinity, at least, in estuaries; the salt water mixes upward, but the fresh does not dilute downward because of the density gradient. The two layers are separated by a "surface of no motion" corresponding to the pycnocline. Over relatively long periods of time, the volumes in the two layers should be relatively constant despite daily variation in tidal or river influences.

When the position of the boundary between the layers is established, the mean volume in the two layers must be calculated. Next, one must calculate the net volume transport in the two layers. The net input in layer B (Q_B) represents the new sea water introduced in each tidal cycle (that is, the tidal prism). The net outflow in the surface layer Q_A can then be expressed as

$$Q_A = Q_B + R$$

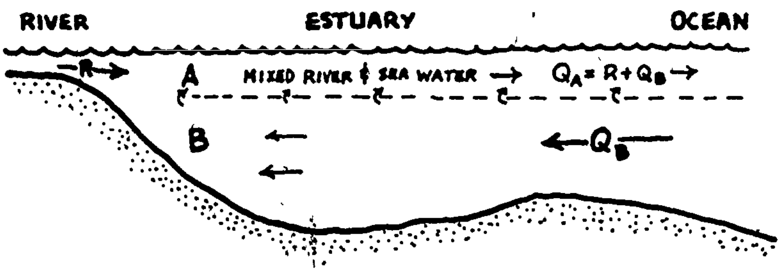

FIG. 25 Net circulation in an estuary with terminology used in exchange calculations.

where R is the measured amount of river water entering the estuary. If data are insufficient to determine R, use the expression

$$Q_A = a(U_E t_E - U_F t_F)$$

where a is the area of the seaward boundary of the surface layer A, U_E and U_F are the mean ebb and flood currents, respectively, and t_E and t_F the durations of ebb and flood flow. The exchange ratios for the two layers can then be calculated from the equations

$$r_A = \frac{Q_A}{A} \quad \text{and} \quad r_B = \frac{Q_B}{B}$$

These ratios represent the fraction of volume A (r_A) that is lost to the sea in a tidal cycle and the fraction of B (r_B) that passes upward into section A. A useful expression for the mean exchange ratio within the estuarine system is

$$r = \frac{r_A + r_B}{2}$$

We can now state the fundamental equation for volume of contaminant C remaining in a tidal estuary after t tidal cycles as

$$C_t = A(1 - r_A)^t + \frac{tr}{(1-r)} B(1-r)^t$$

This assumes complete mixing at high tide of each cycle and thus describes the systematic depletion of the contaminant in the estuary.

In practice, it is useful to draw a graph showing flushing directly as a function of tidal cycles. To do this easily, the expression above can be simplified and the two water bodies treated separately to yield the relations

$$Y_1 = (0.35)^m A \qquad m = \frac{t}{r_A} = 1, 2, \ldots$$

and

$$Y_2 = (0.35)^n \frac{B}{(1-r)} \qquad n = \frac{t}{r} = 1, 2, \ldots$$

These can be plotted on the same graph, with unit lengths on the abscissa corresponding to the reciprocals of their r values. The sum of the curves $Y_1 + Y_2$, then, represents the concentration of contaminant remaining in the estuary system after any desired number of tidal cycles. A typical plot of these curves (Y_1, Y_2, and $Y_1 + Y_2$) is shown in Figure 26, where A is taken as 10 units, B as 14 units, Q_A is 0.4, and Q_B is 0.3 units. The ordinate, which represents units of volume, may also express the percentage of original contaminated volume remaining, assuming there is 100 percent at $t = 0$ and 0 percent at the point where the flushing curves become asymptotic (parallel the abscissa).

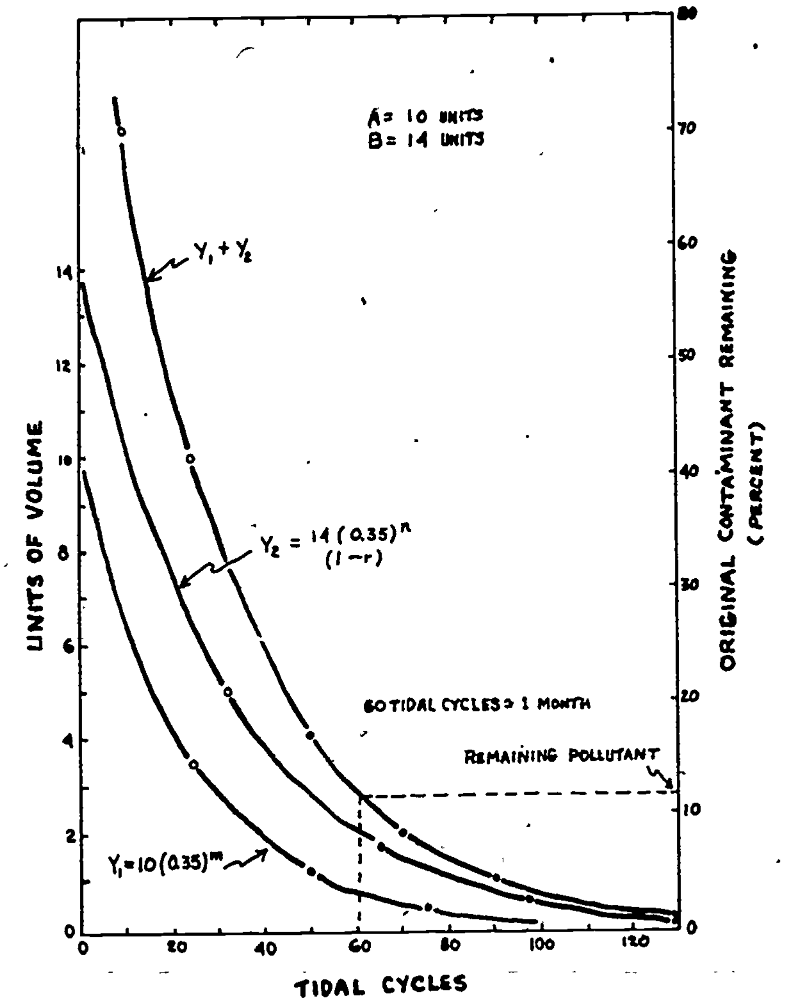

FIG. 26 Flushing curves indicating rates of removal of an estuarine pollutant by tidal action.

In embayments with no fresh-water input, a similar flushing curve can be derived, using an average exchange ratio

$$r_{av} = \frac{H-L}{H}$$

where $H-L$ is the tidal-prism volume and H is the high-tide volume. For flushing time in such embayments, r_{av} is substituted for r and r_A of the preceding equations.

Once flushing curves have been derived for an estuary, they are simple to use. Regarding Figure 26, one might ask, for example, how much of the original pollutant would still be in the estuary after 30 days (60 tidal cycles). Reading upward from 60 tidal cycles to the curve, it is clear that about 12 percent of the pollutant would still be present–roughly 4 percent in the mixed layer and the remainder in the deeper water. The actual concentration in physical terms could then be computed from the original volume of pollutant and the known volumes of the two reservoirs.

POSTSCRIPT

You have now been exposed briefly to varied aspects of estuarine surveys. Throughout, emphasis has been on practicalities and simple approaches to the complex problems you will encounter. Most techniques, except the flushing computations, are equally applicable to limnology—the study of lakes. The flushing of lakes is another very poorly resolved problem, for lake waters often mix completely only in the winter, and so, in effect, you must substitute "yearly" for "tidal" cycles. Hence, pollutants can build up much more rapidly to dangerous levels in lakes, where their removal is more likely to be by chemical or biological reactions than by the simple physical mechanisms stressed for estuaries.

The next part of the module is an exercise based on a hypothetical class study of an estuary. Its purpose is to provide dry-run practice for those who do not have a readily available estuary, and it includes both the data and something of the circumstances under which estuarine surveys are conducted. The information is not complete, but in the real world significant decisions are made every day on the basis of less comprehensive studies than this one.

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HYPOTHETICAL BAY-A "MODEL" ESTUARY IN THE MODERN WORLD

INTRODUCTION

Hypothetical Bay is a delightful, small estuary located on the west coast of a continent (Fig. 27). The climate is temperate and the countryside is rural. The vicinity boasts relatively little "development" (no industries), but there are grandiose plans for the improvement of the entire region. The master plan for Hypothetical Bay includes a moderate-sized oil refinery, some related chemical industries, and possibly a small nuclear-power generation facility. The local unemployment situation is such that there is strong pressure from the Chamber of Commerce to develop the bay area immediately.

The bay is 5 or 6 miles long and extends westward from tide water on its tributaries, North River and South River, to empty into the ocean. Runoff from the two rivers is considerable at all seasons, and an appreciable tide, dominated by the semidiurnal component, has a spring range of about 14 feet. Weather is usually equitable along this coast, but there are equinoctial storms. Because of the relatively high and consistent runoff, circulation within the estuary is of the salt-wedge type, with a lens of brackish or fresh water overlying deeper water of normal salinity.

The characteristics of Hypothetical Bay will be provided in a following section as raw data—precisely the sort of information that might be obtained from a student base-line project on the estuary. This material must be appropriately corrected, plotted, and interpreted. The study of Hypothetical Bay can serve either as a substitute or as practice for the study of a real estuary. Minor features have been simplified, but the general problem is as complex as a natural estuary, and, in fact, most of the data presented have been collected in real estuaries by college students. You are advised that there may be errors or inconsistencies in the field data—just the sort of errors that may occur when you actually go out into the field. You will have to decide what are acceptable data, and in some situations you will be forced to use information that is not strictly consistent with your preconceptions. Statistically indefensible assumptions will have to be made, at least on a trial basis, during the analysis of these data. Beware!

THE MASTER PLAN FOR HYPO BAY

Hypothetical Bay lies in a broad coastal-plain region over a hundred miles from any large city. The countryside is gently rolling, with a well-established economy based largely on dairy farming and poultry production. Woods, second-growth mixed-deciduous forest, are widespread but are used only as woodlots; there is no commercial lumber production in the vicinity. There is, however, commercial clam, crab, and lobster production from the bay area and the adjoining shelf, but there are no large processing facilities. In terms of money, the most important local industry has been the digging of clams, which are iced and shipped for gourmet consumption. These clams come from the broad tidal flats at the head of the bay and along the north shore. The local species, *Venus hypothetica,* can tolerate a very broad range of salinity

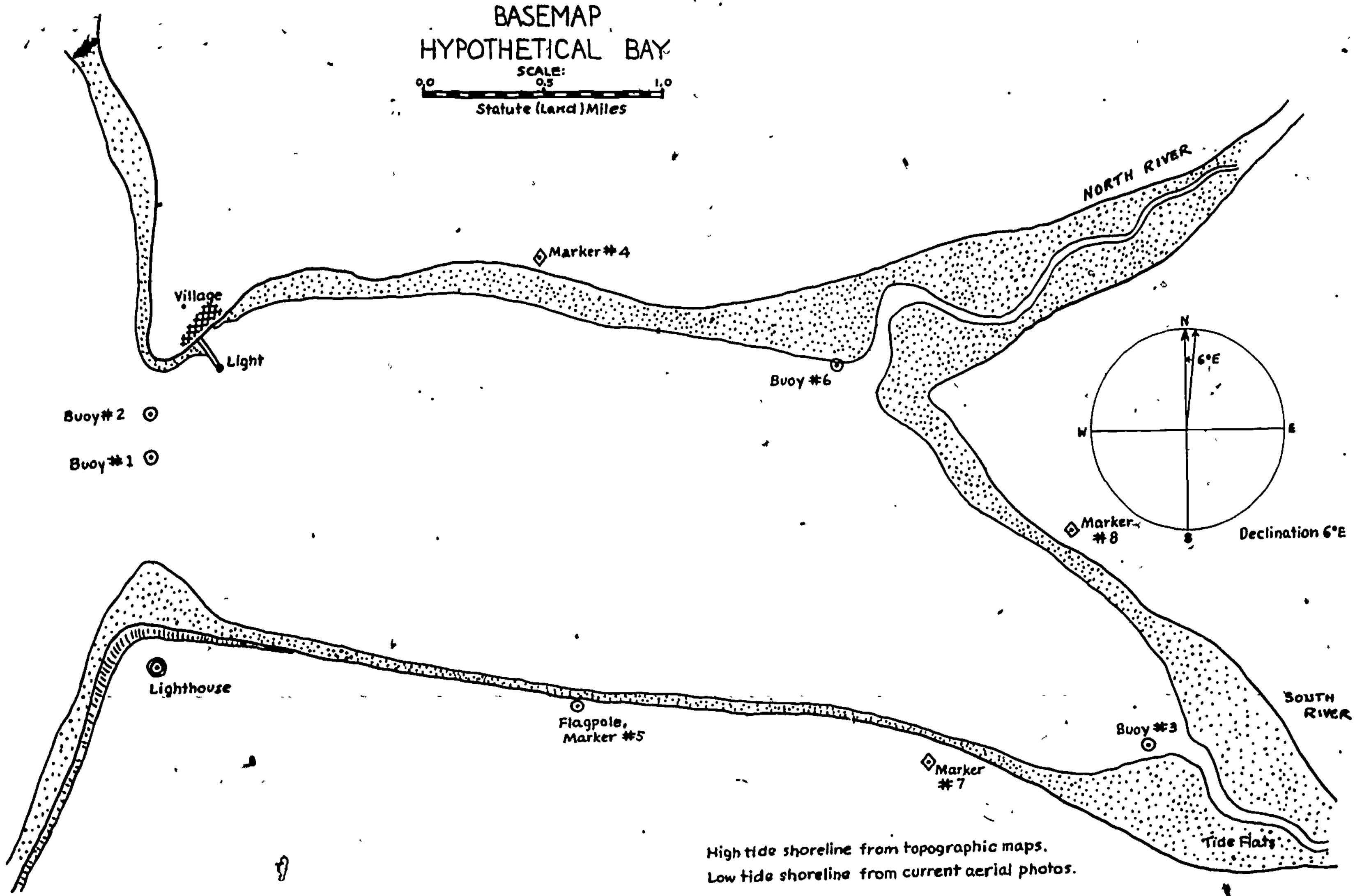

FIG. 27 Index map of Hypothetical Bay (reduction of enclosed map).

conditions but not high water temperatures. If winter temperatures rise above 16°C or summer temperatures above 22°C, the clams' reproductive cycle is disrupted seriously. In the past, they have proved to be intolerant of sewage, and they are not now found close to the village. In recent years, many vacationers have come to the area, buying up shorefront property but not significantly altering the regional economy. Some sport fishing is conducted from the village of Hypo Bay. A railroad and a fairly good road system connect the area to the neighboring metropolitan area. The present year round population of the village is about 2000, while that of the entire region is no more than 10,000, perhaps 2000 additional residents come for the summer. Domestic waste-disposal systems are simple either septic tanks or raw-sewage outfalls leading into the bay. A considerable population of waterfowl feeds and nests in the vicinity.

A massive multiple-use plan for the Hypothetical Bay region has just been made public. This has been under study for a number of years by local, state, and federal planning agencies, and the final integrated plan is now open for discussion. The principal features of the planned development are:

1 A petroleum-chemical industrial complex to be located just east of the village. This complex will include dock facilities for small tankers and freighters (for which extensive dredging will probably be required), and a central plant close to tidewater for cooling and (limited) disposal of wastes.
2 A nuclear-power generation facility to be built south of the bay, probably on the headland near the lighthouse. Both intake and outfall for the power-plant cooling water would be some distance offshore.
3 A large shellfish cannery (to permit local processing) planned for the village itself.
4 A super highway (to service the anticipated development) to connect Hypo Bay with the metropolitan area and a full-sized jet airport to be located inland.

The plan has been discussed in an excited fashion by factions both favoring and opposing development. The proponents (led by the local Chamber of Commerce) emphasize the creation of sorely needed new jobs and a viable tax base to finance schools, roads, and other badly needed local improvements. The opponents (including many summer residents of the Hypo Bay area) cite the (assumed) destruction of natural environments and the consequent degradation of the local quality of life. As it happens, environmental impact statements related to the plan emphasize the sociologic aspects of development. There is virtually no information available on the local oceanography, and all estimates of the physical and biological impact of development are conjectural. A series of hearings has been scheduled to be held in about 6 weeks to discuss the problem, and a temporary injunction prohibiting any construction until after the hearings has been obtained by a national conservation society. Studies funded by the conservation groups, as well as by state and federal agencies and by the petroleum and nuclear-power corporations, have been hurriedly initiated, but all of these groups seem to have some clearly indentifiable special interest.

CLASS STUDY OF HYPO BAY

All the planned studies of Hypo Bay are being conducted by groups who have very definite preconceptions either for or against development. Your class in environmental science decides to do within the brief time available its own study of the area and to prepare its own recommendations for development. Data collection and reduction must be done in the space of just a month, using homemade equipment, borrowed open boats, and the limited facilities available in the laboratory. (Equipment is described in the first part of the module and in Appendix A.) It is understood from the start that some sort of compromise development plan will probably gain acceptance, so it is decided to attempt to consider, in the final analysis, all possible combinations.

After discussion, it is decided that the field work must include:

1 Careful sounding of the bay to permit preparation of a bathymetric chart
2 Observation of tidal-current patterns and velocities
3 Careful determination of the physical characteristics of the water column

These data must be reduced to permit the production of maps and cross sections that can be used to estimate the possible influence of the proposed developments on the estuary. The necessary plots will be

1. A bathymetric chart contoured at 2-fathom intervals
2. Cross and longitudinal sections of salinity and temperature at several sites within the bay
3. A map of tidal currents—especially direction and velocity as they might affect the concentration or dispersal of any pollutants
4. Some sort of "water budget" for the bay system depending upon inflow and outflow of both seawater and river water

Ultimately, estimates of dispersal or flushing time for the system must be made, and specific recommendations for the avoidance or amelioration of possible pollution problems must be formulated

DATA COLLECTION AND INITIAL REDUCTION

Bathymetric Survey

The available nautical charts of the Hypo Bay area show only the anchorage near the village and a few scattered soundings. The first class project, beginning on the morning of the sixteenth and using a borrowed powerboat equipped with flashing-dial fathometer, is to conduct a thorough bathymetric survey of the bay. Before starting out, several conspicuous landmarks are identified and a number of temporary survey markers erected at critical places around the bay. The locations of these are carefully marked on the base map, an enlargement of the topographic map of the area, the low-tide line had already been drawn in from aerial photos taken at extreme low water (see the enclosed map). Starting the first survey run a little after 10 A.M., the scheduled time of high tide, two students at a time man the boat, one steering carefully at a set speed of about 5 mi/hr., the other reading and recording fathometer soundings at 1-minute intervals—thereby placing the soundings about 400 feet apart. Trading off the chores with others from time to time, they work almost continuously until after 4 P.M. (The tides during the projected 4-day period of the class study are given in Table 3; the data collected are in Appendix B.)

Because the bathymetric chart is essential to much of the development of the study, the data in Appendix B should be worked up first. To make the chart, the soundings must first be corrected for tidal effects to a uniform datum, in this area the reference plane is Mean Low Water. To determine the changes necessary, a tide curve for the time of the study must be made and each sounding appropriately corrected. (The soundings and corrections for the first two survey lines appear in Appendix B.) Then the survey lines must be drawn on your base map and the corrected depths entered at the proper locations. The chart is then contoured like any terrestrial map, at a convenient interval (2 fathoms–approximately 4 meters–is a useful value). When you are satisfied with your depth contours, they should be traced from your working copy to a clean version of the chart.

TABLE 3 Tides in Hypothetical Bay during Proposed Period of Class Study

	High Tides				Low Tides			
	A.M.		P.M.		A.M.		P.M.	
Date	Time	Feet	Time	Feet	Time	Feet	Time	Feet
16 Fri	0900	+12.0	2126	+11.9	0249	+0.4	1514	+0.7
17 Sat	0950	+11.7	2215	+11.7	0336	+0.7	1603	+0.8
18 Sun	1040	+11.5	2303	+11.5	0428	+0.8	1651	+0.9
19 Mon	1130	+11.5	2354	+11.4	0518	+0.9	1740	+0.9

Note: Standard times—add 1 hour for daylight time.

Restated more explicitly, the initial data-reduction steps should be:

- *a* Prepare from the data in Table 3 a graph of tidal heights for the study period. Label high tides, low tides, slack water, and ebb and flow stages. Reproduce six of the tide curves for later use.
- *b* From the raw bathymetric data in Appendix B, first identify specifically the times of each individual survey run, then determine appropriate tidal corrections, and apply them to the data.
- *c* On a transparent overlay over your base map, plot the survey lines, enter the corrected soundings, and finally draw the isobaths.

Water and Current Studies

While the bathymetric study is in progress, other students set out to select and locate a series of standard sampling stations. Arbitrarily, they choose 10 sites that provide good general coverage of the bay, and very carefully they locate each site by sextant angles (see Table 4) and buoy it with a strong line attached to a solid anchor so that survey craft can tie on when sampling begins the next morning.

- *d* Locate on your base map the sampling stations. Tidal corrections have been made for the depth at each station, and these soundings should also be entered on the chart; they may assist you in smoothing out the isobaths.

Three boats, all open outboards, are available for class use; therefore, the class splits into three teams, each comprising six or seven students, two of whom at least are thoroughly familiar with small boats. Each team is responsible for a series of observations through an entire lunar day at its assigned stations. To handle the sampling afloat and perform laboratory and additional field analyses ashore, the class decides to split each team into two approximately equal-sized crews, the crew afloat switching with the crew ashore at the end of each round of station sampling.

Each team has a base camp at which there are gas and oil for the outboards, food and drink for the crews, and some sort of shelter; Team A uses a shed on one of the piers at the village, while Teams B and C camp near Markers 4 and 8, respectively. As much as possible, the shore crews plan to run salinity analyses (by hydrometer) on the water samples collected, record the tide heights and waves at the base camps, and (during low tide) sample and tabulate the local intertidal and littoral creatures. Afloat, each team has a single water-sampling bottle with thermometer, a supply of small plastic bottles, a biplane current drogue, a magnetic compass, and several drift cans. Team C, responsible for the four stations at the head of the bay, receives the only available temperature-salinity (*T-S*) probe, with 60 feet of sensor wire. Each team is equipped also with a pair of portable CB transceivers in order to coordinate its activities.

While the most experienced boat handlers conduct the bathymetric survey and select and buoy the sampling stations, the rest of the class practices with the equipment. It soon becomes obvious that to come close to an ideal schedule, people will really have to move fast; so the fewer the mistakes and malfunctions, the better.

In theory, each sampling station is to be occupied eight times during the lunar day, at each slack water and half tide starting with the 1050 hours high tide on the seventeenth. Whenever a station is occupied, water samples are to be collected at the surface, at depths of 1, 2, and 5 meters, and then at intervals of 5 meters to the bottom. Team B, in the center of the estuary, has the bottom-triggering water sampler—also equipped with a thermometer. The sampling is to be conducted as rapidly as possible, the temperature recorded immediately, and a sample put aside and marked for salinity measurement. Team C, with the *T-S* probe, is to record the temperature-salinity profile at half-meter intervals to the bottom. As soon as the samples are collected at a station, the team will run the biplane current meter at the surface, at mid depths, and at the bottom. As time (and energy) permits, the drift cans are to be released and tracked during the maximum-flow periods of the rising and falling tide, these cans are individually numbered so that a release by one team can be monitored by other teams.

During the actual sampling period, these procedures are followed:

1 Boat arrives at station and is tied to the buoy; sextant angles or bearings are taken to make sure the buoy has not dragged from position.

TABLE 4 Sampling-station locations, Hypothetical Bay

Inshore Survey Sheet

Vessel: #2	Date: 16 June	Locality: Hypo Bay	Depth Indicator: Lead line	Observers: Randall Wright	Sheet No.: 1 of 1

Station No.	Time	Depth (ft.) (Corrected)	Tide Correction	Sextant Angles Left	Sextant Angles Right	Land marks used for angles Left	Land marks used for angles Center	Land marks used for angles Right	Remarks	
1	–	26′	–	48°34′	52°26′	light on village jetty	Flagpole #5	Lighthouse	Mid-channel	Team 'A'
2	–	54′	–	56°00′	56°38′	Marker #4	"	"		
3	–	18′	–	56°44′	65°04′	"	"	"		
4	–	16′	–	54°46′	34°40′	Flagpole #5	Lighthouse	Jetty light		Team 'B'
5	–	64′	–	71°26′	42°22′	"	"	"		
6	–	48′	–	40°52′	48°00′	Lighthouse	Jetty light	Marker #4		
7	–	15′	–	22°06′	26°14′	Flagpole #5	Lighthouse	Jetty light	N. River Channel	Team 'C'
8	–	42′	–	22°36′	24°06′	"	"	"		
9	–	58′	–	54°22′	52°52′	Marker #8	Buoy #3	Marker #7		
10	–	13′	–	54°00′	17°10′	Marker #7	Buoy #6	Marker #8	S. River Channel	

2 The water bottle is mobilized, and sampling commences. (When the bottle is at sampling depth, a minute is allowed for the thermometer to equilibrate; then the bottle is triggered and hauled up.) Immediately upon recovery of the water bottle, the temperature is read and recorded; then a small bottle (500 milliliters) is filled and labeled for salinity measurement, and another sample can be taken. The time the temperature is read is recorded as the sampling time.

3 As soon as the last water sample has been collected, the biplane drogue is deployed. When a consistent drift is observed at the desired depth, the angle and direction (a magnetic bearing) of deflection are recorded.

4 When current measurements are finished, the motor is started, and the boat proceeds to the next station.

With sampling well underway, it is discovered that a little over 2 hours is required for each team to complete a round of its stations. This means that the teams must work almost continuously and there is often no more than a half-hour break between rounds—barely long enough for refueling, dropping off samples, and changing crews. The class is extremely lucky in the weather, which remains pleasant, and in their equipment: no major breakdowns occur in either the boats or the sampling gear. Teams A and B manage to complete their planned sequence of sampling, but Team C encounters difficulties and is forced to abbreviate its observations. Its temperature-salinity probe functions very well until the evening when it begins to produce erratic readings. The manual for the device proves unhelpful, and after replacement of the battery fails to improve performance, operations are continued with a sampling bottle. Because it is impossible for Team C to cover all its assigned stations without the probe, Station 10, in the mouth of South River, must be abandoned.

At 1019 hours on the eighteenth, Team B completes its last current measurement and prepares to cast loose from the buoy at Station 6. All sampling data are in! (The data sheets are reproduced in Appendixes C to E, just as they were collected by the teams.) However, before transforming any more data to more usable form, a few comments are in order concerning the data themselves and the limitations of the sampling equipment. It is important to remember that the data have been collected hurriedly, under rather awkward conditions, and that fatigue was a real problem toward the end of the study. In general, though, they have been collected very carefully; so the major limitation on the accuracy of the study lies in the equipment used. The thermometers used by Teams A and B can be read only to the nearest full degree Celsius; that used by Team C to $0.1 \pm 0.1°$ C. The temperature-salinity probe can be read to 0.1°C, but reproducibility is rather poor, and that data can be accepted only to ±0.3°C. When operated as a salinometer, limits of accuracy are $\pm 0.2°/_{oo}$. Below $5.0°/_{oo}$, the probe (which measures salinity as a function of conductivity) is less reliable—with limits of $\pm 0.5°/_{oo}$. Salinity measurements by hydrometer are accurate to $\pm 0.2°/_{oo}$. Owing to the problems of taking precise bearings in a small boat, current measurements of direction are reliable to about 5°, and normally they have not been recorded with more precision. Deflection angles were read to the nearest degree and, therefore, may be as much as 0.5° off the true values; thus, the derived current velocities may be ±2 to 4 cm/sec, ignoring operator error. Because of boat motion and other mechanical difficulties, observed velocities less than 15 cm/sec are not regarded as meaningful. The drift-can experiments were not a great success; only four have been observed more than twice. (The data sheets for these are reproduced in Appendix D.)

MORE DATA REDUCTION

Resuming the transformation of data to more usable form, the current observations made with the biplane drogues can be reduced most easily by calculating enough points for each biplane to draw a curve of deflection angle plotted against current velocity. This has been done for one of the biplanes (Fig. 28). When the curve for a particular biplane has been made, correct current velocities can then be read directly from the curve. The drift-can observations must be plotted as well, preferably integrated with the current measurements. (The current data are presented in Appendixes C and D.)

Although you probably already sense how to go about it, the following steps may help:

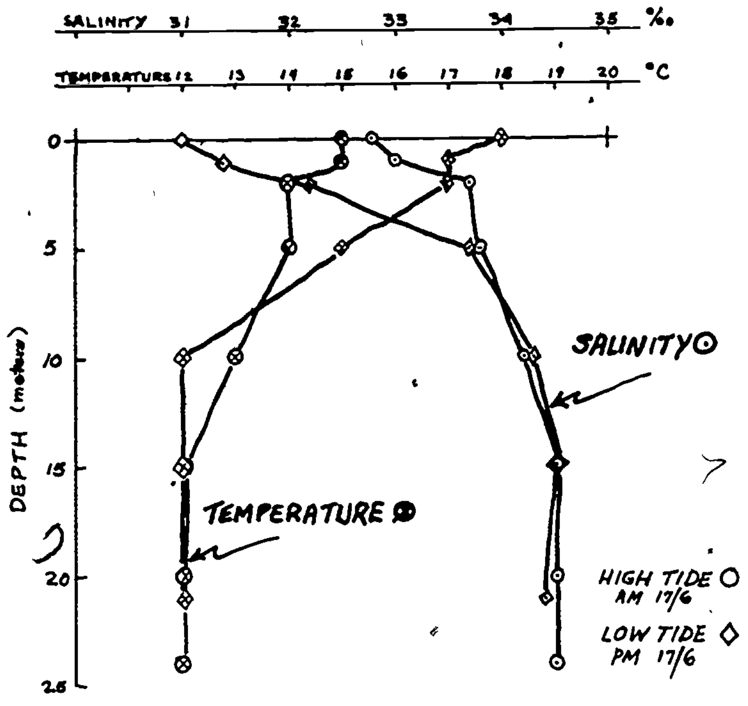

FIG. 28 Temperature and salinity profiles for Station 5. Note that uniformity in waters below 10 meters and the difference between the high- and low-tide characteristics at the surface.

e Prepare calibration curves for each of the biplanes used in the current studies.

f Calculate the current velocities using these calibration curves.

g Team A was responsible for Stations 1 to 3. Using one of the tide curves reproduced earlier—in step *a*—record the actual times of measurements on the tidal cycle. For each station, use a different colored pencil. (This will allow you to evaluate more fully the meaning of the current velocities.) The same procedure should be followed for the stations surveyed by Teams B and C. (After completing this, you can—and should—form some conclusions regarding the nature of the current directions during high tide, ebb, low tide, and flood at each station.)

The temperature and salinity data (Appendix E) can be processed in a number of ways. Initially, it is useful to make up rough graphs of the basic information for each station. This has been done for several series of observations at two stations (Figs. 29 and 30). These plots can be quite useful, showing the temperature-salinity characteristics at various tidal stages, the degree of separation between deep and surface waters, and the location of the thermocline, halocline, and pycnocline. Here in Hypo Bay, the waters tend to be of two types—a surficial mixed layer with highly variable *T-S* parameters and a deeper layer that approaches normal sea water in its characteristics. At a given station, there is often a cyclic change in characteristics depending upon the tidal-current influences, and clearly surface waters are exchanged much more rapidly than deep waters. If the station data are plotted to a uniform scale on tracing paper or Mylar film, comparisons at a station or between stations can be made readily.

The following steps may help you to reduce the *T-S* data:

h Add to the remaining duplicated tide curves the actual times of the temperature-salinity measurements—one curve for each team's stations.

i Prepare temperature-salinity profiles that are typical at high tides and low tides. (The curves you just modified will enable you to quickly find and compare equivalent measurements and arrive at average profiles.)

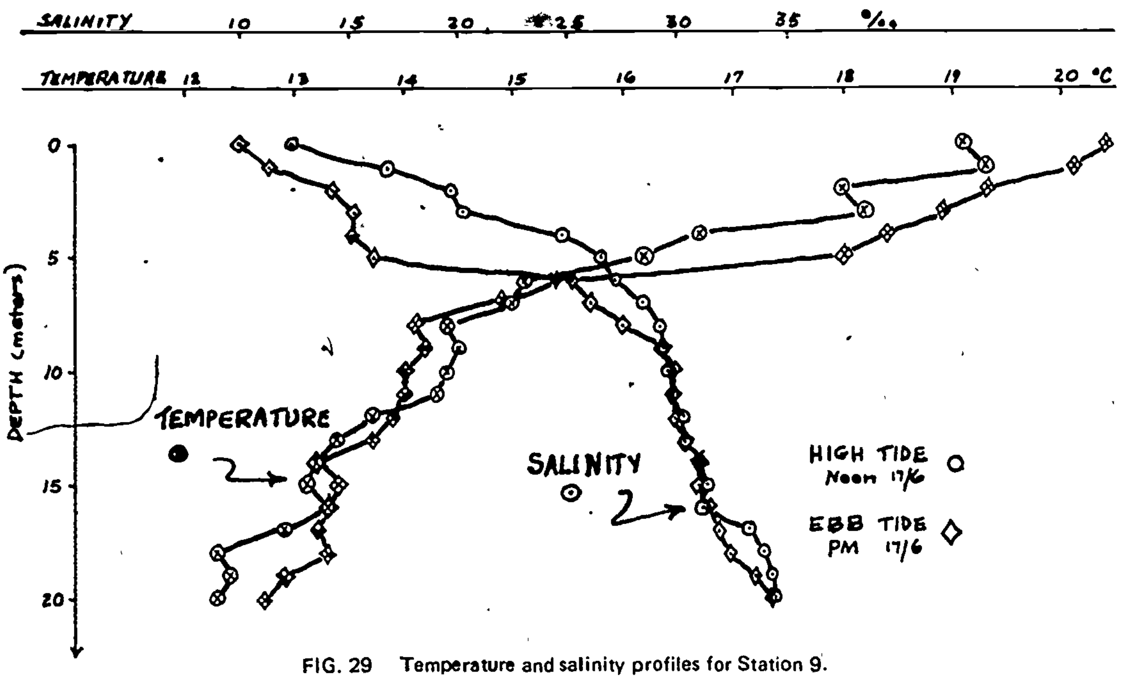

FIG. 29 Temperature and salinity profiles for Station 9.

j Combine the *T-S* profiles with the graphs of current characteristics for each station. (Upon completing all of the preceding steps, you should know well the nature of the raw and processed data.)

The fluvial contribution to Hypo Bay must be estimated from the low-tide observations in the two principal tributaries. To do this, determine the percentage of fresh water in the water column and the average current velocity, and approximate the cross-sectional area of the channel where the measurements were taken. This is *not* a very precise technique but is the only method possible in this situation.

After the data have been processed roughly, "average" or "typical" characteristics for the various parts of the bay can be defined. Looking ahead to the final hearings on the bay development project, it will be necessary to discuss probable long-term processes in the bay. Charts and sections showing the following information would probably be useful:

1 Cross sections showing water bodies within the bay (fresh, mixed, and salt)
2 Charts of current directions and velocities, possibly with hypothetical trajectories for effluents of various sorts introduced at different parts of the system
3 Charts of surface- and deep-water characteristics, and their observed variability

A considerable amount of rather prosaic data reduction is necessary to produce these plots; if computer facilities are available, their use would greatly expedite the process.

PRELIMINARY SYNTHESIS

When all raw data have been processed, final summary computations and at least tentative determinations of the critical parameters must be made. Circumstances are such that you cannot count on the opportunity for further intensive studies in the Hypo Bay area; so you must base your conclusions on the data already in hand. Necessary operations will include:

1 Careful estimation of the volume of the estuary at high and low tide to permit calculation of maximum flushing rates. For a first approximation of flushing time F in tidal cycles, use the relationship

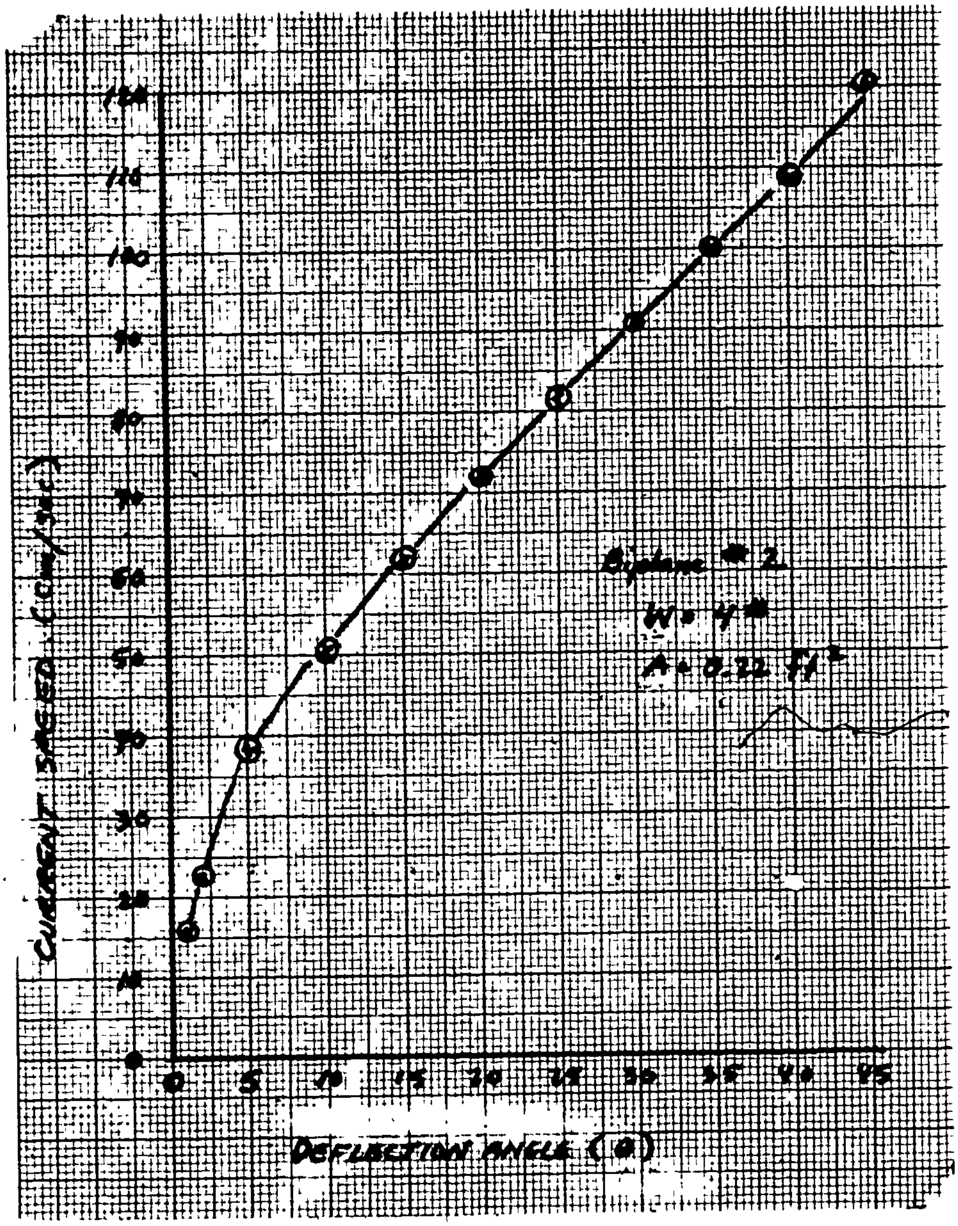

FIG. 30 Calibration curve for biplane current drogue 2, calculated from $V = 0.92 \sqrt{(W \tan\theta)/A}$.

$$F = \frac{L + H}{H}$$

where L is water volume in the basin at low tide and H is the volume at high tide. Complete mixing is assumed, so F represents only the lower limit of flushing time; actual time is likely to be much longer. Refine these computations, if time allows, using the Hydrographic Office technique discussed in the first part of the module.

2 From the tidal-prism volume H-L and the known inputs of river water (observations at low tide), determine a water budget for the bay, and extend this (on the assumption that you really encountered "average" conditions) to produce a yearly summary of water volumes. The original on which Hypo Bay has been modeled was in a region with a strongly maritime climate and

comparatively little seasonal variation in runoff; for your study assume seasonal variations corresponding to your local climate.

3 Assume various possible combinations of development in the Hypo Bay area, and then prognosticate the possible results. Consider for each combination what measures would tend to minimize alteration of the environment.

Based on this material, prepare a summary report with your own conclusions and recommendations to be circulated at the hearings. Proceed on the assumption that some development is inevitable and that a totally negative report will be rejected. Be careful to distinguish between your own actual data and computations ("facts") and your conclusions, which will undoubtedly reflect some of your own prejudices.

APPENDIX A-1: COMMERCIAL EQUIPMENT USEFUL FOR CLASS STUDIES

Sextant: The Davis Standard Mark III Marine Sextant with instruction book, available from

Davis Instruments Corporation
857 Thornton Street
San Leandro, California 94577

(a cheap but effective plastic yachting sextant—well designed for small-boat work).

Protractor: The Davis vernier-reading three-arm protractor (translucent plastic)—also available from Davis Instruments. This is not essential but is extremely useful for plotting positions, bearings, and survey lines.

Compass: Any good-sized magnetic compass with provision for taking sights is adequate.

Thermometers: Good-quality full-immersion thermometers are needed, reading to ±0.1°C in the −5 to +30°C range. Armored thermometers are preferred for obvious reasons.

Hydrometers: Routinely, these come in sets of three instruments covering the salinity range from 0 to 30°/oo. They are available from various suppliers including

Ward's Natural Science Establishment, Inc.
P.O. Box 1712
Rochester, New York 14603

Reagents kits: A wide variety are available from diverse sources. An excellent selection of material is provided by Ward's and by

LaMotte Chemical Products Company
Chestertown, Maryland 21620.

Salinometers, temperature profilers, and other black boxes: Most such instruments are too delicate or expensive for routine class use, but under certain circumstances they may be very useful. Suppliers include:

Beckman Instruments, Inc.
Cedar Grove Operations
89 Commerce Road
Cedar Grove, New Jersey 07009

General Oceanics, Inc.
5535 NW Seventh Avenue
Miami, Florida 33127

Environmental Devices Corporation
Tower Building
Marion, Massachusetts 02738

Heath Company
Benton Harbor, Michigan 49022
(inexpensive temperature profilers and fathometers)

Hydro Products
P.O. Box 2528
San Diego, California 92112

Martek Instruments, Inc.
879 West Sixteenth Street
Newport Beach, California 92660

APPENDIX A-2: SPECIFICATIONS OF CURRENT DROGUES USED IN STUDY

Biplane current drogue 1
Surface area = 12 X 12 in. = 1.0 $ft.^2$
Weight in water ≐ 7 lb.

Biplane current drogue 2
Surface area = 4 X 8 in. = 0.22 $ft.^2$
Weight in water = 4 lb.

Biplane current drogue 4
Surface area = 4 X 8 in. = 0.22 $ft.^2$
Weight in water = 5.2 lb.

APPENDIX B: BATHYMETRIC SURVEY

Data Sheet 1 of 4

Date: 16/6/72 Observers: Holland & Lewis
Locality: Hypo Bay

TIME	DEPTH	CORR.	TRUE DEPTH
LINE A - Across mouth of bay at High Water Slack. Speed Aprx. 5 Kts, Bearing 000°T. Start at Stake, 420' offshore			
10-12	06	-12	-06
13	09		-03
14	13		01
15	23		11
16	32		20
17	36		24
at Buoy #1 → 18	45		33
19	62		50
Buoy #2 → 20	37		25
21	24		12
at Beach → 22	0		-12
LINE B - from Buoy # 2 (bay mouth) to Buoy # 3 (South River). Speed aprx. 5 Kts, Bearing 109°T. Start at Buoy # 2			
10-38	45	-12	33
39	60	"	48
40	61	"	49
41	64	"	52
42	68	"	56
43	72	"	60
44	74	"	62
45	74	-11	63
46	74	"	63
47	73	"	62
48	73	"	62
49	73	"	62
50	73	"	62
51	73	"	62
52	73	"	62
53	73	"	62

TIME	DEPTH	CORR.	TRUE DEPTH
10h54m	73	-11	62
55	72	"	61
56	73	"	62
57	73	"	62
58	72	"	61
59	71	"	60
11h00m	70	-10	60
01	69	"	59
02	66	"	56
03	64	"	54
04	64	"	54
05	63	"	53
06	62	"	52
07	62	"	52
08	60	"	50
09	57	"	47
10	56	"	46
11	56	"	46
12	56	"	46
13	54	"	44
14	52	"	42
15	52	"	42
16	50	"	40
17	50	"	40
18	46	"	36
19	44	"	34
20	35	"	25
Buoy #3 → 21	22	"	12
22	08	"	-4
23	09	"	-3
24	10	"	-2
25	05	"	-7

Date: 16/6/72 **Observers:** Rapp & Pestrong

Locality: Hypo Bay

LINE C - From South River Buoy (#3) to Survey Marker #4

Speed Aprx. 5kts., course 309°T

Start at Buoy #3

TIME	DEPTH	CORR.	TRUE DEPTH
11h38m	12	-9	
39	33	"	
40	40	"	
41	45	"	
42	47	"	
43	47	"	
~~43~~ 44	48	"	
45	51	"	
46	55	"	
47	57	"	
48	58	"	
49	58	"	
50	57	-8	
51	57		
52	60		
53	61		
54	62		
55	62		
56	62		
57	60		
58	60		
59	59		
12h00m	56		
01	50		
02	44		
03	38		
04	32		
05	20		
06	06		

END Aprx 500' offshore

LINE D - Survey Marker #4 across to Flagpole (#5)

Speed Aprx. 5kts, Course 175°T

Start aprx 600' Offshore near #4

TIME	DEPTH	CORR.	TRUE DEPTH
13h10m	07		
11	18		
12	35		
13	47		
14	55		
15	60		
16	67		
17	68		
18	67		
19	67		
20	66		
21	65		
22	60		
23	55		
24	45		
25	17		
26	—		

LINE E - Flagpole (#5) to Buoy #6

Speed aprx 5kts, Course 040°T

Start c. 200' off

TIME	DEPTH	CORR.	TRUE DEPTH
13h50m	02		
51	26		
52	40		
53	50		
54	56		
55	60		
56	65		
57	65		
58	65		
59	66		
14h00m	65		
01	64		
02	62		

Date: 16/6/72
Locality: HYPO BAY

Observers: Fenner
Holland

TIME	DEPTH	CORR.	TRUE DEPTH

LINE E, Concluded

TIME	DEPTH	CORR.	TRUE DEPTH
14h 03m	54		
04	44		
05	35		
06	32		

END, 50' from Buoy #6

LINE F, Buoy #6 toward Lighthouse S. of bay mouth
Speed aprx 5Kts, Course 248°T
Start at Buoy #6

TIME	DEPTH	CORR.	TRUE DEPTH
14h 16m	15		
17	20		
18	34		
19	38		
20	47		
21	50		
22	55		
23	61		
24	63		
25	64		
26	66		
27	66		
28	66		
29	66		
30	66		
31	66		
32	66		
33	64		
34	~~58~~ 62		
35	57		
36	54		
37	52		
38	50		
39	41		
40	31		
41	15		
42	01		

LINE G – end of 'F' to Light at end of Village Pier (#7)
Speed aprx 5 Kts, Course 355°T
Start @ Low tide Line, So. Shore

TIME	DEPTH	CORR.	TRUE DEPTH
14h 50m	01		
51	25		
52	39		
53	42		
54	46		
55	49		
56	52		
57	54		
58	56		
59	53		
15h 00m	40		

LINE H. – Buoy #1 @ Bay mouth to Buoy #6 at North River
Speed 5 Kts, Course 083°T
Start at Buoy #1

TIME	DEPTH	CORR.	TRUE DEPTH
15h 15m	36		
16	38		
17	49		
18	53		
19	56		
20	62		
21	64		
22	64		
23	64		
24	64		
25	65		
26	65		
27	64		
28	63		
29	62		
30	60		

Date: 16 June 1972
Locality: Hypo Bay
Observers: Lewis, Wright

TIME	DEPTH	CORR.	TRUE DEPTH
LINE H - Concluded			
15h 31m	54		
32	53		
33	51		
34	50		
35	49		
36	49		
37	43		
38	438		
39	34		
40	30		
41	25		
42	20		
43	13		
End just short of Buoy # 6			
LINE I - Buoy #6 south toward Survey Marker # 7			
Speed 5 kts, Course 168° T			
Start at Buoy # 6			
15h 50m	05		
51	25		
52	24		
53	35		
54	38		
55	43		
56	50		
57	56		
58	61		
59	64		
16h 00m	59		
01	50		
02	43		
03	39		
04	25		
05	06		
END c. 20' off tide flats			

TIME	DEPTH	CORR.	TRUE DEPTH
LINE J - Survey Marker # 7 to Marker # 8			
Speed 5 kts, Course 032° T			
Start ~200' from High Water, 30' Offshore			
16h 10m	07		
11	31		
12	41		
13	42		
14	46		
15	40		
16	37		
17	25		
18	05		
End about 15' off tide flats			

END FOR DAY 888

APPENDIX C-1: CURRENT MEASUREMENTS

Data Sheet 1 of 4

DATE:	AREA:	INSTRUMENT:	OBSERVERS:
17 June	Hypo Bay	Biplane # 2	Team A

STATION	TIME	DEPTH (M)	CURRENT DIRECTION	CURRENT DEFL. ∡	CURRENT VELOCITY
1	1659	0	262°	—0—	
1	1705	3	265°	1°	
1	1712	6	—	—0—	
2	1759	0	085°	1°	
2	1807	10	089°	2°	
2	1815	15	—	—0—	
3	1844	0	097°	2°	
3	1852	3	100°	3°	
1	1938	0	090°	2°	
1	1942	3	090°	3°	
1	1948	6	088°	2°	
2	2028	0	084°	12°	
2	2032	10	081°	10°	
2	2039	15	090°	6°	
3	2118	0	102°	14°	
3	2122	2	104°	8°	
3	2128	5	099°	10°	

DATE:	AREA:	INSTRUMENT:	OBSERVERS:
17 June	Hypo Bay	Biplane #1	Team B

STATION	TIME	DEPTH (m)	(Mag) CURRENT DIRECTION	DEFL. ∡ (°) VELOCITY
4	1043	0	296	5
	1045	3	288	3
	1047	6	—	-0-
5	1218	0	—	-0-
	1222	10	265	2
	1229	20	171	2
6	1340	0	304	4
	1343	5	295	2
	1346	10	—	-0-
4	1430	0	290	14
	1432	2	294	17
	1437	5	282	10
5	1526	0	268	13
	1530	10	270	11
	1534	20	262	3
6	1620	0	265	7
	1623	7	264	3
	1629	15	270	2

DATE: 17 June | **AREA:** Hypo Bay | **INSTRUMENT:** Biplane # 1 | **OBSERVERS:** Team B

STATION	TIME	DEPTH (M)	CURRENT DIRECTION	CURRENT DEFL. ∡	CURRENT VELOCITY
4	1715	0	278	4	
	1718	2	290	2	
	1724	4	282	2	
5	1810	0	—	0	
	1812	10	091	3	
	1815	15	084	4	
6	1859	0	098	3	
	1902	8	094	5	
	1905	15	093	2	
4	1949	0	091	8	
	1951	2	094	10	
	1955	5	094	6	
5	2047	0	082	12	
	2050	10	089	10	
	2054	20	091	11	
6	2130	0	086	16	
	2134	10	089	18	
	2139	15	086	14	

DATE:	AREA:	INSTRUMENT:	OBSERVERS:
17-18 June	Hypo Bay	Byl... #1	Team B

STATION	TIME	DEPTH	CURRENT DIRECTION	DEFL. ∡	VELOCITY
4	2244	0	269	8	
	2246	2	265	10	
	2249	5	264	4	
5	2340	0	264	3	
	2344	10	260	2	
	2350	20	269	(1)?	V. weak
6	0034	0	272	(1)?	"
	0038	10	—	-0-	
	0042	15	066	2	
4	0212	0	265	22	
	0215	2	268	16	
	0218	4	268	18	
5	0305	0	271	15	
	0308	10	268	14	
	0312	20	268	7	
6	0355	0	264	9	
	0359	10	268	6	
	0402	15	270	6	

APPENDIX C-2: CURRENT MEASUREMENTS

Data Sheet 1 of 4

DATE:	AREA:	INSTRUMENT:	OBSERVERS:
17 June	Hypo Bay	Biplane #2	Team A

STATION	TIME	DEPTH (m)	CURRENT DIRECTION (Magnetic)	DEFL. ∢	VELOCITY
1	1105	0	271°	3°	
1	1114	4m	263°	4°	
1	1122	8m	281°	2°	
2	1208	0	278°	2°	
2	1217	10	280°	2°	
2	1225	15	271°	1°	
3	1255	0	281°	3°	
3	1303	2	283°	2°	
3	1310	5	282°	1°	
1	1340	0	269°	16°	
1	1348	3	272°	12°	
1	1356	7	264°	10°	
2	1458	0	276°	13°	
2	1504	10	276°	10°	
2	1518	15	281°	9°	
3	1558	0	270°	4°	
3	1606	2	278°	6°	
3	1619	5	269°	2°	

DATE:	AREA:	INSTRUMENT:	OBSERVERS:
17-18 June	Hypo Bay	Biplane # 2	Team A

STATION	TIME	DEPTH (m)	CURRENT DIRECTION	DEFL. ∡	VELOCITY
1	~~2256~~ 2258	0	082°	3°	
1	2304	4	090°	6°	
1	2310	8	088°	3°	
2	2354	0	—	-0-	
2	2359	10	205°	1°	
2	~~2400~~ 0008	15	256°	2°	
3	0047	0	—	-0-	
"	0053	2	090°	1°	
"	0100	5	084°	3°	
1	0209	0	277°	21°	
"	0212	3	282°	22°	
"	0215	6	274°	16°	
2	0309	0	276°	20°	
"	0312	10	274°	18°	
"	0315	15	279°	18°	
3	0350	0	261°	20°	
	0352	3	261°	7°	
	0356	5	264°	2°	

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DATE: 18 June | AREA: Hypo Bay | INSTRUMENT: Bipler #2 | OBSERVERS: Team A

STATION	TIME	DEPTH (m)	CURRENT DIRECTION	CURRENT DEFL. ∡	CURRENT VELOCITY
1	0506	0	0	-0-	
	0509	3	278°	2°	
	0512	6	281°	3°	
2	0605	0	——	-0-	
	0610	10	276°	4°	
	0614	15	070°	2°	
3	0643	0	075°	2°	
	0645	2	083°	4°	
	0647	5	086°	2°	
1	0807	0	080°	8°	
	0809	3	085°	7°	
	0812	6	082°	8°	
2	0900	0	087°	15°	
	0903	10	090°	19°	
	0909	15	082°	13°	
3	0948	0	100°	16°	
	0952	2	102°	10°	
	0955	5	099°	11°	

DATE:	AREA:	INSTRUMENT:	OBSERVERS:
18 June	Hypo Bay	Biplane # 1	Team B

STATION	TIME	DEPTH	CURRENT DIRECTION	CURRENT DEFL.	CURRENT VELOCITY
4	0505	0	261	3	
	0507	2	264	2	
	0510	4	—	—0—	
5	0603	0	269	4	
	0609	10	272	3	
	0614	20	269	(1) ?	v. weak
6	0705	0	—	—0—	"
	0708	6	265	(1)	
	0712	12	269	(2)	
4	0818	0	260	15	
	0820	2	268	14	
	0824	5	262	25	
5	0919	0	268	16	
	0922	10	270	8	
	0929	20	270	3	
6	1012	0	271	19	
	1015	10	270	20	
	1019	15	272	16	

APPENDIX C-3: CURRENT MEASUREMENTS

Data Sheet 1 of 3

DATE:	AREA:	INSTRUMENT:	OBSERVERS:
17/6/72	Hypo Bay	Biplane #4	Team C

STATION	TIME	DEPTH	CURRENT DIRECTION	DEFL. ∠	VELOCITY
7	1045	0	216°M	16°	
"	1050	2	219°M	21°	
"	1056	5	220°M	12°	
8	1139	0	328°	3°	
"	1144	8	314°	5°	
"	1151	12	300°	4°	
9	1230	0	355°	2°	
"	1237	10	340°	5°	
"	1242	15	330°	3°	
10	1314	0	299°	12°	
	1317	2	298°	7°	
	1320	5	290°	2°	
7	1345	0	220°	36°	
	1347	2	220°	40°	
	1350	5	220°	32°	
8	1430	0	316°	26°	
	1434	8	314°	29°	
	1442	12	314°	22°	
9	1544	0	328°	22°	
	1549	10	324°	26°	
	1555	20	324°	26°	

DATE: 17/6 AREA: Hypo Bay INSTRUMENT: Biplane #4 OBSERVERS: Team C

STATION	TIME	DEPTH	CURRENT DIRECTION	DEFL. 4	VELOCITY
10	1625	0	295	33	
	1627	2	295	31	
	1629	4	295	26	
7	1710	0	220	24	
	1712	2	220	30	
	1714	4	220	22	
8	1740	0	332	2	
	1744	7	329	1 ?	
	1750	12	320	2 ?	(very faint)
9	1804	0	318	2	
	1810	10	320	3	
	1815	20	320	2	
10	1840	0	293	6	
	1843	3	290	4	
7	1942	0	225	8	
	1945	2	225	14	
	1950	5	225	6	
8	2100	0	005	2	
	2104	7	328	4	
	2108	12	—	-0-	
9	2225	0	071	6	
	2229	10	082	9	
	2235	15	075	4	

OMIT STATION #10

DATE:	AREA:	INSTRUMENT:	OBSERVERS:
18/6	Hypo Bay	Biplane # 4	Team C

STATION	TIME	DEPTH	CURRENT DIRECTION	CURRENT DEFL. ∡	CURRENT VELOCITY
7	2410	0	235	22	
	2412	2	230	30	
	2415	5	230	26	
8	0055	0	278	10	
	0059	10	290	18	
	0103	15	263	12	
9	0159	0	330	12	
	0205	10	325	14	
	0209	15	325	10	
(omit Sta #10)					
7	0450	0	220	26	
	0453	2	225	28	
	0459	4	225	24	
8	0552	0	254	4	
	0555	5	260	7	
	0602	10	262	5	
9	0657	0	320	9	
	0702	10	316	6	
	0706	15	316	2	

(omit station # 10)

APPENDIX D: DRIFT-CAN DATA

DRIFT-CAN DATA

~~INSHORE SURVEY SHEET ... OF ALASKA~~

Vessel: | Date: 17-18 June | Locality: Hypo Bay | Depth Indicator: | Observers: | Sheet No.: 1 of 2

CAN No.	Time	Depth	Tide Correction	Sextant Angles Left	Sextant Angles Right	Land marks used for angles Left	Land marks used for angles Center	Land marks used for angles Right	Remarks
A3	1900/17								RELEASE @ STA. # 3
	2130/17								AT STA. # 6
	0050/18								AT STA. # 8
	1022/18								AT STA. # 4
B3	1440/17								RELEASE @ STA. #6
	1645/17			53°41'	60°33'	Light House	Jetty light	Marker #4	
	1905/17			35°00'	55°43'	"	Buoy #1	Buoy #2	
	0840/18			54°39'	95°06'	"	Jetty light	Marker #4	
C1	1025/17								RELEASE @ STA. #7
	1450/17			34°05'	83°22'	Light House	Jetty light	Marker #4	
	1820/17			58°00'	28°07'	Marker #5	Light House	Jetty light	015°M - Jetty light
	0105/18						Bearing		338°M - Buoy #1
									178°M - Lighthouse

DRIFT-CAN DATA

~~INSHORE SURVEY SHEET - BMS, U. OF ALASKA~~

Vessel:	Date: 17-18/6	Locality: Hypo Bay	Depth Indicator:	Observers:	Sheet No.: 2 of 2

~~Station~~ CAN No.	Time	Depth	Tide Correction	Sextant Angles Left	Sextant Angles Right	Land marks used for angles Left	Land marks used for angles Center	Land marks used for angles Right	Remarks
C4	1300/17								RELEASE @ STA. #10
									320°M to Buoy #6
	1650/17	GROUNDED ON TIDE FLAT; RELAUNCHED ←							184°M to marker #7
									097°M " " #8
	1725/17								AT STA. #8
	1845/17								AT STA. #5
	1915/17								MIDWAY BETWEEN STAT. 5 & 4.

APPENDIX E-1: INSHORE T-S PROBE SURVEY SHEETS

Vessel: TEAM A | Date & Time: 17 June | Locality: Hypo Bay | Instrument: Bottle #3 | Observers: [redacted] "A"

Station (Time) No.	Depth	Temp. °C	S‰	Station No.	Depth	Temp. °C	S‰	Station No.	Depth	Temp. °C	S‰
1 (1030)	0	14	33.5	1 (1320)	0	16	32.8	1(1640)	0	16	33.0
1 (1033)	1 m	13	33.6	1 (1322)	1	14	33.1	1(1643)	1	15	32.9
1 (1039)	2 m	13	33.8	1 (1325)	2	14	32.9	1(1648)	2	[illegible]	33.1
1 (1045)	5 m	13	33.7	1 (1332)	5	13	33.6	1(1652)	5	14	33.5
1 (1056)	10 m	12	34.2								
				2 (1412)	0	16	32.5	2(1722)	0	15	33.0
2 (1135)	0	14	33.8	2 (1414)	1	14	33.7	2(1725)	1	14	33.5
2 (1137)	1 m	13	33.4	2 (1418)	2	14	33.6	2(1729)	2	14	33.6
2 (1143)	2 m	13	33.9	~~2 (1422)~~	~~5~~	ANCHOR DRAGGING. REPOSITION		2(1734)	5	12	33.9
2 (1149)	5 m	12	34.5	2 (1431)	5	14	33.7	2(1739)	10	12	34.4
2 (1154)	10 m	12	34.5	2 (1440)	10	13	33.9	2(1747)	15	12	34.5
2 (1200)	15 m	12	34.5	2 (1451)	15	12	34.3	[illegible]			
3 (1235)	0	13	33.4	3 (1535)	0	14	33.6	3(1824)	0	13	33.8
3 (1239)	1 m	13	33.9	3 (1538)	1	13	33.7	3(1828)	1	12	33.8
3 (1244)	2 m	12	34.3	3 (1545)	2	12	33.9	3(1834)	2	12	34.2
3 (1251)	5 m	12	34.5	3 (1551)	5	12	34.1	3(1840)	4	12	34.4
(HIGH TIDE)				(EBB)				(LOW TIDE)			

N.B. - DAYLIGHT SAVING TIME . . .

Vessel: | Date & Time: 17 June - 18 June | Locality: Hypo Bay | Instruments: Bottle # 3 | Observers: Team A

Station No. (Time)	Depth	Temp. °C	S‰	Station No.	Depth	Temp. °C	S‰	Station No.	Depth	Temp. °C	S‰
1(1925)	0	14	33.3	1(2230)	0	14	33.7	1(0150)	0	15	32.9
1(1928)	1	13	33.6	1(2234)	1	14	33.9	1(0153)	1	15	33.4
1(1931)	2	13	33.9	1(2240)	2	12	33.9	1(0159)	2	14	33.9
1(1936)	5	12	34.5	1(2246)	5	12	34.5	1(0204)	5	13	34.2
				1(2252)	10	12	34.5				
2(1958)	0	13	32.9					2(0231)	0	15	32.8
2(2001)	1	13	33.3	2(2320)	0	14	33.5	2(0234)	1	14	33.6
2(2008)	2	13	33.8	2(2323)	1	13	33.8	2(0242)	2	14	33.7
2(2013)	5	12	34.5	2(2329)	2	13	33.8	2(0250)	5	12	34.0
2(2018)	10	12	34.5	2(2334)	5	12	34.5	2(0258)	10	12	34.1
2(2024)	15	12	34.5	2(2340)	10	12	34.5	2(0302)	15	12	34.3
				2(2350)	15	12	34.5				
3(2052)	0	12	34.1					3(0[illegible]4)	0	13	33.6
3(2059)	1	12	34.4	3(0022)	0	12	34.0	3(0328)	1	12	33.7
3(2105)	2	12	34.5	3(0027)	1	12	34.0	(Malfunction) 3(0340)	2	12	33.9
3(2112)	5	12	34.5	3(0035)	2	12	34.5	3(0348)	5	12	33.9
				3(0043)	5	12	34.5				
(RISING TIDE)				(HIGH TIDE)				(EBB)			

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Vessel: | Date & Time: 18 June | Locality: Hypo Bay | Instrument: Bottle #3 | Observers: 'Team A'

Station No.	Depth	Temp. °C	S‰	Station No.	Depth	Temp. °C	S‰	Station No.	Depth	Temp. °C	S‰
1(0445)	0	15	33.0	1(0745)	0	14	33.7				
1(0448)	1	14	33.6	1(0748)	1	13	33.9				
1(0455)	2	12	33.8	1(0756)	2	13	34.0				
1(0501)	5	12	34.1	1(0803)	5	12	34.5				
2(0524)	0	14	33.3	2(0828)	0	13	33.9				
2(0529)	1	14	33.8	2(0831)	1	13	339				
2(0536)	2	14	33.9	2(0835)	2	13	34.2				
2(0542)	5	12	34.2	2(0841)	5	12	34.5				
2(0550)	10	12	34.5	2(0848)	10	12	34.5				
2(0558)	15	12	34.5	2(0855)	15	12	34.5				
3(0626)	0	13	34.0	3(0923)	0	12	34.3				
3(0629)	1	12	34.2	3(0926)	1	12	34.3				
3(0635)	2	12	34.5	3(0931)	2	12	34.5				
3(0639)	5	12	34.5	3(0943)	5	12	34.5				
	(LOW TIDE)				(FLOOD)						

APPENDIX E-2: INSHORE T-S PROBE SURVEY SHEETS

Data Sheet 1 of 3

Vessel: (time - Daylight) Date & Time: 17 June 1972, Daylight Time Locality: Hypo Bay Instrument: Bottle #5 Observers: Team B

Station No.	Depth	Temp. °C	S‰	Station No.	Depth	Temp. °C	S‰	Station No.	Depth	Temp. °C	S‰
4(1030)	0m	16	33.6	4(1415)	0	17	29.8	4(1700)	0	18	30.2
4(1033)	3m	15	33.4	4(1419)	2	16	31.1	4(1704)	2	16	30.9
4(1040)	6m	14	33.8	4(1425)	5	14	31.9	4(1710)	5	16	32.4
5(1108)	0	15	32.8	5(1455)	0	16	30.6	5(1733)	0	18	31.0
5(1112)	1	15	33.0	5(1500)	1	16	32.4	5(1736)	1	17	31.4
5(1119)	2	14	33.6	5(1505)	2	15	33.0	5(1740)	2	17	32.2
5(1128)	5	14	33.8	5(1509)	5	15	33.3	5(1748)	5	15	33.7
5(1139)	10	13	34.1	5(1514)	10	12	34.2	5(1752)	10	12	34.3
5(1150)	15	12	34.5	5(1519)	15	12	34.5	5(1759)	15	12	34.5
5(1157)	20	12	34.5	5(1523)	23 (bottom)	12	34.5	5(1805)	21 (bottom)	12	34.4
5(1215)	24 (bottom)	12	34.5								
				6(1546)	0	16	31.4	6(1829)	0	16	31.8
6(1243)	0	15	33.4	6(1549)	1	14	32.0	6(1832)	1	15	32.3
6(1248)	1	14	33.7	6(1555)	2	14	32.8	6(1838)	2	14	33.4
6(1259)	2	13	33.9	6(1604)	5	12	33.4	6(1842)	5	12	33.4
6(1310)	5	12	34.4	6(1610)	10	12	33.8	6(1849)	10	12	33.9
6(1322)	10	12	34.5	6(1616)	15	12	34.2	6(1854)	15	12	34.6
6(1332)	15	12	34.5								

HIGH EBB LOW

INSHORE T - S PROBE SURVEY SHEET -

Vessel:

Date & Time: 17-18 June 1972

Locality: Hypo Bay

Instrument: Bottle #5

Observers: Team B

Station No.	Depth	Temp. °C	S‰	Station No.	Depth	Temp. °C	S‰	Station No.	Depth	Temp. °C	S‰
4(1940)	0	15	32.9	4(2232)	0	15	32.9	4(0200)	0	16	31.7
4(1943)	2	15	33.5	4(2236)	2	14	32.8	4(0203)	2	14	32.6
4(1946)	5	13	33.9	4(2240)	5	13	33.9	4(0209)	5	13	33.2
5(2009)	0	14	33.1	5(2259)	0	15	32.4	5(0230)	0	15	31.8
5(2012)	1	13	33.2	5(2302)	1	13	33.7	5(0233)	1	15	32.4
5(2018)	2	13	33.7	5(2307)	2	13	33.9	5(0238)	2	14	33.1
5(2021)	5	13	33.7	5(2312)	5	13	34.5	5(0241)	5	12	33.7
5(2028)	10	12	34.0	5(2319)	10	12	34.6	5(0249)	10	12	34.2
5(2034)	15	12	34.6	5(2325)	15	12	34.5	5(0254)	15	12	33.5
5(2040)	20	12	34.5	5(2330)	20	12	34.4	5(0300)	(bottom) 22	12	34.4
5(2045)	22 (bottom)	12	34.6	5(2335)	24 (bottom)	12	34.5				
								6(0325)	0	14	32.5
6(2105)	0	13	33.6	6(0005)	0	13	33.7	6(0329)	1	14	33.3
6(2108)	1	13	33.6	6(0009)	1	12	33.9	6(0333)	2	12	34.2
6(2112)	2	12	34.1	6(0014)	2	12	34.3	6(0338)	5	12	34.4
6(2116)	5	12	34.5	6(0018)	5	12	34.5	6(0342)	10	12	34.5
6(2121)	10	12	34.5	6(0023)	10	12	34.5	6(0349)	15	12	34.5
6(2127)	15	12	34.6	6(0030)	15	12	34.4				

FLOOD | HIGH | EBB

Vessel:

Date & Time: 18 June 1972

Locality: Hypo Bay

Instrument: Bottle # 5

Observers: Team B

Station No.	Depth	Temp. °C	S‰	Station No.	Depth	Temp. °C	S‰	Station No.	Depth	Temp. °C	S‰
4(0450)	0	15	32.6	4(0805)	0	15	32.3				
4(0456)	2	14	32.7	4(0809)	2	13	33.5				
4(0500)	5	13	33.2	4(0814)	5	12	33.8				
5(0523)	0	16	32.4	5(0839)	0	15	32.7				
5(0526)	1	15	33.2	5(0842)	1	14	33.4				
5(0531)	2	14	33.7	5(0848)	2	14	33.9				
5(0537)	5	12	34.0	5(0856)	5	12	34.2				
5(0542)	10	12	34.4	5(0904)	10	12	34.5				
5(0549)	15	12	34.6	5(0910)	15	12	34.6				
5(0558)	20 (bottom)	12	34.6	5(0915)	22 (bottom)	12	34.5				
6(0631)	0	15	32.9	6(0942)	0	14	33.0				
6(0635)	1	13	33.4	6(0946)	1	14	33.7				
6(0640)	2	13	33.2	6(0950)	2	13	34.1				
6(0646)	5	12	34.0	6(0955)	5	12	34.4				
6(0652)	10	12	34.4	6(1003)	10	12	34.5				
~~6(065[illegible]~~	~~15~~	Hit Bottom,	No sample.	6(1008)	15	12	34.5				
? Anchor moved	inshore	?									

LOW — FLOOD

APPENDIX E-3: INSHORE T-S PROBE SURVEY SHEETS

Data Sheet 1 of 5

Vessel: | Date & Time: 17/6/72 | Locality: Hypo Bay | Instrument: T-S Probe | Observers: Team C

Station No.	Depth (meters)	Temp. °C	S‰	Station No.	Depth	Temp. °C	S‰	Station No.	Depth	Temp. °C	S‰
7 (1030)	0	20.4	2.6	8 (1114)	0	18.4	19.1	9 (1204)	0	19.1	12.4
	0.5	20.6	0.0		0.5	18.0	19.4		1	19.3	16.8
	1	20.0	1.4		1	18.0	19.7		2	18.0	19.7
	1.5	19.7	1.0		2	16.9	19.9		3	18.2	20.2
	2	19.4	4.9		3	16.7	20.2		4	16.7	24.8
	2.5	19.4	5.0		4	15.9	22.8		5	16.2	26.5
	3	16.8	12.4		5	15.4	25.4 ~~26.5~~		6	15.1	27.2
	3.5	14.3	19.3		6	15.3	26.3		7	15.0	28.4
	4	14.4	22.4		7	15.4	26.5		8	14.4	29.2
	4.5	14.1	26.1		8	14.9	26.6		9	14.5	29.3
	5	14.0	26.9		9	14.5	26.7		10	14.4	29.6
	5.5	14.0	28.7		10	14.6	28.1		11	14.3	29.7
	6	13.9	29.3		11	14.3	28.4		12	13.7	30.3
	6.5	14.1	29.2		12	14.5	29.3		13	13.4	30.4
	7	14.3	30.1		13	14.4	29.9		14	13.2	31.0
	7.5	14.4	30.3		14	14.5	29.8		15	13.1	31.3
T.D (1040)	8.1	14.3	31.9		15	14.2	33.9		16	13.3	31.1
				(1135)	16	12.8	33.8		17	12.9	33.2
				T.D	16.9	12.4	34.2		18	12.3	33.8
									19	12.4	34.2
								(1225) T.D.	20+	12.3	34.4

(HIGH)

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Vessel:
Date & Time: 17/6/72
Locality: Hypo Bay
Instrument: T/S Probe
Observers: Team C

Station No.	Depth	Temp. °C	S‰	Station No.	Depth	Temp. °C	S‰	Station No.	Depth	Temp. °C	S‰
10(1300)	0	20.4	8 0	7(1330)	0	21 1	3.1	8	9	14.5	26.9
	1	20.1	10.0		1	20 4	2.6		10	14.6	27 9
	2	19.7	10 2		2	19 9	7 2		11	14.4	29.7
	3	19.5	10.9		3	19.9	8.4		12	14.2	30.0
	4	18 9	14 4		4	17.9	12.7		13	14.0	30.4
	5	17 2	19 3		5	16.9	13.5		14	13.6	33.1
(1309)	6	16 0	25 9	(1340)	6	16.4	18.2	(1422)	15	12.9	33.4
TD:	69	15.4	27 6	T.D =	6 5	16.2	20.4	TD:	c. 16	12.2	34.0
				8(1405)	0	19.8	5.0	9(1510)	0	20.4	10.0
					1	20.0	7 4		1	20.1	12.4
					2	19 9	6.3		2	19.3	14.2
					3	19 4	12.0		3	18.9	15.2
					4	19.2	14.4		4	18.4	15.1
					5	17.6	14.3		5	18.0	16.1
					6	16.9	16.2		6	15.4	25.2
					7	16.2	19.5		7	14.9	26.0
					8	15.3	22.1		[illegible]	14.1	27.5

HIGH EAB

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Data Sheet 3 of 5

Vessel:		Date & Time: 17/6/72			Locality: Hypo Bay			Instrument: T.S Probe		Observers: Team C	
Station No.	Depth	Temp. °C	S‰	Station No.	Depth	Temp. °C	S‰	Station No.	Depth	Temp. °C	S‰
continued 9	9	14.2	29.4	10	4	17.4	14.9	8	10	14.2	33.0
	10	14.0	29.7	(1620)	5	16.7	22.0		12	13.6	33.2
	11	14.0	29.8	TD = 5.6 m				(1735)	14	13.8	33.7
	12	13.9	29.9					(TD = 14.3)			
	13	13.7	30.4								
	14	13.2	31.0	7(1700)	0	22.0	0				
	15	13.4	30.9		1	20.5	4.1	9(1749)	0	19.9	0
	16	13.3	31.4		2	20.1	8.0		1	19.7	5.0
	17	13.2	31.7		3	19.4	13.4		2	19.4	7.0
	18	13.3	32.3		4	18.6	13.7		4	18.2	12.3
	19	12.9	33.5	(1706)	5 (TD)	17.1	14.4		6	17.9	17.0
(1533)	20	12.7	34.3						8	14.4	26.2
(TD >20m)									10	13.9	28.4
				8(1725)	0	19.6	5.0		12	13.9	30.2
					1	19.6	5.0		14	13.5	31.0
10(1614)	0	20.1	0.0		2	19.4	5.9		16	13.2	32.1
	1	20.4	0.0		4	19.0	8.4		18	12.9	34.0
	2	20.2	7.0		6	17.3	14.5	(1754)	20	12.9	34.1
	3	19.3	10.2		8	15.5	20.4	TD > 20m			

(LOW)

Date & Time: 17/6/72 Locality: Hypo Bay Instrument: T S Bridge Observers: Team C

Station No.	Depth	Temp. °C	S‰	Station No.	Depth	Temp. °C	S‰	Station No.	Depth	Temp. °C	S‰
6(1929)	0	20.4	0		2	25.5	18.2	9(2140)	0	19.3	5.0
	1	20.4	0		4	26.5	19.0	2145	1	18.9	13.0
	2	20.2	5.0		6	25.4	21.8	2152	2	18.4	12.1
	3	19.1	11.4		8	27.0	22.7	2200	5	17.5	20.1
(1934)	4	17.4	19.0		10	25.1	25.7	2209	10	13.7	30.4
TD	= 4.5				12	25.6	28.1	2218	15	13.2	32.3
~~[illegible]~~				(2025)	14	24.2	30.4				
				T.D.	= 15			OMIT	STATION # 10 RETURN		
7(1930)	0	22.7	0	ERRATIC READING FROM PROBE ON				TO REPAIR PROBE.			
	1	23.1	5.3	TEMPERATURE MODE, RUN							
	2	22.8	10.1	BOTTLE CHECK BIL. # 2							
	3	22.8	19.5	(2035) 8	0	17.9	15.9				
	4	22.8	22.1	(2040)	2	16.5	17.9				
(1937)	5	24.4	28.5	(2044)	5	14.3	19.4				
TD	= 59	?		(2055)	10	14.2	26.1				
				TAKE PROBE TO CAMP FOR CHECK,							
8(2004)	0	24.4	15.7	CONTINUE WITH BOTTLE							
	1	23.3	15.9								

FLOOD

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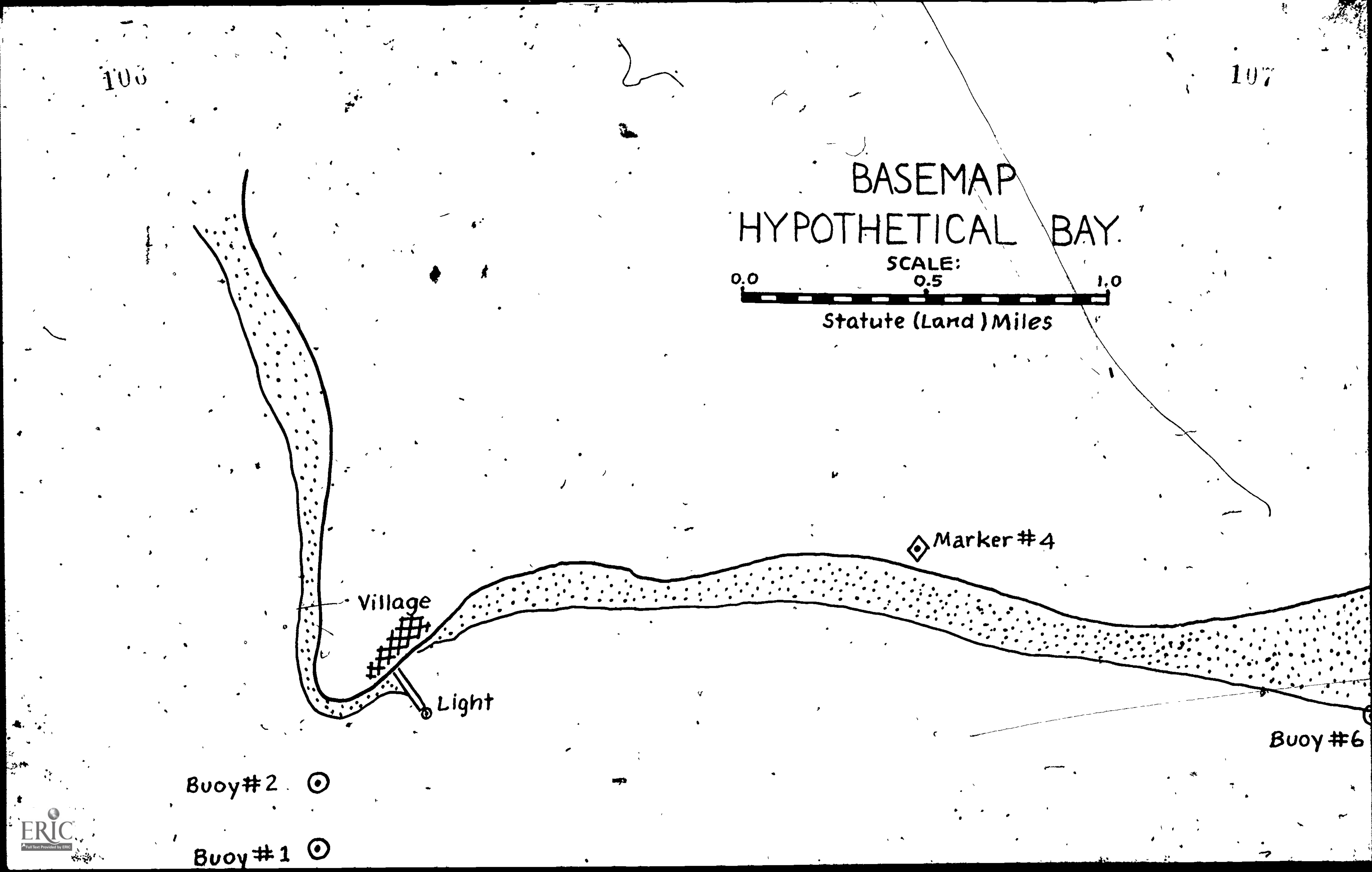
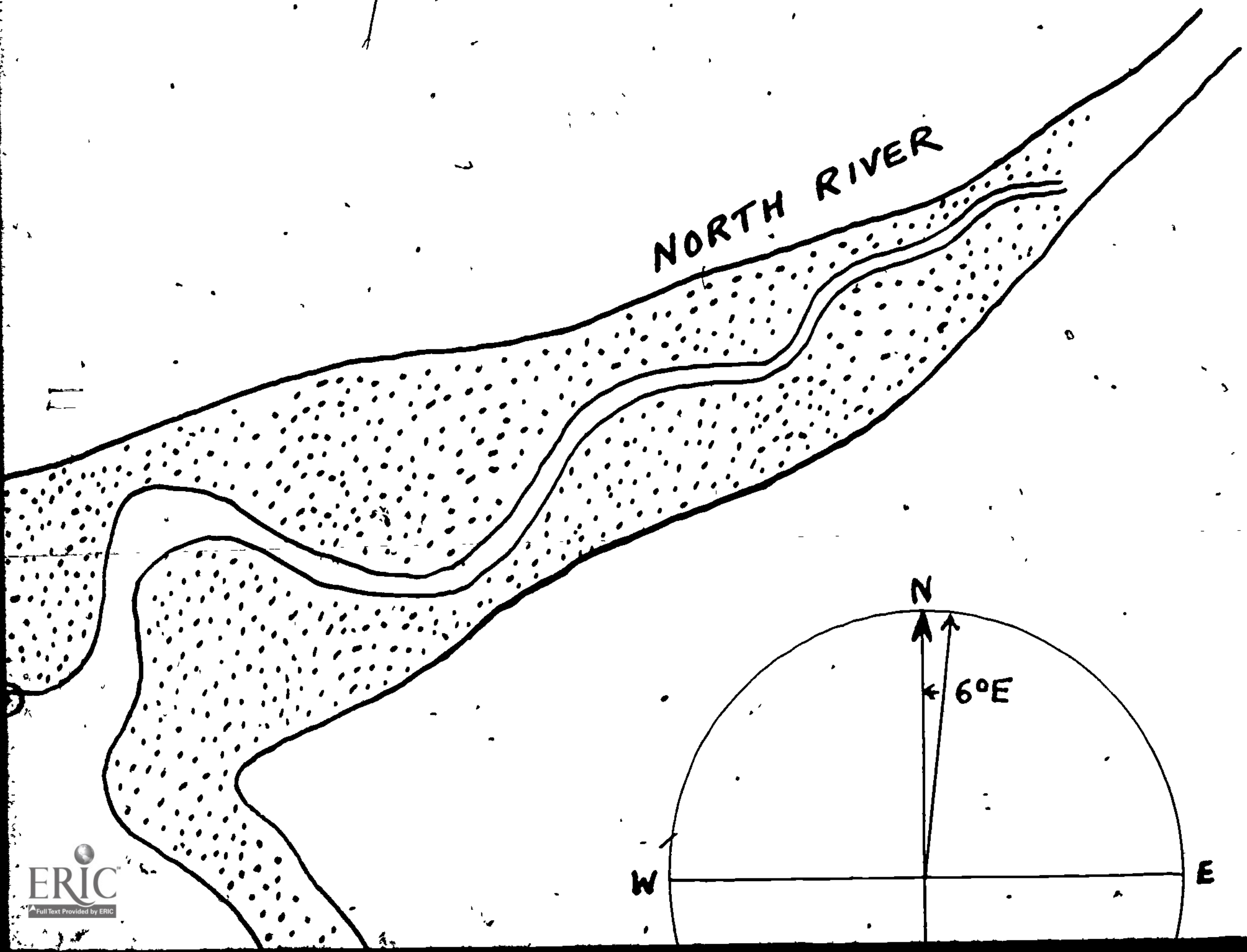
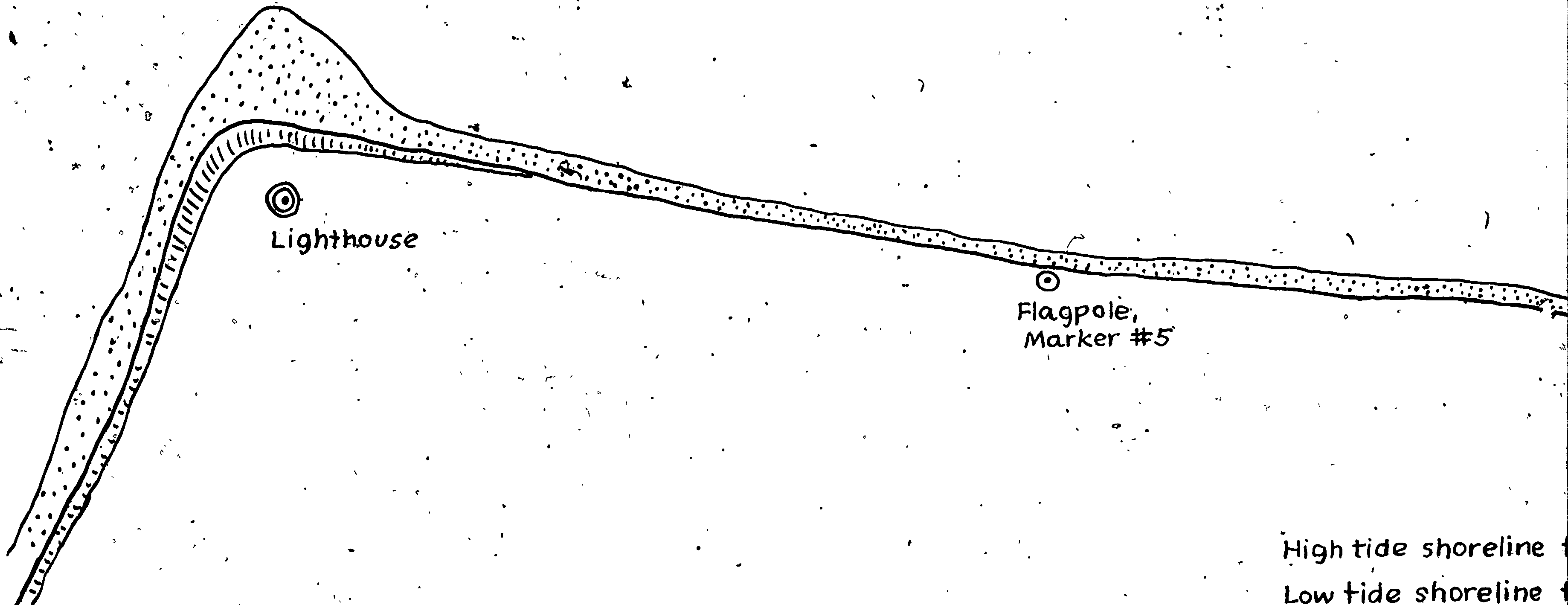
Data Sheet 5 of 5

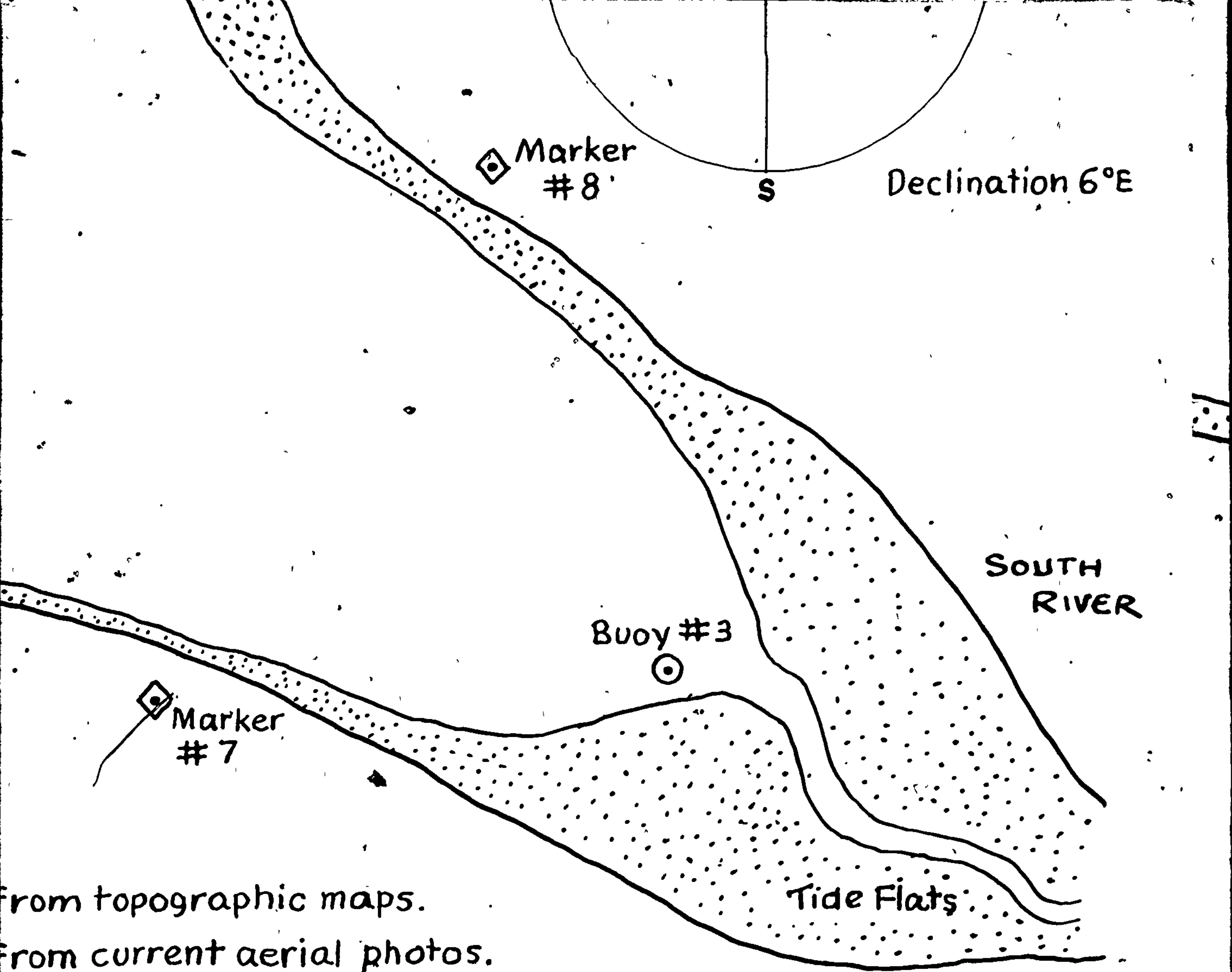
Date & Time: 17-18 June 1972 Locality: Hypo Bay Instrument: Bottle #2 Observers: Team C

Station No.	Depth	Temp. °C	S‰	Station No.	Depth	Temp. °C	S‰	Station No.	Depth	Temp. °C	S‰
7(2350)	0	19.8	3.0	OMIT EBB TIDE OBSERVATIONS							
(2355)	2	19.0	8.0	TROUBLE WITH GEAR							
(2401)	5	15.2	19.8								
8(0028)	0	18.7	16.5								
(0033)	5	16.1	25.0	7(0430)	0	21.1	0				
(0040)	10	14.9	28.3	(0439)	2	20.6	5.0				
(0049)	15	14.3	31.4	(0445)	4	18.1	12.0				
9(0120)	0	19.2	14.3	8(0519)	0	20.0	7.0				
(0125)	5	16.0	25.9	(0530)	5	18.4	12.8				
(0132)	10	14.8	28.9	(0545)	10	15.2	20.9				
(0140)	15	14.0	32.1		~~15~~						
(0152)	20	12.5	34.4	9(0622)	0	20.0	5.0				
				(0630)	5	18.5	12.9				
OMIT STATION #10				(0639)	10	14.0	20.7				
				(0650)	15	13.4	32.3				
					~~20~~ OMIT STA. 10						
			HIGH								


BASEMAP
HYPOTHETICAL BAY
SCALE:
0.0
0.5
1.0
Statute (Land) Miles
Marker #4
Village
Light
Buoy #6
Buoy #2
Buoy #1


NORTH RIVER
N
6°E
W
E


Lighthouse
Flagpole,
Marker #5
High tide shoreline
Low tide shoreline



from topographic maps.

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