EFFECT OF WASTE DISCHARGES INTO A SILT-LADEN ESTUARY A CASE STUDY OF COOK INLET, ALASKA

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Publication No. IWR 26

November, 1972

ACKNOWLEDGEMENTS

The work upon which this report is based was supported in part by funds (Proj. B-015-ALAS) provided by the United States Department of the Interior, Office of Water Resources Research, as authorized under the Water Resources Act of 1964, as amended.

Additional support was provided by the Borough of Anchorage, Alaska.

The authors wish to thank Don Rosenberg of the Institute of Marine Sciences, University of Alaska, for his assistance with the cruises.

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ABBREVIATIONS USED IN THE TEXT

ml(s)	milliliter(s)
mg/l	milligrams per liter
ppm	parts per million
ppb	parts per billion
$^{o}/oo$	parts per thousand
mgal	million gallons
C	degrees Celsius
F	degrees Fahrenheit
ft	feet
sq ft	square feet
cu ft	cubic feet
mi	mile
sec	second
hr	hour
BOD	Biochemical Oxygen Demand

PREFACE

Cook Inlet is not well known. Although its thirty-foot tidal range is widely appreciated, its other characteristics, such as turbulence, horizontal velocities of flow, suspended sediment loads, natural biological productivity, the effects of fresh water inflows, temperature, and wind stresses, are seldom acknowledged. The fact that the Inlet has not been used for recreation nor for significant commercial activity explains why the average person is not more aware of these characteristics. Because of the gray cast created by the suspended sediments in the summer and the ice floes in the winter, the Inlet does not have the aura of a beautiful bay or fjord. The shoreline is inhospitable for parks and development, the currents too strong for recreational activities, and, because of the high silt concentration, there is little fishing. Yet, Cook Inlet, for all its negative attributes, can in no way be considered an unlimited dumping ground for the wastes of man. It may be better suited for this purpose than many bays in North America, but it does have a finite capacity for receiving wastes without unduly disturbing natural conditions.

This report was written for the interested layman by engineers and scientists who tried to present some highly technical information in such a manner that it could be understood by environmentalists, concerned citizens, students, decision makers, and lawmakers alike. In attempting to address such a diverse audience, we risked failing to be completely understood by any one group. However, all too often research results are written solely for other researchers, a practice which leads to the advancement of knowledge but not necessarily to its immediate use by practicing engineers nor to its inclusion in social, economic, and political decision-making processes. We hope this report will shorten the usual time lag between the acquisition of new information and its use. Several additional reports will be available for a limited distribution. These will be directed to technicians who wish to know the mathematical derivations, assumptions, and other scientific details used in the study. Technical papers by the individual authors, published in national and international scientific and engineering journals, are also anticipated.

INTRODUCTION

The fact that all of the Anchorage area's sewage flows untreated into Cook Inlet has scientific interest, particularly because of its effect on the environmental quality of Inlet waters and adjacent beaches. In addition, when one realizes that approximately one-half of Alaska's population lives and works in the Anchorage area, this problem assumes a more immediate significance. In this era of environmental awareness, many residents will be concerned with the disposal facilities presently under construction, their effectiveness, and the likelihood of their expansion in the near future.

What environmental effects can be expected if significant quantities of domestic sewage are discharged into a far northern estuary having a great quantity of glacial silt? And what is the present environmental state of Knik Arm as a result of the historical discharge of all of Anchorage's wastes? These were the questions we sought to answer. The first has significance for many areas along the Alaska coastline. The second is directed specifically to Knik Arm.

Background

The physical environment determines which biological communities can exist in a body of water If these conditions and communities are changed in any way from their natural state through man's influence, the waters are labeled "polluted". We must be careful in using this term since it means different things to different people. Pollution, as used here, refers either to a detectable change in the ecology or to a threat to the public health of the local human population which can be attributed to non-natural events such as the discharge of sewage, waste heat, insecticides, or industrial wastes into the waters. These situations are not mutually exclusive. They can result simultaneously from the same or different discharges, and either one can occur without the other.

The major source of pollution in the upper Cook Inlet area is the domestic waste generated by the Anchorage metropolitan area. Although some industrial wastes undoubtedly make up a part of the waste, in this study they can be neglected. Domestic waste is made up of the water supply of the city plus all the materials put into it during its use in homes, commercial establishments, and industrial operations. Water is usually used for cleaning, cooking, and as a transport medium for removing sanitary wastes. The impurities added by man's use of the water can be further described as being soluble or insoluble, organic or inorganic, flotable or settleable, and biodegradable or nonbiodegradable. Each of these classifications can be further characterized as to chemical composition: carbohydrate, protein, fat, *etc.* Some parts of the waste may be toxic; their mere presence will endanger the well-being of man or other life. The presence of such materials in the domestic waste of Anchorage is rare.

The biodegradable organic fraction of sewage represents a ready source of food for the microorganisms naturally present in the water. Microorganisms must have metabolizable organic matter to stay alive; in addition, they require oxygen for their metabolic processes. But only a limited quantity of oxygen can be dissolved in water, and its concentration is inversely proportional to the water temperature. All other life forms must compete with the microorganisms for this oxygen resource. Thus, if an organic waste put into the water is utilized by the microorganisms for food, more oxygen will be consumed than would have been in the pristine condition. Should the level of oxygen become too low, the water turns septic, a condition which can support only the less desirable (from man's viewpoint) forms of life. The Biochemical Oxygen Demand (BOD) is a measure of the amount of oxygen required by the microorganisms to stabilize (oxidize) the organic matter present in a waste. The test for BOD is usually performed in the laboratory under standard conditions at 20C (68F) for a five-day period. The amount of BOD is expressed as parts per million (ppm), by weight, or as milligrams per liter (mg/l). Since the average domestic waste has a BOD of about 225 mg/l and the oxygen saturation value of water is 11.3 mg/l at 10C (50F), one can readily appreciate the problems that can arise.

Bacteria and viruses are also present in domestic sewage, but the majority of these microbes are harmless to man and other life. They usually die quite rapidly when placed in a cold, estuarine environment. Some, however, have a remarkable capacity for survival under the harshest of conditions and can become a public health menace. They rarely interfere with the natural life cycle of the organisms already present.

Once a waste is discharged into a water course, it is mixed and dispersed, and a significant dilution takes place which serves to prevent the development of severe septic conditions. Approximately sixty percent of domestic sewage is soluble. If the volume of water is very large relative to the amount of waste, and if enough mixing occurs, the soluble portion is practically undetectable. However, some of the waste is of a form which causes it to settle out in the vicinity of the discharge point. It blankets the natural bottom of the body of water and creates a septic situation. Although this deposit generally covers a relatively small area, because of the lack of dispersion it can create rather serious problems.

Our Approach To The Study

Our approach to the study of the pollution potential of Cook Inlet was predicated on the fact that the Inlet is extremely large compared with any man-induced inputs, large enough to have some areas which could be shown to have had no influence from any waste discharge. These areas were to be studied and then used as controls in comparison with areas near existing waste outfalls. The study area and the locations of the more important inputs for this study area, the major fresh water rivers and the sewage outfalls, are shown in Fig. 1.

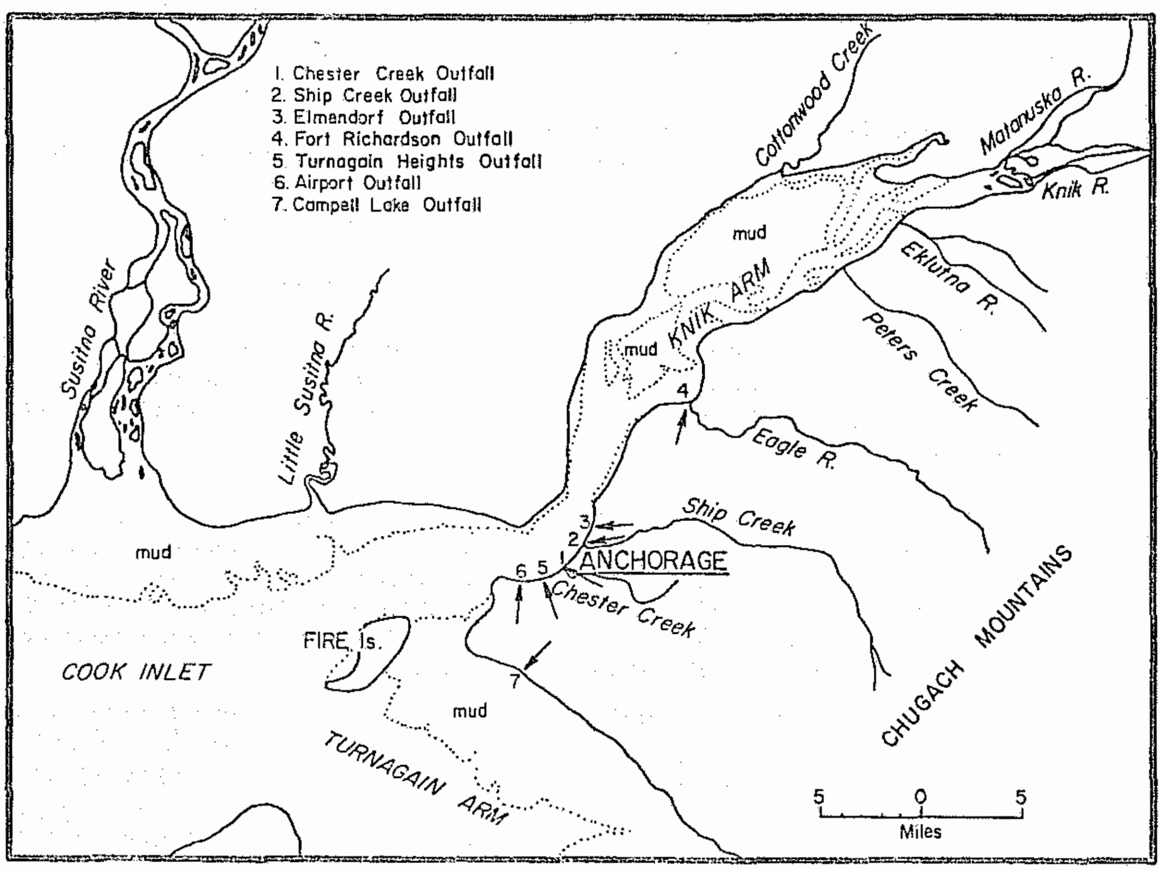


Fig. 1. Map of the Knik Arm region showing the major sewage outfalls (indicated by arrows)

TABLE 1. INSTITUTE OF WATER RESOURCES KNIK ARM CRUISES

	Water Chemistry Nutrients	Salinity	Dissolved Oxygen	pH	Water Temperature	Suspended Solids	Bottom Grabs	Core Samples	Coliform	Tidal Currents	Plankton Dregs
IWR CRUISE #1 Nov. 6-7, 1969, M/V Arctic Wind	9	9	9	8	7	10	8	*	*	*	*
IWR CRUISE #2 March 5, 1970, M/V Chilcoot	10	10	10	5	10	*	11	*	11	*	5
IWR CRUISE #3 May 21, 1970, M/V Chilcoot	8	8	8	8	8	8	19	*	19	*	8
IWR CRUISE #4 Aug. 17, 1970, R/V Acona	9	8	9	8	9	9	14	2	9	2	*
IWR CRUISE #5 Nov. 2-3, 1970, Tug Southwind and Highway Department Barge	*	3	*	*	1	3	*	*	2	1	*
IWR CRUISE #6 Nov. 28, 1970, Helicopter	*	*	*	*	*	*	7	7	*	*	*
IWR CRUISE #7 Dec. 24, 1970, Helicopter	*	*	*	*	*	*	7	7	*	*	*

Numbers indicate the number of sampling stations. 1-5 samples were obtained at each station.

We investigated the following aspects of the Inlet waters:

1. the currents, in order to calculate the mixing and dispersion patterns of the waste materials;
2. the chemical quality, in order to determine whether detectable concentrations of contaminants could be located;
3. the free-swimming microorganisms throughout Knik Arm, in an effort to delineate the area of influence from the existing waste discharges;
4. the bacteriology, in order to determine which organisms were of sewage origin; and
5. the bottom muds near and away from Chester Creek outfall, the major existing outfall, in an effort to assess the effects of the waste discharge on the biological community in the benthic layer.

We expected the greatest influence from domestic sewage to be in the vicinity of the Chester Creek outfall [shown as (1) in Fig. 1] since it contributed most of the waste to the Inlet. Much of the detailed biological and chemical sampling was done in this region. This outfall was expected to exemplify the "worst case" situation since the waste was subjected to no treatment whatsoever and consisted of both soluble and settleable material. Although the pipeline into the Inlet is described as an outfall, it is, in fact, a sewer line extending onto the mud flats which becomes exposed at low tide.

The extent of our field effort is indicated in Table 1. Obtaining field data in Cook Inlet is extremely costly. Not only must a suitable ship be found and chartered, but four to eight technical people must be on board with large amounts of expensive instruments and sampling gear. Analysis of samples, particularly biological samples, is very time-consuming and must be done after the cruise in a well-equipped laboratory. A sampling program sufficient to completely describe Knik Arm alone would cost over three million dollars, a sum out of proportion to the economic base of Alaska.

THE PHYSICAL DISPERSION OF WASTES IN KNIK ARM

Introduction

We turn now to the fate of the waste once it enters the Inlet and becomes dependent upon the natural physical forces of the water mass. Its dispersion depends primarily on the physical environment of the Inlet waters and a number of boundary conditions. The hydraulic characteristics of the Arm dominate the dispersion of the wastes. The primary forces of interest are the thirty-foot tides which generate the tidal currents which in turn act on the wastes as a function of time. If a short time period is considered, the current is very unsteady, varies as a sine curve, has a large traverse, and mainly acts as a transport mechanism to remove the waste from the point of injection. If one considers a longer time span, the net effect of the waste input is different. For instance, when the time span is several weeks, any parcel of waste which has been put into the Arm will return to the point of input twice each tidal cycle, or four times per day. The net result is that the waste, along with the water mass into which it was discharged, simply sloshes back and forth with little or no net movement toward the open sea. It can easily be seen that if a stable, nondecaying material (termed a "conservative" waste) such as a salt, were to be continuously put into the waters of the Arm, it would build up to an extremely high concentration. The fact that this does not occur is attributable to two mechanisms. The first and more important is the dispersion or diffusion action which is characteristic of Cook Inlet's high velocity regime. The dispersion phenomenon acts to transport the wastes into adjacent water masses, thereby constantly diluting the waste with more and more water. The second factor is the fresh water input from the surrounding land mass which tends to push the whole water mass slowly toward the sea and away from the immediate area. Both of these factors are considered in detail in the following pages.

Natural Boundary Conditions

The shorelines, bottom, and other natural geometric boundaries are stable and easily measured. Because the Inlet is an arm of the North Pacific Ocean, its tidal heights and variations are dictated by this body of water. The primary inputs to the Inlet from the land are the fresh water flow and the suspended sediments. From the atmosphere there are the sun's radiation, direct precipitation, wind, and heat. Inputs from the seaward boundary are salinity (the sea water itself) and tidal energy. Of the land, air, and sea inputs, the fresh water, sediment, and tidal forces are dominant.

TABLE 2. MEAN MONTHLY DISCHARGES (cu ft/sec) FOR STREAMS FLOWING INTO KNIK ARM

	JAN	FEB	MAR	APR	MAY	JUN	JUL	AUG	SEP	OCT	NOV	DEC	YEAR
Chester Creek	15.6	13.9	14.1	24.8	27.1	26.2	24.5	25.7	29.3	29.2	21.3	19.3	22.5
Ship Creek	14.8	7.4	7.3	16.6	132.0	419.0	313.0	224.0	204.0	137.0	47.0	28.1	129.0
Eagle River	63.3	55.0	54.4	63.0	282.0	1205.0	1916.0	1876.0	1032.0	352.0	133.0	80.6	597.0
E. Fork Eklutna R.	29.0	25.0	21.1	22.8	99.5	355.0	439.0	389.0	187.0	91.9	47.1	33.5	145.0
W. Fork Eklutna R.	1.2	0.5	0.0	0.6	25.5	246.0	530.0	552.0	196.0	20.7	5.0	2.5	132.6
Knik River	704.0	601.0	454.0	633.0	2426.0	10674.0	26794.0	21291.0	12321.0	4285.0	1943.0	954.0	6924.9
Matanuska River	632.0	527.0	472.0	671.0	2866.0	10487.0	12981.0	10286.0	5153.0	1933.0	929.0	707.0	3900.9
Cottonwood Creek	15.9	15.4	11.9	13.5	13.6	15.7	17.0	19.1	17.5	14.5	13.1	13.1	15.1
TOTAL	1475.8	1240.2	1034.8	1445.3	5871.7	23420.9	43014.5	34662.8	19109.0	6863.3	3130.5	1837.1	11944.6

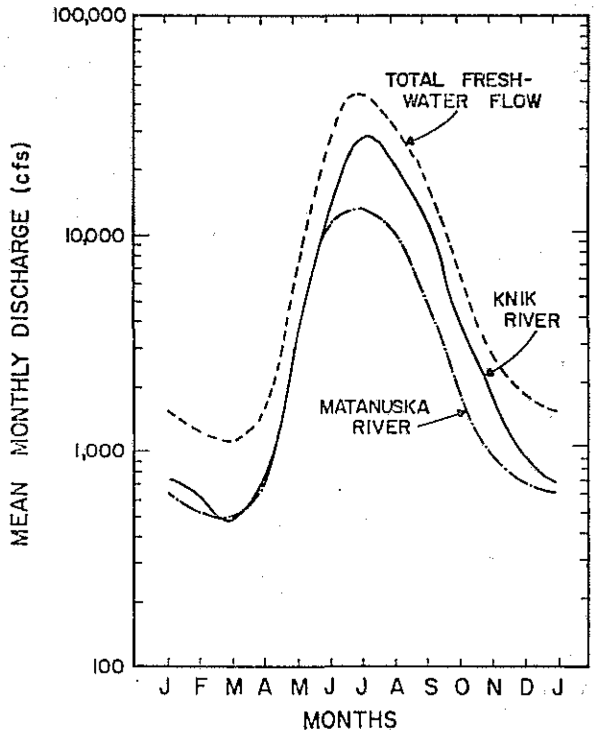


Fig. 2. Time variation of the major freshwater inputs to Knik Arm

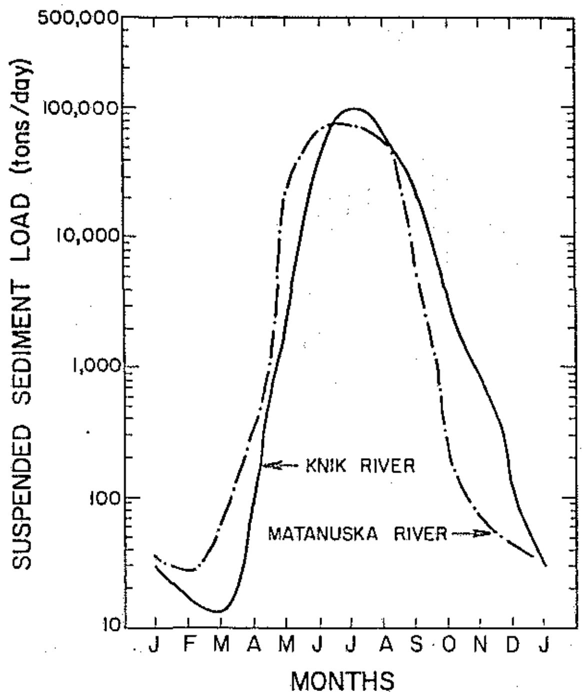


Fig. 3. Time variation of the mean suspended sediment inputs to Knik Arm

The fresh water flow into Knik Arm comes primarily from two sources – the Matanuska and the Knik Rivers (Fig. 1). There are other sources, but as is indicated in Table 2, these two dominate the total flow. The most important characteristics of the fresh water flow are the total flow rate at any given time and the variation within an annual cycle. The average estimated monthly discharge for the two main rivers is shown in Fig. 2 with the collective total for all inputs. Significant flow begins in May and ends in September. As indicated, the sum of the peak flows of the Matanuska and Knik Rivers is 39,800 cu ft/sec (July), compared with a total peak flow of 43,000 cu ft/sec for all sources. The winter period of six-months duration provides practically no flow, with the result that little transport takes place past the Anchorage outfalls. Past records indicate that the flow on a given date varies little from year to year. This is to be expected since both rivers drain large areas and derive their flood flow primarily from snow and glacier meltwaters. Both the size of the basin, which dampens local variations, and the snowmelt, which depends upon the temperature, contribute to this lack of variability. It should be added that the Knik River historically has been subjected to a glacier-dammed breakout at Lake George which has caused peak flows of up to 355,000 cu ft/sec. This breakout has not occurred in recent years, however, and probably was not a significant transport factor when it did occur. At most, its effect was transitory and had little influence upon the long-term considerations described in this report.

The average sediment discharges of the three major rivers are shown in Fig. 3. The data on which these curves are based show much more annual variation than do the water flow data. Although the presence of sediment is of some import to the fate of waste materials, its variability from year to year is of such minor concern that it was considered irrelevant to the project. It is interesting to note, however, that the sediment variation is more pronounced during the two summer months than is the fresh water inflow. This phenomenon is explained by the fact that the fresh water flow is a function of precipitation and temperature throughout the whole drainage basin while the suspended sediment load is a function mainly of the temperature at the higher-elevation glaciers.

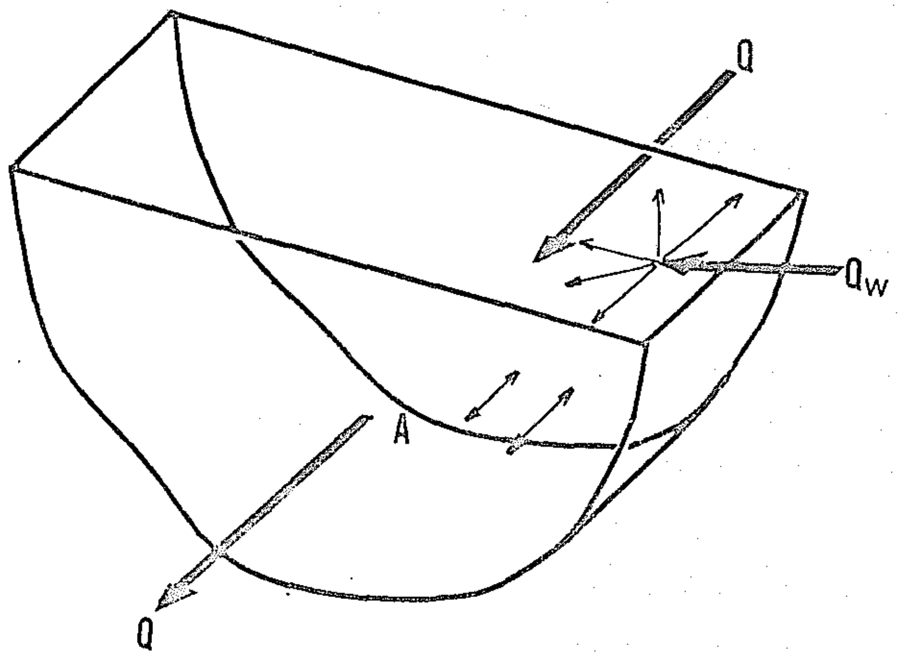


Fig. 4. The control volume

The Dispersion Phenomenon

In studying dispersion, one is concerned with the advective flow (also termed "through-flow"), which moves a water mass from one position to another within the Inlet, and with dispersion, which causes a given parcel of water to be intermixed with the overall water mass. These two features are interrelated and an understanding of one depends upon an understanding of the other. This section will consider the influences which affect the flow and the dispersion mechanism in Knik Arm. In order to gain a good understanding of this phenomenon and its effect on waste discharge, we must have some theory or model on which to base our explanation of physical measurements. The model can also be used to explain certain features which are difficult or impossible to measure as well as to predict future occurrences. In the final part of this section the results of several of our modeling attempts will be considered.

Basis of the Modeling Effort

To facilitate the discussion which follows, we will imagine a theoretical body of water and will label certain of the fluid phenomena associated with it. Our basis for reference will be an imaginary volume contained within the boundaries of the Inlet and an imaginary boundary some distance above the surface of the water. We will call this the control volume (Fig. 4). We will be concerned with the velocity at the upper and the lower end of the control volume, the rise and fall of the water surface elevation, and some measure of the degree of turbulence or mixing at the upper and lower boundaries of the control volume.

If we consider the control volume to be filled with water and to have a through-flow velocity, Q, we can then express the principle of conservation of mass by an equation which accounts for the mass coming into or out of the control volume, changes in the mass of the constituent within the control volume, and decay or growth of the material within the control volume. This equation is:

$$\frac{\partial c}{\partial t} = \frac{E}{A}\frac{\partial}{\partial x} A \frac{\partial c}{\partial x} - \frac{Q}{A}\frac{\partial c}{\partial x} \pm S, \qquad \text{Eq. 1}$$

(1) (2) (3) (4)

where c is the concentration of the substance we are attempting to model, (such as the chloride ion, BOD, or dissolved oxygen), expressed as ppm or mg/l; E is a diffusion coefficient, in sq ft/sec; x is distance, in feet; and A is the cross-sectional area, in sq ft, and a function of the water surface elevation; t is time, in seconds; and Q is the fresh water advective flow, in cu ft/sec. The first term of the equation expresses the rate of increase of a substance, as measured by the concentration within the control volume as a function of time. The second term expresses the net rate of transfer of material into the control volume which is due to turbulent diffusion and shear dispersion at the upper and lower boundaries. The third term describes the rate of transfer of material out of the control volume which is due to the advective flow. The removal or addition of a substance derived from some source within the control volume itself is given by the fourth term, S, most commonly described by the exponential decay function -Kc.

Eq. 1 is written to use the mean values over several tidal cycles for the various parameters; from it were calculated the mean water surface elevation, H, and the oscillating tidal flow, Q, for Knik Arm. These results are shown graphically in Fig. 5.

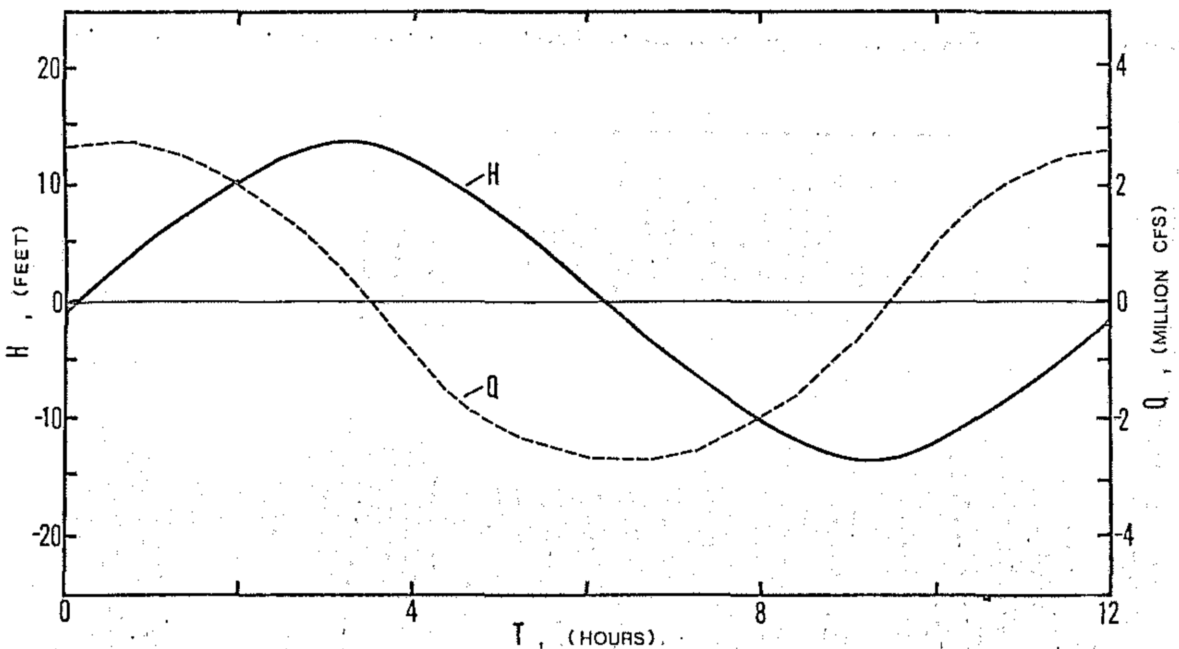


Fig. 5. A plot of the calculated tidal height (H) and tidal flow (Q) over one tidal cycle at the Anchorage city docks

The Mixing Characteristics of the Tidal Currents

To understand the mixing characteristics of the tidal current, we will base our model on the equation which describes the dispersion within a water mass. We will apply this equation to two types of situations. In one we will consider the flow to be only one-dimensional in nature; that is, variations in the concentration of a substance will be predominately up and down the Inlet rather than across. In the other, the two-dimensional model, we will consider variations of flow both up and down and across the Inlet. The advantage of the one-dimensional model is that the mathematical manipulations of the equations and their solutions are fairly straightforward and easily expressed. Its disadvantage, of course, is that important two-dimensional effects cannot be included. The two-dimensional modeling effort has the advantage of explaining effects which the one-dimensional model cannot.

In making our calculations, we will assume a uniform cross-section with the following characteristics: an area equal to 7.11×10^5 sq ft, a top width equal to 15,000 ft (2.84 mi), and a mean depth of 47 ft. This information represents an approximation, of course, but it will be suitable for our purposes here. We will also use average advective velocities calculated from the March and July flow values: March = 0.00146 ft/sec, 126 ft/day, or 0.02 mi/day; July = 0.605 ft/sec, 5,227 ft/day, or 1.0 mi/day. Note that the advective velocity is very small during the six winter months. This is especially evident when it is compared with the high tidal velocities found in Knik Arm – up to 8 ft/sec. Even the July advective flow is small when compared with the tidal velocity, approximately one twentieth of the maximum tidal velocity. However, it is important to remember that the advective flow exerts itself over a long period of time. In a period of one day the average movement of the water mass in July, for example, would be approximately one mile down the Arm. It would seem, therefore, that the advective force is important to the fate of the wastes. However, we must keep in mind the dominance exerted by the tidal mixing phenomenon. As we shall see later, even a large advective flow has little long-term effect.

The One-Dimensional Model. We now are ready to apply the results of the one-dimensional model to the data. We will first consider the Arm to be in a non-time-varying state with no decay of the substance and with a constant cross-sectional area. Eq. 1 then becomes:

$$0 = E\frac{d^2S}{dx^2} - Q\frac{dS}{dx}, \qquad \text{Eq. 2}$$

which has the following solution:

$$S = S_o e^{\frac{Q(x - x_o)}{E}}, \qquad \text{Eq. 3}$$

where $S = S_o$ at $x = x_o$, the location of the source of the substance. This equation is a straight line when plotted as log S versus x; it is useful for calculating the diffusion coefficient, E:

$$\frac{Q}{E} = \frac{\ln S - \ln S_o}{x - x_o} \qquad \text{Eq. 4}$$

If we let S be the salinity of the water, we can use the salinity data from the various cruises, adjusted for location at low tide, to calculate values for E. (These data are shown graphically in Fig. 6). For March, E was found to be 3140 sq ft/sec; for May, 6300 sq ft/sec; for August, 5050 sq ft/sec; for November, 4340 sq ft/sec. The differences in these values are probably not attributable to the time of the year but are simply the result of the error inherent in the sampling process. Their average is 4700 sq ft/sec, or 13.95 sq mi/day, as compared with 7 to 10 sq mi/day given by Harleman (1968) and approximately 10 sq mi/day as given by O'Connor (1967). It is considerably below the value of 443 sq mi/day reported by Marine Advisors (1966) in a previous study.

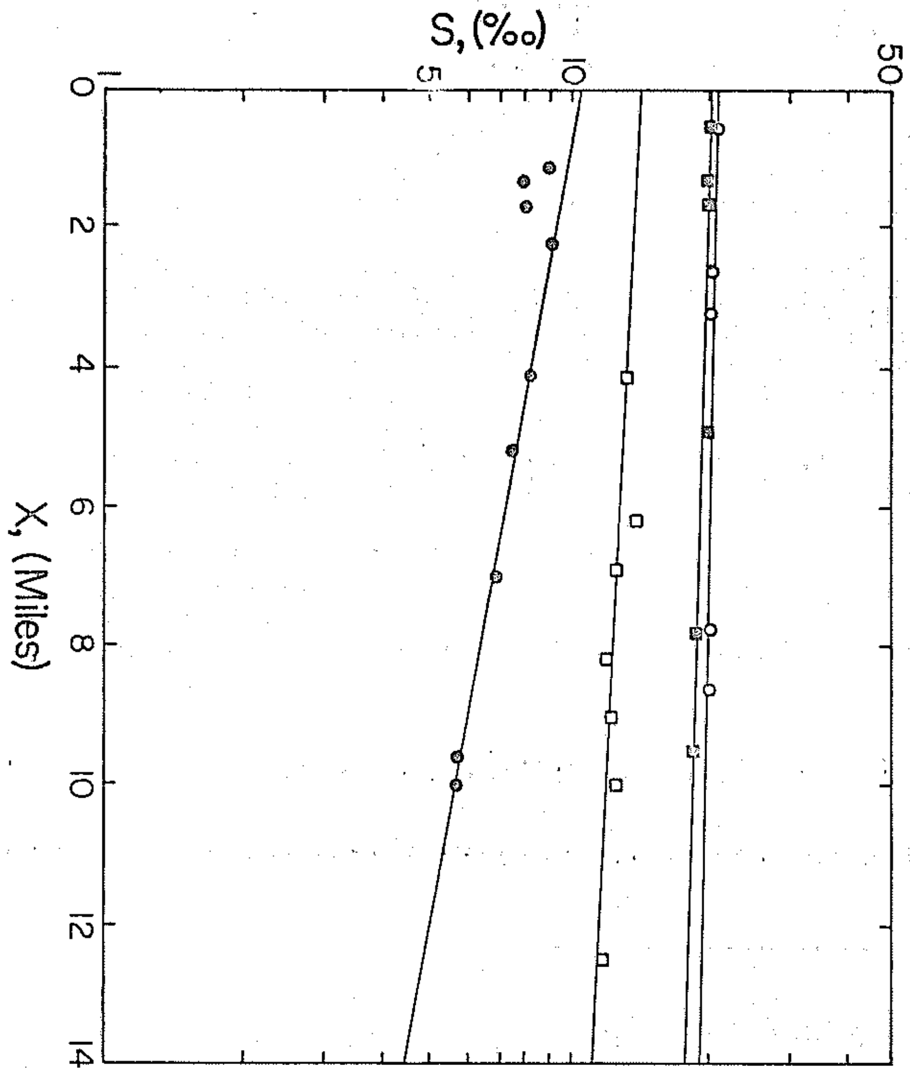


Fig. 6. A plot of salinity (S), in parts per thousand, versus distance upstream (x), in miles, for cruises 1 - 4

We can now use this value of E to calculate the expected concentration of the waste BOD that might exist in the Arm. In doing so, we will make the additional assumption that the waste is subject to a first order, or exponential, decay. With this in mind, we can write the equation:

$$0 = E\frac{d^2c}{dx^2} - Q\frac{dc}{dx} - KC. \quad \text{Eq. 5}$$

The solution to this equation is:

$$c = c_o e^{\frac{Qx}{2E}[1 \pm m]} \quad \text{Eq. 6}$$

where

$$m = \sqrt{1 + 4KE/Q^2} \quad \text{Eq. 7}$$

We can calculate the concentration at a section across from the outfall as:

$$c_o = W/Qm, \qquad \text{Eq. 8}$$

using a waste discharge rate of W = 4.1 mgal/day x 100 ppm BOD and values of Q of 97.787 mgal/day for July and 669 mgal/day for March. The m in the equation weights the die-off constant, K, the diffusion coefficient, E, and the velocity, Q, in such a way as to account for all three factors. When the appropriate values for m and Q are included with W in Eq. 8, the approximate concentrations of the BOD in the section across from the outfall can be calculated to be: c_o for March = 0.003226 ppm; c_o for July = 0.003873 ppm. Substituting these values for c_o into Eq. 6, we can calculate the distribution of BOD upstream and downstream from the outfall. The result is a very low initial concentration which drops off rapidly, both upstream and downstream from the outfall (See Fig. 7). Note the small difference between the curves for July and March; this gives an indication of the significance of the tremendous mixing of the Inlet as well as the importance of the die-off rate.

These computations and the graphs in Fig. 7 illustrate important points about the hydrodynamics of Knik Arm in relation to waste distribution. What we have here is essentially a huge mixing basin which is being continually mixed twice a day by the tidal currents. Although the mixed water is also moving slowly downstream because of the advective fresh water flow, the mixing is so intense that this advection has no appreciable effect on the concentration of BOD in the vicinity of the outfall. Another point which should be noted is that even if the waste discharge were high, the BOD would be reduced to almost 10 percent of its value within 20 miles upstream and downstream of the outfall point.

We could also apply the equation used in the computation of the waste concentration to compute the dissolved oxygen concentration. Using a similar procedure, we can calculate the maximum deficit of dissolved oxygen at the section across from the outfall to be 0.00561 mg/l. The distribution of this deficit would be almost identical, both upstream and downstream, to that of the waste concentration as measured by BOD.

The Two-Dimensional Model. As we have seen, according to the explanation offered by the one-dimensional model, the waste discharge can be expected to have relatively little impact upon the waters of the Inlet. However, keeping in mind the limitation of such one-dimensional models, one might have expected a somewhat different result, because even though it is the narrowest part of the Inlet, Knik Arm is still relatively shallow and wide. In order to take into consideration differences across the Inlet, we undertook a preliminary modeling effort to account for two-dimensional effects. The basis for this model was essentially the same equation we used for the one-dimensional model except that it extended in both directions. The assumptions underlying the two-dimensional model were these: fresh water advection is one-dimensional; depth is constant; and dispersion is accounted for both across up and down the Inlet. In all cases the computations were made considering the system to be at equilibrium. Because the mathematical equations for this type of configuration, with these assumptions, are very difficult to solve directly, we used a computer simulation.

A variety of cases were considered. A single outfall was compared with a distribution of outfalls; high advective summer flows were compared with nearly zero flow in the winter; and various decay constants were considered. Various geometries of the model were studied, and different locations of the outfall (at shore, one-quarter of the way across the Arm, and half-way across the Arm) were evaluated. Two examples are shown in Figs. 8 and 9. The first illustrates the concentration contours that result when a die-off constant of 0.46/hr is used; the second shows the result when there is no die-off. In each the concentration is re-

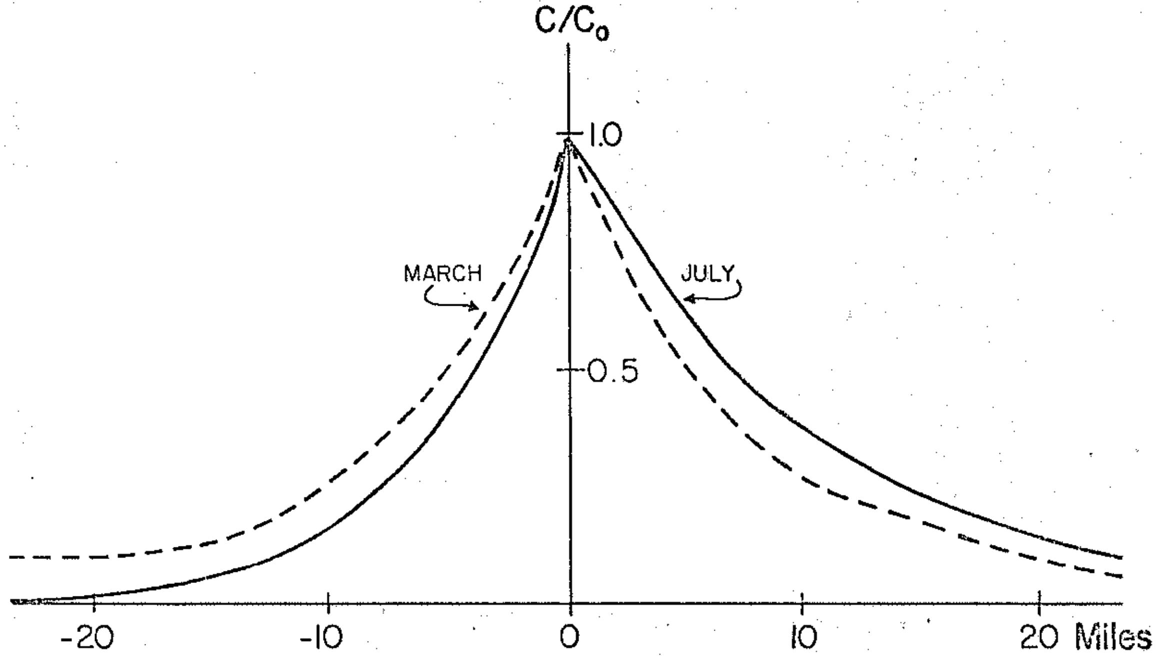
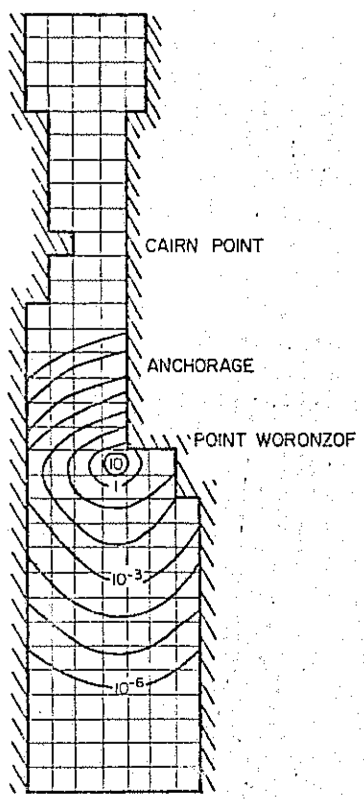


Fig. 7. A plot of c/c_o versus distance (negative values indicate distance upstream)



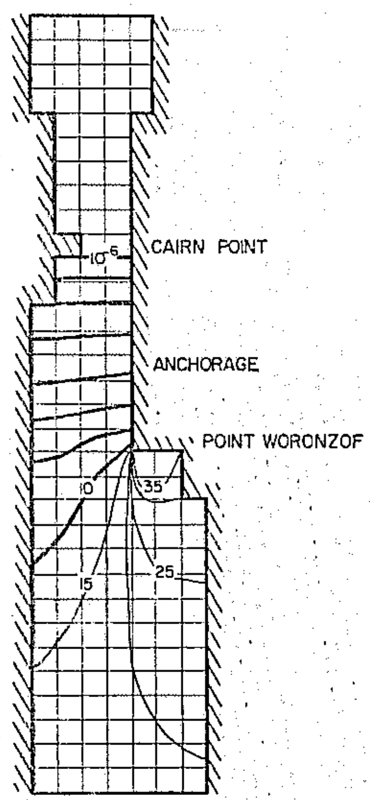


Fig. 8. Concentration contours resulting from diffusion modeling with a die-off constant (K) of 0.46/hr (contour lines in powers of 10, with the original concentration at 10 at one-fourth the distance across Knik Arm. E = 250 sq ft/sec; A = 3333 ft; Q_x = 0.1 ft/sec)

Fig. 9. Concentration contours resulting from diffusion modeling with no die-off: K = 0.0/hr (Heavy lines indicate intervals of powers of 10; light lines intervals of 5. The original concentration at the shore is 10. E = 250 sq ft/sec; A = 3333 ft; Q_x = 0.1 ft/sec)

presented as a percentage of the concentration at the outfall. It must be kept in mind that the concentration at the outfall is diluted in the rectangle which includes the outfall point. As we learned from the first model, this concentration is extremely low; therefore, the other concentrations are correspondingly low. These distributions give a fairly good indication of the effects of two dimensions and of the effects of moving the outfall.

Summary

The conclusions to be made from the hydrodynamic studies can be briefly summarized as follows:

1. In terms of its ability to assimilate wastes, Cook Inlet, and in particular Knik Arm, should be considered to be a completely and continuously mixed basin. It is somewhat misleading to speak of "tidal flushing." The tides do not flush anything; they move the water back and forth and mix it intensely.

2. While the fresh water input is significant, it does not appear to be appreciably important to waste discharge, primarily because the waste decays. This decay, in combination with the intense mixing, results in little difference in the sewage concentration upstream and downstream from the outfall. However, fresh water advection does affect the concentration of conservative substances. In fact, it was this effect which enabled us to estimate the diffusion coefficient in this area.

3. A one-dimensional model adequately explains many of the effects of waste discharge into the water mass. It clearly illustrates the effects of various decay constants on the distribution of wastes discharged into the Inlet.

4. The two-dimensional model improves our estimate somewhat and illustrates the inadequacies of the one-dimensional model, especially in the vicinity of the outfall.

It should be remembered that in all of our models we assumed the water depth to be constant and the water mass to be completely mixed. This was the best we could do with the information available. Nevertheless, we did obtain useful results and were able to make certain statements about the fate of the waste discharged into the Inlet. One factor for which we have not accounted is near-shore movement. For a considerable distance from the shore the water is shallow. It does not have a high velocity and is therefore not mixed as intensely as the deeper water in the middle of the Inlet. We feel that additional studies should be devoted to these near-shore waters, in particular to the effects of any flow separation which might occur as water flows past various points in the Inlet.

ENVIRONMENTAL STUDIES

Introduction

In this section of the report we describe the physical, chemical, and biological characteristics of the water mass having ecological significance. The physical characteristics include temperature and suspended sediments. The chemical characteristics of greatest importance are salinity, pH, dissolved oxygen, the inorganic nutrients phosphorus and nitrogen, and the organic materials which serve as a food source for the indigenous biota. The biological features are usually considered to be the result of the physical, chemical, and hydrodynamic characteristics. The larger organisms, such as salmon and other fish, are of primary importance to man; however, they were not considered in our study since they are transitory species and use upper Cook Inlet as a migration path only. Of greater concern to us were the macroorganisms (very small but visible to the naked eye), the microorganisms, and the benthos organisms (the bottom dwellers).

The data collected on the sampling cruises yielded a vast amount of information about the areal distributions of the various physical, chemical, and biological indices of pollution. These parameters are of consequence in that they disclose the deleterious effects of a waste discharge long before an environmental catastrophe occurs. The information we obtained indicates that the domestic waste has had some effect on the environment, but so far it has not been harmful. Nevertheless, the continuation of existing practices could show adverse effects within a relatively few years. This possibility has been recognized by the State and Borough. A new plant for the treatment of waste and the facilities for its ultimate discharge into the Inlet are under construction.

Physical Characteristics

Temperature. Water temperatures were measured near the surface, at mid-depth, and near the bottom of all stations. These measurements showed that there was little thermal stratification in the vertical direction at any of the stations. The difference in temperature from the top layer to the bottom layer of water was usually less than 0.1C. This information confirms the hydrodynamic description of the Inlet in this area as completely mixed. Water temperatures varied more widely from season to season with a range from -1.1C in March to 12.4C in August. This observation was expected since biological activity in a water mass increases with increasing temperature. A waste discharge, therefore, would have greater influence in the summer than in the winter.

In addition, the waters are ice-covered for three to four months. A number of factors important to the biota are influenced not only by temperature but also by light penetration.

Suspended Sediments. Suspended sediments are those solid materials which are kept in suspension because of their extremely small size and physical characteristics and the energy input to the system. They range in size from colloidal to rather large particles, the maximum size being dependent upon the energy of the system and the turbulence.

The waters of upper Cook Inlet are extremely muddy and have a very heavy suspended sediment load. This material is derived from the glaciers and glacier streams discharging into the upper Inlet. The material has been referred to in this report as glacial silt and it is a dominant characteristic of many Alaskan estuaries. There are very few populated areas in the world located near the glaciers and silt-laden streams that are typical of a large part of Alaska.

Suspended sediment measurements were made at the surface, mid-depth, and at the bottom by routine gravimetric analysis. The results of these tests are quite complex when viewed from a short time span since the amount of suspended sediment varied with the tides at the time of sampling. For instance, at one station on the November cruise, suspended sediments were 300 mg/l at the surface and 1700 mg/l at 30 ft. At another station, two hours later, values of 2100, 1400 and 2000 mg/l were measured at the surface, mid-depth, and near bottom, respectively. (It is also worth noting that the total suspended sediment load varies with the season although not as drastically as some of the other parameters). These values are extremely high for an estuary the size of Cook Inlet and can be considered to greatly reduce the quality of water in question. The greatest effect of suspended sediments is related to their influence on the transmission of sunlight through the water column. Although a murky, solids-laden water is not conducive to many forms of life for several reasons, of greatest significance is the fact that light cannot penetrate to any great depth.

Chemical Characteristics

pH. The chemical measure of pH is used to describe the relative acidity or alkalinity of a water. The pH scale varies logarithmically from 0 to 14: 0 being acidic, 14 being alkaline, and 7 being neutral. The pH is important to all life forms and to the chemical reactivity of a body of water. Most life forms require a nearly neutral pH to carry on their metabolic processes. The pH of an environment can be changed by a number of factors, such as the introduction of acid or alkaline liquids from waste, by water flowing over a geological formation and dissolving various chemicals from it, or by the natural life processes themselves.

The pH of the Knik Arm waters was measured in a manner similar to that used for the temperature measurements. It was found that there was little variation in the pH either areally or with depth. One would not expect a difference in pH from the water surface to the bottom because of the demonstrated degree of turbulence in Knik Arm. The lowest pH measured was approximately 7.7, observed during May, and at that time the pH varied less than 0.2 throughout the Knik Arm area. The highest pH observed was slightly greater than 8.3; this was measured in August. The pH range from 7.7 in the cold period of the year to 8.3 in the warm can be explained by normal chemical equilibrium processes. The data indicated that the waste discharges had little influence on the pH of the waters.

Dissolved Oxygen. The amount of oxygen that a body of water can contain is a function of temperature (varying inversely with it), the extent of reaeration from the atmosphere, and biological activity. Most textbooks on oceanography, chemistry, and ecology have tables listing oxygen concentration versus temperature for either distilled water or a standard sea water. Cook Inlet, with its high concentration of suspended material, not only has many of the same constituents as sea water, it also has the solids which, in themselves, reduce the ability for the natural waters to hold oxygen in solution. The oxygen saturation value for Cook Inlet waters is therefore variable.

Measurements of the dissolved oxygen in the water were made at all stations and depths on all cruises. Subject to rapid change, it was determined in the field within a few minutes after the water was withdrawn from the Arm. Dissolved oxygen concentrations ranged from 6.9 mg/l in August to 9.1 mg/l in March. The range of saturation values for sea water is from 8.5 mg/l at 18C to 11.3 mg/l at 0C. When the suspended sediment loads are taken into account, the water in Knik Arm can be said to be very nearly saturated with respect to dissolved oxygen. The seasonal variation in dissolved oxygen concentrations is a reasonable one in that the lower values occur during the warmer months when biological activity, and therefore oxygen consumption, is greater. Very little variation was noted from station to station. Some variation would be expected if the waste input were a significant factor in oxygen depletion. The oxygen levels throughout Knik Arm are very nearly equal to the concentrations one would expect were there no waste input. We concluded that there was no recognizable oxygen depletion due to any of the existing waste outfalls.

Salinity. The term salinity denotes the quantity of dissolved inorganic salts per kilogram of sea water. Sea water has a salinity of approximately 34.6 parts per thousand ($^{o}/oo$), which is equivalent to 34,600 mg/l. The salinity of an estuary is somewhat less than that of the open ocean because of the fresh water inflow which dilutes it appreciably. The salinity of Cook Inlet waters varies from 6 $^{o}/oo$ in the summer to slightly more than 20 $^{o}/oo$ in the winter. Considering the total basin, one can see that this variation is significant in that other chemical characteristics of the water, particularly the oxygen saturation values, are depen-

TABLE 3. NUTRIENT ANALYSES

Cruise No.	Date	Total N mg/l			Total P mg/l			Silica mg/l		
		Ave.	Max.	Min.	Ave.	Max.	Min.	Ave.	Max.	Min.
1	Nov. 6, 1969	0.237	0.323	0.141	0.0022	0.0028	0.0009	1.27	1.49	1.04
2	Mar. 5, 1970	0.191	0.210	0.113	0.0074	0.0074	0.0031	1.27	1.40	0.73
3	May 21, 1970	0.147	0.171	0.094	0.0097	0.014	0.0053	1.34	1.69	0.73
4	Aug. 17, 1970	0.21	0.344	0.142	0.0066	0.012	0.0	2.39	2.53	2.22

dent upon salinity. The salinity of Cook Inlet is nevertheless closer to that of sea water than fresh water. We observed little variation in salinity between samples taken at the same station at the same time at the surface, mid-depth, and lower depth — additional evidence of a high degree of mixing in the Inlet. In the absence of strong turbulence, fresh water is often seen to override the salt water where the fresh water streams flow into the estuary. Although this layering occurs to a small degree in the Cook Inlet water mass, such an occurrence is not significant from the standpoint of waste disposal and diffusion.

Because of the greater than 100 percent change in salinity from midwinter to midsummer, the Inlet may be considered an important transition zone between the fresh water and the sea water. This salinity change, which imposes certain stresses upon the microorganisms, coupled with the high levels of suspended sediment, causes the total biological productivity of the Inlet to be quite low.

Nutrients. The term "nutrients" refers to the nitrogen and phosphorus compounds on which the basic biological productivity of an area usually depends. Nutrients act in the aqueous environment in a manner similar to that of the fertilizers commonly applied to the land. Of course, substances other than nitrogen and phosphorus are needed for growth: organic matter, carbon dioxide, vitamins, growth factors, and trace elements, for example. But in nature one of these two elements is usually scarce and is said to limit the productivity of the water. With man's intervention, however, they can reach concentrations which are no longer growth-limiting. The result is the acceleration of growth in a body of water which leads to premature aging of that water, a process labeled "eutrophication." Thus, nutrients are a useful parameter for gauging the influence on a water mass of man's activities. In this study nutrient concentrations were measured to determine whether they were at a level high enough to cause eutrophication.

Silica ($Si0_2$) concentrations were measured in conjunction with the nutrient analyses. (Silica is important to diatoms, a group of organisms which uses it as a building block in the formation of their cell bodies).

Water from the open sea, which is considered uncontaminated and fairly uniform throughout the world, has a phosphorus concentration of 0.07 mg/l. Nitrogen is 0.5 mg/l and silica, 3.0 mg/l. These substances are considered trace elements in sea water, which has a total dissolved solids concentration of 33,000 mg/l. Other values reported for nitrogen, in the nitrate (NO_3) form, range from 0.01 to 0.8 mg/l. For phosphorus, in the phosphate form (PO_4), they range from 0.001 to 0.1 mg/l. These are fairly wide ranges. Their relevance lies in whether the waters of Cook Inlet are high in these constituents relative to sea water.

The average, minimum, and maximum values for total nitrogen [which includes the ammonia (NH_3), nitrite (NO_2), and nitrate (NO_3) forms], total phosphorus, and silica obtained on the four cruises in our sampling program are shown in Table 3. The average value for each of the constituents in the table is the result of 25 individual samples taken at the surface, mid-depth, and near the bottom at each station. All three constituents were found in concentrations lower than those normally found in the open sea. Of course, the waters of Cook Inlet are at no time equivalent to sea water because of the fresh water input, which varies from summer to winter. The fresh water input itself obviously is the source of most of the nitrogen, phosphorus, and silica. The concentrations reflect by their variance from season to season the input from the land mass from which they are derived. It is interesting to note, for instance, that while the highest value for nitrogen was in November and the lowest in May, the highest values for phosphorus were found in May and the lowest in November. While these observations led us to speculate as to their cause, the data were insufficient to confirm any one explanation. Silica concentrations are also seen to depend upon the season of the year. Silica in August is nearly double values recorded earlier in the year. Thus, the major portion of the silica appears to be derived from the inflow from the glacier-fed streams.

No correlations were discovered between parameters measured at the surface, mid-depth, and bottom — additional evidence of the well-mixed nature of Knik Arm. The data were plotted on a map of the area showing the stations and the concentrations of a given parameter at each station. There is one map for each of the surface, mid-depth, and bottom samples, as well as one for each of the parameters: phosphate, nitrate, nitrite, ammonia, and silica. Three examples are shown in Figs. 10, 11, and 12. Fig. 10 shows the phosphate concentrations at the surface on August 17th. It is obvious that some variation occurs throughout the Knik Arm area although none of the values can be directly attributed to a waste input. It is likely that the other characteristics of the Inlet are responsible for this variation. Fig. 11 shows the nitrate concentrations at the surface for the May 21st cruise. Once again, the nitrates do not correlate with the waste inputs. In fact, the nitrate values measured in the Chester Creek area are much lower than those measured in other areas of the Arm. This result is what one would expect to find in a region adjacent to a waste outfall carrying raw sewage. The ammonia concentrations measured at the surface on the May 21st cruise are shown in Fig. 12. Ammonia was high in the immediate vicinity of the Chester Creek outfall and lower in all other areas. This observation is, indeed, indicative of a waste discharge; however, 28 parts per billion (ppb) is an extremely low concentration and is not likely to have significant ecological impact on Knik Arm. Thus, one can state conclusively that there is evidence of the waste input in the Inlet waters immediately adjacent to the Chester Creek outfall but that the concentrations found are well below those found in the open ocean. It is doubtful that significant ecological effects will ensue. The nutrient data for the whole upper Cook Inlet area indicate that this area should be very nonproductive of free-swimming, photosynthetic organisms, the organisms of predominant interest so far as eutrophication is concerned.

Biological Characteristics

Any estuary contains a diversity of organism types; such was found to be true to a degree in Cook Inlet. From the standpoint of total biomass, however, Cook Inlet itself is a very nonproductive body of water. Therefore, the fact that a large number of different species was found is significant in two respects. First, because the water itself is not characteristically polluted, the small biomass cannot be attributed to pollutional loads. Second, additional pollutional loads much greater than those already imposed upon the Inlet would not interfere substantially with the natural ecological cycle. Our primary conclusion from the biological information obtained is that the fate of the discharged waste is influenced more by the physical characteristics of the Arm than by the biological. A more detailed discussion of the biological data will be published as a separate report and will be useful as baseline information for the area.

Bacteria. Coliforms are a group of bacteria common to the intestines of warm-blooded animals. One would expect to find some of these organisms in any body of water, but if they are found in very high concentrations, they are an indication that the water is contaminated with human sewage. One would expect to find coliform organisms in the Cook Inlet

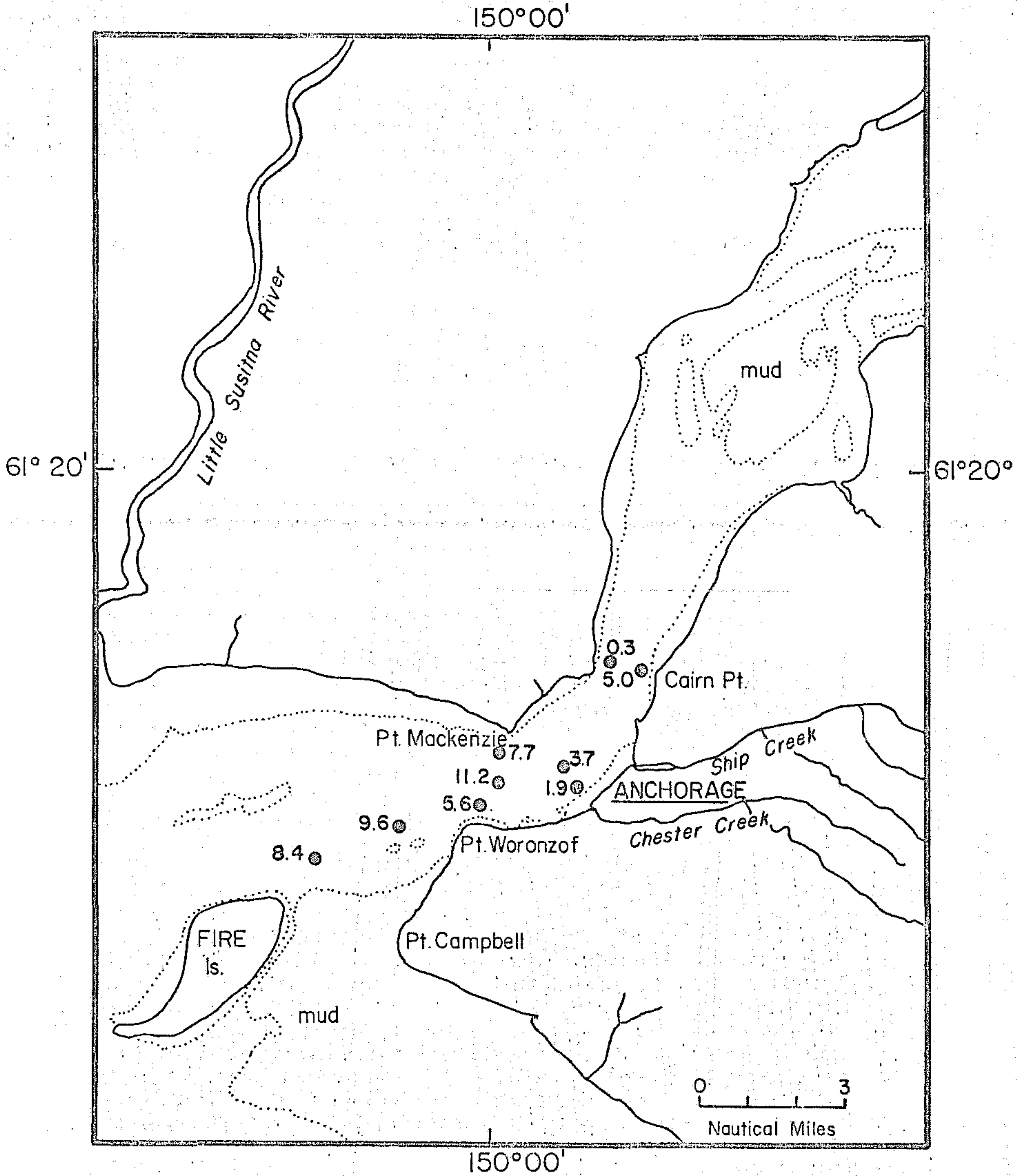


Fig. 10. Surface phosphate concentrations (ppb) for cruise #4, August 17, 1970

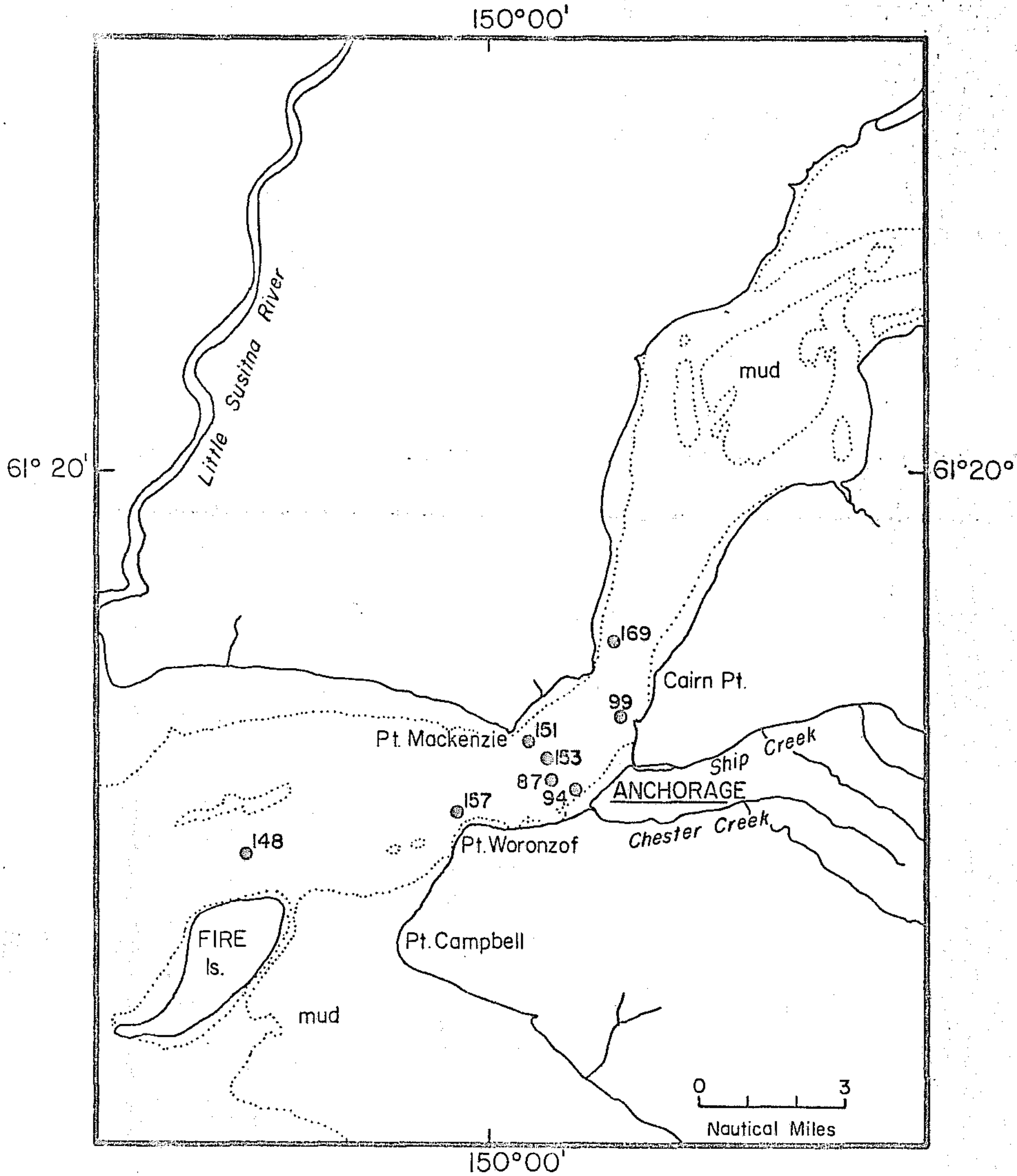


Fig. 11. Surface nitrate concentrations (ppb) for cruise #3, May 21, 1970

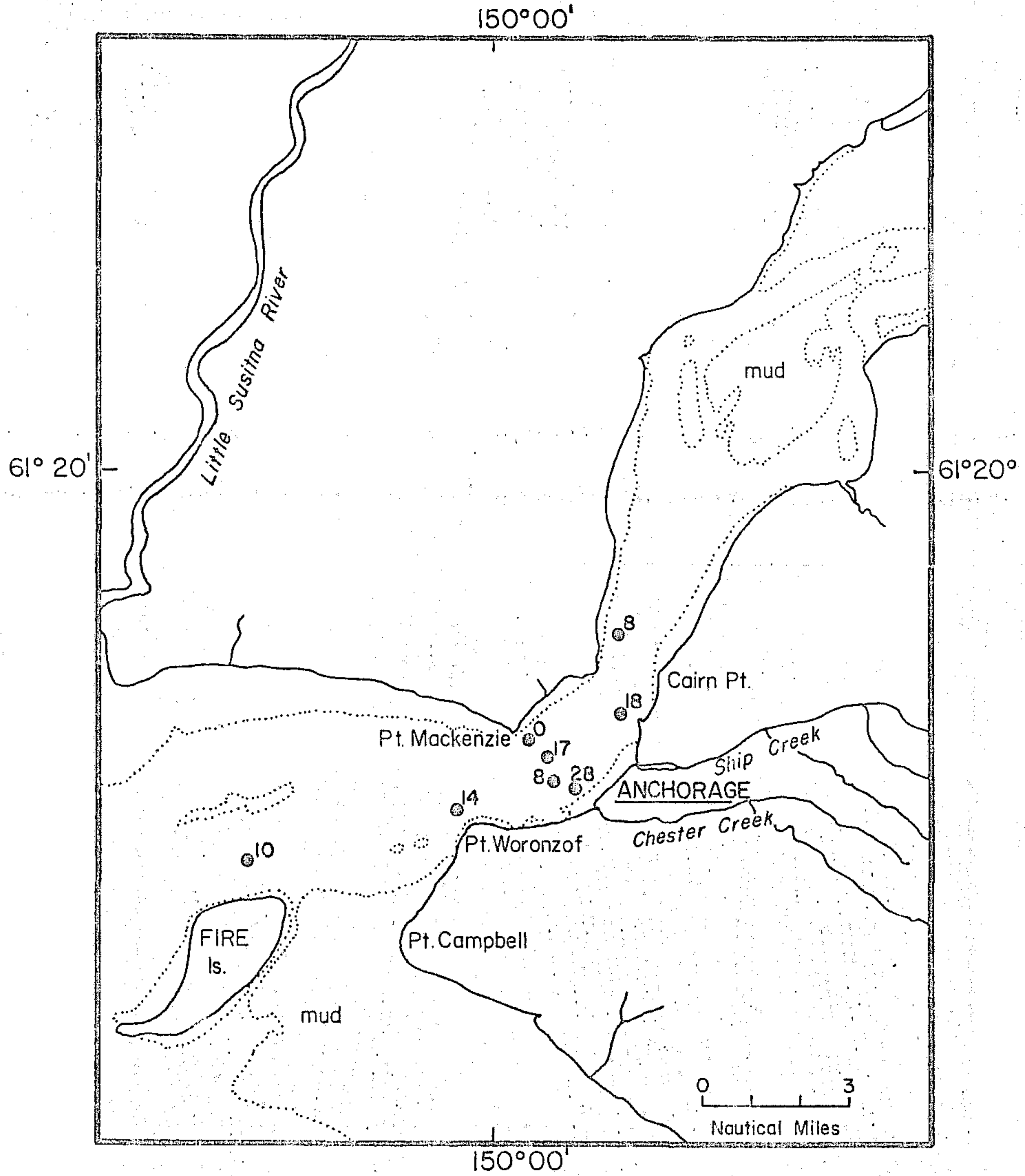


Fig. 12. Surface ammonia concentrations (ppb) for cruise #3, May 21, 1970

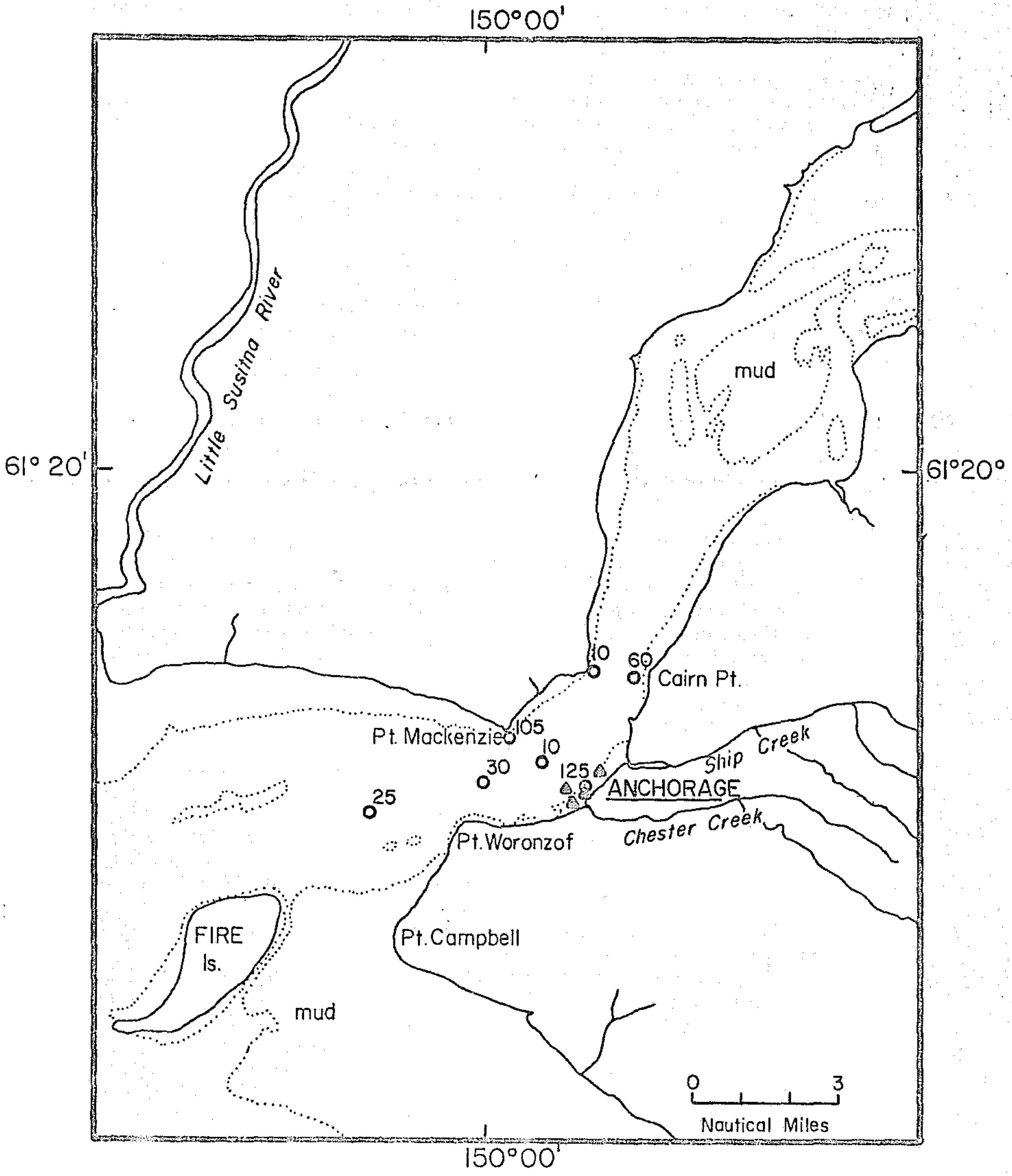


Fig. 13. Surface coliforms for stations on cruise #2, March 5, 1970 (numbers indicate coliforms/100 mls; ▲ indicates that coliforms were "too numerous to count")

area near the existing waste outfalls since the waste underwent no treatment. However, once the bacteria enter the Inlet waters, an environment not conducive to coliform survival, a significant die-away occurs. This die-off, coupled with increasing dilution, should result in fewer coliforms in areas away from the waste outfall.

A total of 97 bacteriological samples were collected and analyzed for coliforms. The analyses were performed by taking samples in a 1600-ml Nansen bottle at various depths and immediately subjecting them to filtration through a Millipore Filter Portable Water Analysis Assembly and subsequent incubation at 35C for 24 hrs. The filters were then examined for the shiny, metallic-green colonies typical of coliforms. These colonies were counted and the number of coliforms per 100 ml of sample was calculated. Of the 97 samples, 18 were positive for coliforms. The results are shown in Fig. 13. This figure shows that coliform counts were highest in the vicinity of Chester Creek and near Cairn Point, both areas adjacent to sewage outfalls. Other data indicate that more coliforms were found in the surface samples than in the bottom samples or samples taken at depth.

These results are as we expected for Knik Arm. The number of coliforms found is not excessive and does indeed show that waste can be detected in the Inlet, particularly in waters bordering a waste outfall. In many respects a coliform analysis can be considered a more sensitive indicator of pollution than many of the chemical parameters. Therefore, we believe the coliform data confirm the two-dimensional type of distribution of sewage that was discussed earlier. The areas of high coliform density may be thought of as a "sewage field," or that area receiving the greatest amount of waste. As the coliforms are mixed with the Inlet waters, their concentration naturally declines and eventually, because of dilution and die-off, reaches a low background level. Our data indicate, relative to this point, that coliforms are found in varying degrees throughout a large part of the Inlet depending upon tides, location, and other parameters.

Plankton. Plankton are the small organisms found throughout the water mass. They are sampled by towing a very fine net through the water for a specified period of time. Our results indicate that Knik Arm is similar to any temperate or cold-climate estuarine system in that the numerical standing crop increases in the summer months in response to the warmer temperatures. Unlike many estuaries, Cook Inlet has a high sediment load which limits the phytoplankton growth by decreasing the available solar energy on which their productivity depends. Our studies indicated that the areas upstream from Chester Creek, toward the Knik and Matanuska Rivers, exhibited a lower percentage increase in phytoplankton from May to August than did areas immediately adjacent to or below Chester Creek. Although this increase may be indicative of organic enrichment, the difference is more likely to be due to normal sampling error, since the technical reliability of the values obtained for the phytoplankton crop are greatly diminished because of interference from suspended sediments. Although many samples were taken and analyzed, we could not say definitely whether organic enrichment had occurred as a result of the waste input. Most sources state that heavy sediment loads are detrimental to both phytoplankton and fish; thus, a very low productivity is indicated for Cook Inlet. Regardless of the amount of waste put into it, little eutrophication would be expected to occur.

Benthic Organisms. Bottom samples were taken throughout the Inlet on all cruises. An obvious gradation from a clean, sandy bottom with few organisms to an organic clay bottom with both more species and greater numbers of each species was seen. There was a much denser population of organisms in the samples taken near the waste outfalls. The fact that the wastes were discharged in the mud areas near the shore and not in mid-channel with its cleaner, sandy and rocky bottom is important. The clays and muds trap organic materials more readily than do the coarser, more granular sands. Since any colloidal or suspended organic material which settles to the bottom and is entrapped there is a potential food source for the benthic organisms, the clays and muds are more conducive to the growth of those organisms.

Samples taken toward the center of the Inlet contained very few organisms; in fact, some had none. Samples taken on the far side of the Inlet, in bottom material similar to that found near Chester Creek, also contained few organisms. On the other hand, high concentrations of a number of different species were found in the immediate vicinity of the Chester Creek outfall. This finding indicates that this area has been significantly enriched and is continuing to be enriched by the organics in the domestic sewage. This result was not unexpected since approximately 40 percent of the BOD of the raw waste is in the form of suspended solids and could easily become entrapped in the muds surrounding the outfall. Thus, it was concluded that the suspended material should be removed from the waste prior to its discharge into the Inlet.

CONCLUDING REMARKS

The physical, chemical, and biological data indicate that some pollution of the Inlet waters near the Chester Creek and Cairn Point outfalls has occurred but that the water mass as a whole is not polluted. It is doubtful that it could ever become polluted, even with a population of two or three million residing in the Anchorage area. Because of the high degree of turbulence and heavy sediment loads, large quantities of domestic waste, probably as much as 200 mgal/day, can be discharged into the Inlet without causing an undesirable situation to arise. This conclusion is based solely on a domestic waste discharge. Non-organic industrial wastes and/or toxic materials, on the other hand, could cause considerable problems, and treatment for such wastes should be instituted. In addition, as the enrichment of the bottom muds around the Chester Creek outfall indicates, there is a need for primary treatment of the domestic wastes.

The half-moon-shaped bay between Point Woronzof and Chester Creek is conducive to a large eddy current which may tend to concentrate the wastes emanating from the Chester Creek outfall in this area. At the time this study was performed, it was assumed that the new outfall would be placed farther out in the Inlet than it is. The fact is that the outfall at Point Woronzof is on the boundary of this probable eddy area. It is recommended, therefore, that biological sampling be done in the area surrounding the new outfall location and in the area between the new outfall and Chester Creek. Additionally, it is recommended that the bottom area near Chester Creek be sampled after the waste discharge there ceases in order to determine whether and what kind of recovery can occur. This new information will give a better historical picture of the bottom sediments and their biota than is now available. It will also show whether the increased productivity observed in the benthic layer was a function of the waste input and the eddy current or the result of a natural concentration of organics in these clays.

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