RESULTS OF A JOINT U.S.A./U.S.S.R. HYDRODYNAMIC AND TRANSPORT MODELING PROJECT
APPENDICES B, C, AND D

by

John F. Paul and William L. Richardson
Large Lakes Research Station
Environmental Research Laboratory-Duluth
Grosse Ile, Michigan 48138
U.S.A.

Alexandr B. Gorstko
Institute of Mechanics and Applied Mathematics
Rostov State University
Rostov-on-Don
U.S.S.R.

and

Anton A. Matveyev
Hydrochemical Institute
Hydrometeorological Services
Novocherkassk
U.S.S.R.

ENVIRONMENTAL RESEARCH LABORATORY
OFFICE OF RESEARCH AND DEVELOPMENT
U.S. ENVIRONMENTAL PROTECTION AGENCY
DULUTH, MINNESOTA 55804

DISCLAIMER

CONTENTS

Appendices

APPENDIX B

BACKGROUND ON THE SEA OF AZOV AND LAKE BAIKAL ECOSYSTEMS

(Translation of the Russian text prepared by Alexander B. Gorstko and Anton A. Matveyev).

INTRODUCTION

The contacts between Soviet and American specialists engaged in under the agreement for cooperation between the USSR and USA in the area of prevention of pollution of natural waters have shown a considerable similarity in the approaches to the mathematical modeling of the ecosystems of bodies of water. However, existing differences in methodology lend special importance to the problem of comparing results of modeling of the same objects by different methods. The following three bodies of water were selected as such objects:

(1) The Sea of Azov - an ecosystem model that can serve as a reference standard has been worked out;

(2) Lake Baikal - a body of water under intensive study by the USSR Hydrometeorological Service;

(3) Lake Michigan - a body of water under study by the U.S. Environmental Protection Agency.

The present material forms the basis for constructing mathematical models of the ecosystems of the first two bodies of water. It presents the characteristics of these ecosystems, the necessary data on the catchment basins, the existing information, and problems for whose solution the models are created.

The Sea of Azov is used as an example for describing a model of water exchange between different parts of a body of water.

CHAPTER 1

THE "SEA OF AZOV" SIMULATION SYSTEM ("SEA OF AZOV" SS)

1. Ecological Sketch of the Sea of Azov. Problems Requiring the Creation of a Model.

The construction of the "Sea of Azov" SS is based on extensive natural scientific information on the object being modeled. It is not possible here to give a detailed description of the processes and phenomena occurring in the ecosystem, since this would take up too much space. We will, therefore, confine ourselves to a fairly brief sketch, which will be completed with a characterization of the problems for the solution of which the "Sea of Azov" SS in intended.

The Sea of Azov is a comparatively small body of water located between 45° and 47° N and 35° and 39° E. Its area is 38,000 km^2, and the seawater volume ≈ 320 km^3. The Sea of Azov is shallow; maximum depth is of the order of 13 meters, and average depth, about 8 meters.

The sea is inhabited by:

332 species of phytoplankton

155 species of zooplankton;

180 species of benthos;

104 species of fish.

All the species are far from being of equal importance to the life of the ecosystem as a whole. This made it possible to limit the modeling to only the most important ones:

20 species of phytoplankton comprising 95% of the phytoplankton biomass;

12 species of zooplankton comprising 92% of the zooplankton biomass;

6 species of benthos comprising 88% of the benthos biomass;

9 species of fish comprising 90% of the fish biomass.

With time, under the action of various factors and processes, both abiotic and biotic, a change in the biomasses of the enumerated species takes place. In order to gain a correct understanding of the pattern of these changes, we will give a more detailed description of the processes taking place in the sea, and of the characteristics of the individual trophic levels of the ecosystem.

External Factors

The rates of the processes in an ecosystem depend significantly on a number of factors determining the state of the environment, the so-called external factors, which include temperature conditions, wind activity over the water area of the sea, solar activity, precipitation, evaporation, etc. They can all be broken down into three groups: climate-governed factors, hydrometeorological factors subjected to anthropogenic influence, and parameters of effective control of the ecosystem. The values of these factors are available in the form of series of past observations, actual, and predicted values. When the processes in the ecosystem are simulated, the possibility of their different realization for different values of external factors is taken into consideration.

Dynamics of the Waters

One of the key processes in the Sea of Azov is the water exchange between different parts of the sea and the associated redistribution of the solutes, suspensions and organisms. The dynamics of the seawater are essentially determined by the wind, and the horizontal water exchange is determined by the wind-generated system of currents. Typical of the Sea of Azov is the short time lag of the process. Because of the shallowness of the sea and unstable wind conditions, the speed and direction of currents at any point of the water area change very rapidly.

According to the data of the Hydrometeorological Handbook for the Sea of Azov,[16] wind currents with speeds of 2-10 cm/sec have the highest frequency (up to 60%). Currents with speeds of 10-20 cm/sec, corresponding to winds of 5-10 m/sec, have a frequency of about 30%. The maximum current speed does not exceed 60-80 cm/sec.

During the cold half of the year, winds of the eastern quarter of the horizon prevail above the sea. Their frequency during this period amounts to an average of 45-50%, and the frequency of westerly winds, about 30%. The wind speed during the fall and winter periods reaches an average maximum of 6-7 m/sec. Storms with easterly winds of over 10-15 m/sec also occur at that time.

In spring and summer, the directions of transport of the air masses change; the frequency of western vectors increases to 38-45% and that of eastern vectors decreases to 25-30%. Later (July, August), the wind speed drops to the annual minimum, which amounts to a long-term average of 4.2 m/sec. In the course of a year, the frequency of northerly and southerly winds does not usually exceed 10%, and the frequency of calms is approximately 7%.

Winds of the eastern quarter of the horizon raise the water level on the western shores of the sea and lower it on the eastern shores. The effect of westerly winds is opposite. The level differences between regions of the sea opposite in the latitudinal direction may reach 4-5 m. Lasting winds lead to the establishment in the sea of a fairly stable profile of the water surface with the maximum possible slope for a given wind pressure.

In addition to wind, a role is also played in the level dynamics of the sea, and hence in the displacement of water masses, by the specific proportion of the elements of its water balance, primarily the runoff, atmospheric precipitation, evaporation, and water exchange with the Black Sea through the Kerch Straits.

Data on a long-term (1923-74) average water balance are listed in Table 1. Some characteristics of its component elements are given below.

TABLE 1. WATER BALANCE OF THE SEA OF AZOV (1923-74)
(km^3/year)

Gain		Loss	
River runoff	37.3	Evaporation	34.2
Precipitation	14.2	Runoff into Black Sea	48.6
Inflow from Black Sea	32.9	Runoff into Sivash	1.4
Inflow from Sivash	0.3		
TOTAL:	84.7	TOTAL:	84.2

The main volume of the continental runoff into the Sea of Azov is due to the inflow from the Don (* km^3; variation coefficient of annual runoff, 0.30) and the Kuban' (* km^3; variation coefficient of annual runoff, 0.19).

According to calculations of the State Institute of Oceanography (GOIN), the average annual precipitation on the sea surface is 14.2 km^3, and the variation coefficient is 0.17.[15]

The long-term average evaporation from the surface of the Sea of Azov is 34.2 km^3, and the variation coefficient is 0.06.

*Translator's Note: Figures missing in the original text.

The water exchange of the Azov and Black Seas is the most dynamic component of the water balance. During the period under consideration, the maximum annual runoff of Azov waters was measured in 1932 and found to be 67.1 km^3, and the minimum, 38.8 km^3, was noted in 1950. The extremes of annual inflow of Black Sea waters were 38.1 km^3 (1950) and 28.9 km^3 (1932), respectively, and the extremes of the net water exchange were 38.1 km^3 (1932) and 0.7 km^3 (1950). The coefficient of variation of mean annual values of water exchange through the Kerch Straits is 0.56.

The annual distribution of the main elements of the water balance is presented in Table 2.

Oxygen

Dissolved oxygen, which plays a decisive part in many processes, holds a unique position among the abiotic parts of the ecosystem.

The chief sources of oxygen supplied to the water mass are its production by photosynthesis and invasion from the atmosphere. During the cold season, these incoming items are approximately equal, and in summer, photosynthesis is estimated to produce 60 to 90% of the total oxygen supply.

The dissolved oxygen is expended on the respiration of organisms and degradation of organic matter of the pelagic zone and bottom. The latter process is mainly due to the activity of the microflora, and is therefore biochemical in nature. The Sea of Azov is characterized by a high rate of biochemical oxygen consumption (demand) (BOD_1); an average of 0.44-0.60 ml of O_2/ℓ day, and in the Don estuary, up to 0.70 ml of O_2/ℓ day. This is chiefly determined by the substantial concentrations of organic compounds accumulated in it. Since the consumption values cited are usually lower than the total oxygen supply (about 0.9 ml of O_2/ℓ day in 1974-75),

TABLE 2. ANNUAL DISTRIBUTION (%) OF MAIN ELEMENTS OF THE WATER BALANCE OF THE SEA OF AZOV

Element of Balance	Jan	Feb	Mar	Apr	May	June	July	Aug	Sep	Oct	Nov	Dec
	Winter*		Spring			Summer			Fall			Winter
Don River runoff	4.8	6.1	8.8	14.9	13.9	9.0	8.2	7.5	7.2	7.6	7.2	4.8
Kuban' River runoff**	5.0	4.9	7.9	9.0	13.5	13.3	12.5	9.3	5.0	4.5	5.7	9.4
Precipitation		25.4			20.3		28.9			25.4		
Evaporation		7.3			10.7		53.9			28.1		
Runoff into Black Sea		29.2			30.5		17.0			23.3		
Inflow from Black Sea		33.1			18.8		19.4			28.7		
Net water exchange		19.6			56.8		11.8			11.8		

*All data for winter are given for the Dec-Feb period.
**After the construction of the Krasnodar storage reservoir.

there is practically never any oxygen deficit in the surface layers of the sea. This however is not the case in the bottom layers. A very high rate of oxygen consumption is observed in the "water-ground" contact zone. Thus, BOD_1 for the bottom sediments of the sea during the warm period of the year amounts to about 4 g of $0_2/m^2$ day, while in Taganrog Bay this value is 10.5 g of $0_2/m^2$ day. For this reason, in the bottom layer, the oxygen content often drops to zero, and so-called obstruction phenomena take place.

It has been found that the oxygen consumption of the ground varies with the ground type. Table 3 gives average values of oxygen consumption at 10°C under optimum oxygen conditions.

TABLE 3. CONSUMPTION OF OXYGEN BY GROUNDS

Type of Ground	Oxygen Consumption at 10°C (of $0_2/m^2$ day)
Clayed silt	3
Fine silt	2.5
Coarse silt	1
Sand with shells	0.7

However, the state of the oxygen regime of the sea is not determined solely by the ratio of the gain and loss items of the balance. A very important role is played by regulating factors, i.e., temperature, quality of organic matter, salinity, hydrodynamic activity of the period, and vertical stratification of the waters. Their combined action determines the present oxygen regime.

Since 1960, the phenomena of the summer oxygen deficit in the bottom layers have become practically annual. On average, for 1960-75, the area bounded by the iso-oxidation line of 60% saturation (boundary of sublethal oxygen content) amounted to about 10,000 km^2, or over 25% of the water area of the sea. A complete absence of oxygen and consequent death of bottom fauna were recorded over a considerable area. Among the reasons for such a marked deterioration of the oxygen regime, the following may be cited:

(1) A depression of wind activity in 1957-73 that was most appreciable during the entire observation period and that reduced the dynamic aeration of the water masses and especially of the bottom layers of the sea.

(2) A 0.5° increase in the mean annual temperature of the waters of the Sea of Azov.

(3) A decrease in photosynthetic activity.

(4) An increase in the density stratification of the waters of the sea.

The present oxygen deficiency of the Sea of Azov has well-defined negative ecological aftereffects.[8]

Biogenic Elements

The concentration of nitrogen and phosphorus-containing compounds in the sea is regulated by both the proportion of their balance components and the kinetics of the internal turnover. We will begin by considering the components of the nitrogen balance.

On average, during the decade, 1966-75, the river runoff into the Sea of Azov brought 67.43 thousand tons of nitrogen (Don - 37.67, Kuban' - 29.76 thousand tons) and 6.48 thousand tons of phosphorus (Don - 3.15, Kuban' - 3.33 thousand tons). It should be noted that these values are unstable and depend on anthropogenic activity.

The average total concentration of mineral and organic compounds of nitrogen in precipitation falling on the sea surface amounts to 1400 mg/m^3, and that of phosphorus compounds, 45 mg/m^3. Since the mean annual precipitation on the sea surface is 14.2 km^3, it may be assumed that the inflow of nitrogen and phosphorus with this item of the balance will amount to 19.9 and 0.6 thousand tons, respectively.

There is one more incoming item - the inflow of nitrogen and phoshorus with materials from abrasion of the shores. Quantitative estimates are given in Table 4.

TABLE 4. INFLOW OF TOTAL NITROGEN AND PHOSPHORUS INTO THE SEA OF AZOV WITH MATERIALS FROM COASTAL ABRASION

Region of coastal zone	Amount of abrasion material, million tons	Average content		Inflow, tons	
		N	P	N	P
Temryuk - Primorsko-Aktarsk	0.20	0.066	0.010	130	20
Region of Primorosko-Aktarsk	0.38	0.050	0.010	190	40
Genichesk - Belosarayskaya sand bar	12.60	0.048	0.010	6000	1250
Northern shore of Taganrog Bay	0.64	0.050	0.010	320	63
Southern shore of Taganrog Bay	0.67	0.030	0.011	200	72
Yeyskiy Peninsula	1.70	0.034	0.009	580	150
Taman and Kerch Peninsulas	0.66	0.050	0.010	330	70
TOTAL	16.85	0.047 (sic)		7750	1665

Since phosphorus in coastal sediments is represented chiefly by sparingly soluble compounds, its change to the dissolved state may be asumed equal to 10% of the total inflow, i.e., 0.16 thousand tons/year. For nitrogen, this value reaches 50%, and the inflow into the water amounts to 3.88 thousand tons/year.

Another important item of the balance is the water exchange with the Black Sea. Since the average concentration of nitrogen in Black Sea waters is 350 mg/m^3, and that of phosphorus, 27 mg/m^3, their total inflows from the Black Sea are 11.4 and 0.9 thousand tons, respectively. According to the calculations of G.D. Makarova,[12] the average content of nitrogen and phosphorus in waters of the Sea of Azov region preceding the straits is 1110 and 80 mg/m^3. For a 49.8 km^3 runoff from the Sea of Azov, the annual loss of nitrogen and phosphorus-containing compounds from this balance item amounts to 45.3 and 4.0 thousand tons, respectively.

We have examined the gain and loss balance items of biogenic compounds. It should be noted, however, that the power of the producing system of a sea depends not so much on the balance of biogenic compounds as on the rate of their internal turnover. Therefore, information on the nitrogen and phosphorus content is insufficient for estimating and predicting the state of the ecosystem of a sea.

Basic diagrams of nitrogen and phosphorus turnovers in bodies of water are known rather well, and we will not dwell on them here. Let us only note that according to data pertaining to the period of the natural regime of the Sea of Azov, the rate of its nitrogen and phosphorus turnover was 7 and 8 cycles per year, respectively. Of these, 4-5 were accomplished in summer, 1-2 in spring, and 2-3 in fall.

Recent data[12] indicate a significant reduction in the rates of internal turnover of nitrogen and phosphorus, which now amounts to 2.1 and 6.8 cycles per year, respectively. There is reason to assume that this reduction in rates is due to an increasing salinity of the sea.

Quality of the Waters

The chemical pollution of waters of the Sea of Azov is a significant factor in its biological action, with a negative effect on the ecosystem of the sea. The most common pollution components are petroleum products, phenol compounds, detergents and pesticides. The content of heavy metal salts in the pelagic zone of the sea are at the level of the natural geochemical background.[5]

Because of shallow waters, which provide for a high degree of aeration of the water masses and their satisfactory progressiveness, and also because of its high biological productivity, the Sea of Azov has a high self-purifying capacity. The chief role in self-purification eliminating degradable pollutants is played by biological processes. Participants in these processes are bacteria, fungi, infusoria, rotifers, etc.

In the last few years, considerable work has been done in the Azov Basin to prevent the pollution of the sea and of the rivers emptying into it. A number of water-protection measures have been implemented in plants and population centers located along the Azov coast: Taganrog, Zhdanov, Berdyansk, etc. An effective system of control and sanctions providing for the necessary progress of water-protection measures has been created in the Azov Basin.

A resolution of the Central Committee of the Communist Party and USSR Council of Ministers of 4 February 1976, entitled "Measures to Prevent the Pollution of Black and Azov Basins", stipulates a set of measures providing for the complete cessation by 1985 (and for many large plants, by 1980) of the dumping of untreated household and industrial sewage into the bodies of water of the Azov Basin.

Despite the relatively favorable situation with respect to water quality in the Sea of Azov and the prevailing tendency toward its further improvement, the Water Quality unit, describing the dynamics of concentrations of pollutants and the self-purification processes in the Sea of Azov, has been introduced into the SS for testing different control variants and also for retrospective analysis.

Phytoplankton

The phytoplankton of the Sea of Azov, consisting of 332 species, is the chief producer of organic matter. It thereby largely determines the state of the nutritive base and hence, the living conditions of food fish populations.

Analysis of observations of phytoplankton development has revealed a seasonal rhythm of the production processes within the annual cycle. In the Sea of Azov, one can distinguish two main ecological complexes of algae: a cold-water and a warm-water complex.

In the course of an annual cycle, because of the fluctuation in water temperature, a change in the prevalence of representatives of these two types is observed. This change, combined with the dynamics of biogen-containing compounds, usually determines the presence of three maxima - the spring and fall maxima (with the prevalence of cold-water algae) and summer maximum (with the prevalence of warm-water ones).

The early spring period is characterized by a massive development of temperate and cold-water species of diatoms - Sceletonema costatum, Chaetoceros holsatucus, and in Taganrog Bay - Sceletonema costatum, Chaetoceros rigidus.

The absence of competing algae at that time, low consumption by the animals and a simultaneous high content of biogenic elements in the water enable the cold-water species of algae to form a large biomass, on the order of 14-27 g/m^3, or about 80% of the total phytoplankton biomass.

The reduction of the content of biogenic elements in the water because of their intensive consumption is associated with a sharp reduction in the biomass of algae and an almost complete elimination of algae of the cold-water complex from the plankton. The total phytoplankton biomass decreases to 1.0-0.2 g/m^3. The low level of the phytoplankton biomass lasts until June.

As the seawater warms up to optimum temperatures for warm-water species and as the biogenic elements return to mineral forms accessible to assimilation by phytoplankton, the number of warm-water phytoplankton species, which develop intensively, increases, and at 22-26° a second maximum in the phytoplankton biomass is observed. In the sea itself, phytoplankton is represented by marine and saltwater species of pyrophytic algae (Exuviaella cordata, Prorocentrum micans, Peridinium sp., Goniaulax poliedra). In Taganrog Bay, the summer complex is chiefly represented by saltwater and genetically freshwater species of blue-green, green algae and diatoms. The highest specific value in the total biomass (about 90%) is formed by diatoms (Coscinodiscus jonesianus, Thalassiosira parva) and the blue-green algae (Aphanizomenon flos-aquae, Anabaena flos-aquae, and Microcystis sp.). The phytoplankton biomass in July-August reaches an average of 1.0-3.8 g/m^3 in the sea and 3.3-8.5 g/m^3 in the bay.

The third fall maximum is characterized by the attenuation of production processes of warm-water species of algae and a new maximum in the development of diatoms (Thalassionema nitzschiodis, Zeptoculindrus danicus, Sceletonema costatum, Coscinodiscus jonesianus). The fall "flash" of diatoms is less intense than the spring one.

In winter, the phytoplankton vegetation almost comes to a halt, and its biomass amounts to 0.02-0.5 n/m^3. Seasonal variations in phytoplankton composition and biomass are presented in Table 5.

The substantial phytoplankton biomass fluctuations are caused by different responses of the leading types of phytoplankton to changing environmental factors.

It may be considered established that the chief factors controlling the state of phytoplankton populations are the illumination conditions, temperature, salinity, and concentrations of biogen-containing compounds in the water.

For modeling purposes, we must know the ranges of variation of these factors optimal for the species under consideration (Table 6), as well as the chemical composition of the individual groups and species of phytoplankton (Table 7).

TABLE 5. SEASONAL VARIATIONS IN THE COMPOSITION AND BIOMASS (mg/m^3) OF PHYTOPLANKTON OF THE SEA OF AZOV
(Based on data for 1965-72

Name		April	May	June	July	August	October
				SEA OF AZOV			
Diatoms	a	1401	704	554	334	1030	6035
	b	76	75	58	28	27	93
Pyrophytic	a	290	48	132	785	2600	350
	b	16	4	14	63	68	5
Green	a	22	33	14	36	251	19
	b	1	4	1,5	3	6	5
Blue-green	a	19	20	4	26	58	38
	b	1	2	0,4	2	1,5	0,6
Other	b	6	15	26	4	0,5	0,4
Total Biomass		1845	938	961	1247	3813	6500
				TAGANROG BAY			
Total Biomass	a	6446	1501	3892	3327	8511	7555
	b	100	100	100	100	100	100
Diatoms	a	5570	844	2372	1856	1698	5734
	b	86	56	61	56	20	76
Pyrophytic	a	79	103	90	260	288	72
	b	1	7	2	8	3	1
Blue-green	a	829	120	375	923	5941	2163
	b	12	8	10	28	70	27
Green	a	116	100	256	243	139	714
	b	2	7	7	7	2	9
Other	b	2	2	0,3	1	0,3	0,3

Note: a - biomass mg/m^3
b - percent (%)

Translator's Note: Comma (,) represents a decimal point (.) here and in other tables.

TABLE 6. SOME CHARACTERISTICS OF PHYTOPLANKTON SPECIES SELECTED FOR MODELING

Phase variable	Name		Biological form	Salinity (optimum range (%)	Temperature (optimum range (%)	Nitrogen, opt. conc. mg/l NO_3	NH_4	Phosphorus (optimum concentration), mg/l
X_{25}	Sceletonema	costaium	Diatoms	10,5-13,2	2-8	0,01-0,4	0,01-0,4	0,08-0,32
X_{26}	Coskinodiskus	fonesianus	Diatoms	10,5-12,3	2,8-15	0,01-0,4	0,01-0,4	0,08-0,32
X_{27}	Thalassiasira	decipiens	Diatoms	12,5-13,1	5,1-12,8	0,01-0,4	0,01-0,4	0,08-0,32
X_{28}	Ciclotella	caspia	Diatoms	5-14,3	4-24,5	0,01-0,4	0,01-0,4	0,08-0,32
X_{29}	Leptocylindrus	danicus	Diatoms	10,5-12,3	9,1-16,2	0,01-0,4	0,01-0,4	0,08-0,32
X_{30}	Chaetoeerus	holsaticus	Diatoms	7-13	10-25	0,01-0,4	0,01-0,4	0,08-0,32
X_{31}	Thalassionema	nitzschiodis calcar-aris	Diatoms	5,2-12,8	2-8	0,01-0,4	0,01-0,4	0,08-0,32
X_{32}	Rhizocolenia	cardaia	Diatoms	11-12,9	15-25	0,01-0,4	0,01-0,4	0,08-0,32
X_{33}	Exuviaella	micans	Pyrophytic	9-20	22-26	0,5-0,8	0,01-0,4	0,1-0,3
X_{34}	Paricebtryn	polyedra	Pyrophytic	9-20	22-26	0,5-0,8	0,01-0,4	0,1-0,3
X_{35}	Gonianlox	centicula	Pyrophytic	9-20	22-26	0,5-0,8	0,01-0,4	0,1-0,3
X_{36}	Glenodinium	orbiculare	Pyrophytic	9-20	22-26	0,5-0,8	0,01-0,4	0,1-0,3
X_{37}	Peridinium	aeruginosa	Pyrophytic	9-20	22-26	0,5-0,8	0,01-0,4	0,1-0,3
X_{38}	Microxystis	flos-aquae	Blue-green	10	24-26	0,6-0,2	0,06-0,2	0,03-0,32
X_{39}	Aphanizomenon	flos-aquae	Blue-green	10	24-26	0,6-0,2	0,06-0,2	0,03-0,32
X_{40}	Anabaena	limnetica	Blue-green	10	24-26	0,6-0,2	0,06-0,2	0,03-0,32
X_{41}	Lynobia		Blue-green	10	24-26	0,6-0,2	0,06-0,2	0,03-0,32
X_{42}	Aakistrodesmus		Green	8-9	24-26	5,0	0,2-0,5	0,03-0,32
X_{43}	Scenedesmus		Green	8-9	24-26	5,0	0,2-0,5	0,03-0,32
X_{44}	Oocystis		Green	8-9	24-26	5,0	0,2-0,5	0,03-0,32

TABLE 7. ELEMENTARY CHEMICAL COMPOSITION OF INDIVIDUAL GROUPS AND SPECIES OF ALGAE
(% of dry weight)

Name of Algae	Nitrogen	Phosphorus	Nitrogen: Phosphorus	Site of Sampling	Author
Diatoms	2.49	0.60	4:1	-	Vinogradov 1939
Pyrophytic	4.01	0.57	7:1	-	Vinogradov 1939
Blue-green	7.05	0.89	8:1	Sea of Azov	Vinogradov 1939
Blue-green	9.00	0.46	20:1	Uchinskoye storage reservoir	Guseva 1963
Microcystis aeruginosa	9.10	0.45	20:1	Taganrog Bay	Aldakimova Kasinova 1962

Zooplankton

The zooplankton of the Sea of Azov consists of 185 species pertaining to marine, saltwater relict and freshwater complexes. The sea itself is inhabited mainly by marine forms and some saltwater forms. The copepods *Calanipeda aquae-dulcis*, *Ascartia clausi*, *Acartia latisetosa*, *Centropages ponticus* are widely distributed; *Synchaeta sp*. dominate among rotifera, and among cladocerans, *Podon polyphemoides*. Until recently, the freshwater and saltwater organisms *Daphnia longispina*, *Bosmina longirostris*, and *Calanipeda aquae-dulcis*, etc., dominated in Taganrog Bay. At the present time, because of the salinization of the waters of the sea and bay, the freshwater complexes have lost their leading role.

Despite the abundance of zooplankton species inhabiting the Sea of Azov, the bulk of the zooplankton biomass (up to 80%) is made up of two to three dominant species during each season. A definite seasonal change of dominate groups is also observed.

The early-spring plankton of the sea is chiefly represented by rotifers of the genus Synchaeta (76% of total biomass). Later in the season, Balanus larvae, which account for up to 63% of the total biomass, dominate. The start of massive development of copepods, whose biomass amounts to over 20%, is attributed to that period.

In Taganrog Bay, the copepods comprise 50% of the total zooplankton in spring.

Copepods predominate in the sea in summer, making up 56% of the zooplankton biomass. In Taganrog Bay, the summer dominants are Cladocera (46%), and also Calanipeda aquae-dulics (34%). By autumn, the fraction of copepods in the open sea drops to 26%, whereas the amount of Balanus larvae and rotifers increases. In the bay, a homogeneity of the zooplankton composition, 80% of which is represented by Calanipeda aquae-dulcis is observed at that time.

In winter, a small number of species with a well-defined dominance of copepods is observed in both the sea and bay. The annual variation of biomass is shown in Table 8.

TABLE 8. VALUES OF VARIOUS GROUPS AND SPECIES OF INVERTEBRATES IN ZOOPLANKTON OF THE SEA OF AZOV
(% of mean biomass for 1969-73)

Organisms	Months							
	Apr	May	July	Oct	Apr	May	July	Oct
	Taganrog Bay				Sea of Azov			
Synchaeta	32	5	6	1	76	7	8	1.3
Calanipeda aquae-dulcis	-	35	34	52	-	3	-	64
Acartia clausi (Azov and Black Seas)	47	15.4	24	30	10	19	59	21
Centropages kroijeri	-	-	-	0.7	-	-	7	-
Balanus larvae	-	18	-	5	-	63	-	3.3
Other	21	26.6	36	21.3	14	8	26	10.4

As is evident from the above, the dominant zooplankton species of the Sea of Azov include: among copepods - Acartia clausi, Calanipeda aquae-dulcis, Centropages kroijeri; among rotifers - Synchaeta sp.; among cladocerans - Podon polyphemoides, as well as the periodically appearing larvae of the zoobenthos Balanus.

We will present some data on the ecology of these species, used below for modeling purposes.

The most significant factors affecting the formation of a biocenosis are salinity and temperature. The tolerance ranges and optimum ranges of the values of these factors for various species are analyzed in Table 9.

TABLE 9. RANGES OF ABIOTIC FACTORS AFFECTING THE SURVIVAL RATE OF ZOOPLANKTON

Species	Salinity range for survival rate	Optimum salinity	Temperature range where the species develops normally	Optimum Temperatures	Seasons when the species is present in plankton
Acartia clausi	5.0-14.5	10.0-12.0	10°-25°	23°-25°	year round
Calanipeda aquae-dulcis	1.0-13.0	4.0-7.0	9°-25°	-	year round
Centropages kroijeri	8.5-14.0	11.5-12.4	10°-25°	16.5°-17°	heat-loving form 5-6 months
Synchaeta sp.	0.5-12.0	8.0-11.0	-	5°-10°	April-May and Septebmer-October
Podon poly-phemoides	6.5-12.4	11.5	11°-25°	14°-16°	April and October
Balanus larvae	5-30	10-12	-	14°-16°	April-May and September-October

During their development, the zooplankton organisms go through three successive age stages: nauplii (the smallest young individuals), more mature ones - copepodites, and finally, imagoes - adults. For modeling purposes, it was found useful to distinguish three age groups for copepods, since different processes take place in them at different rates. For the remaining zooplankton species, however, whose lifetimes are much shorter, the age structure is not considered. The times spent by the zooplankton organisms in the various age groups are indicted in Table 10.

TABLE 10. DEVELOPMENT TIME OF VARIOUS STAGES OF ZOOPLANKTON

Species	Stage	Lifetime at 20°
Acartia clausi	nauplii	8
	copepodites	20
	adults	60
Calanipeda aquae-dulcis	nauplii	12
	copepodites	11
	adults	21
Centropages kroijeri	nauplii	10
	copepodites	17
	adults	59
Synchaeta sp.		20
Podon polyphemoides		20
Balanus larvae		14

The duration of these periods depends on temperature, and is consistent with Krog's curve.

Another index - the reproduction rate - is closely related to the thermal regime of a body of water. The zooplankton of the Sea of Azov reproduces over the course of the entire warm period (from April through October). The rate of this process also depends on the organisms' food supply, but it may be assumed as a first approximation that the food factor is not the most important one, and the influence of thermal conditions on the reproduction rate can be taken into account by means of Krog's temperature corrections.

Table 11 gives values of reproduction rate coefficients calculated from the data of Ref. 3.

A key role in the process of zooplankton biomass variation is played by the nutrition process.

TABLE 11. REPRODUCTION RATE COEFFICIENTS

Species	Reproduction rate coefficient (kR) at t = 20° of the region			
Acartia clausi	Sea 0.02	5(Taganrog Bay) 0.05	6(Taganrog Bay) 0.07	7(Taganrog Bay) 0.07
Calanipeda aquae-dulcis	at t° > 9° 24°, 0.03	otherwise	0.01	
Centropages kroijeri	0.04	0.05	0.05	0.05
Podon polyphemoides	0.04	0.01	0.01	0.01
Synchaeta sp.	at t° > 18° 0.01			
Balanus larvae	-	-	-	-

Phytoplankton and detritus form the basis of zooplankton's ration. From the phytoplankton, small cells up to 100 microns in size are consumed. In spring and autumn, their deficiency is compensated by detritus, which amounts to 70-80% of the weight of a food particle. In summer, when the development of small algae reaches a maximum, they dominate in the ration of the zooplankton, but the role of detritus is a major one, as before. The consumption of live feed by the zooplankton is insignificant.

The amount of feed consumed by the zooplankton is calculated on the basis of data on the amount of energy required to cover expenditures on the energy metabolism (respiration and search for food), and also for the formation of new biomass at the expense of both the growth of the organism and reproduction.

If one knows the food assimilability coefficients, which are listed in Table 12 on the basis of Ref. 5, and coefficients of food utilization for

TABLE 12. EXPENDITURES ON METABOLISM AND COEFFICIENTS OF ASSIMILABILITY (u) AND FOOD UTILIZATION FOR GROWTH (K2)*

Species, stage of Development	Weight of one specimen µg	Temperature °C	Expenditures by days one specimen µg	Expenditures by days one specimen °/o	K2	
Acartia	12,9	13-14	5,31	41,2		
	13,4	18-20	6,63	49,5	0,11	0,77
	14,5	21-23	7,09	48,9		
Calanipedo	54,7	8-11	17,9	32,7		
	54,7	13-15	20,2	36,9	0,11	0,77
	54,7	22-23	15,2	27,8		
Centropages	19,5	21-23	6,5	33,3	0,08	0,77
Synchaeta	6,2	14-16	2,69	43,4		
	8,8	23-24	5,33	60,5	0,11-0,28	0,77
Copepoda nauplii	1,4	13-15	0,96	68,4		
	1,4	14-16	1,08	77,1	0,23-0,36	0,77
	1,2	22-24	1,39	115,8		
Copepoda copepodites	3,6	9-11	1,56	43,3		
	3,6	14-16	4,98	138,3	0,3	0,8
	3,6	23-24	2,50	69,3		
Balanus larvae	15,5	11-13	2,43	16,0		
	15,5	21-22	4,61	29,7	0,4	0,48
	15,5	24-25	6,54	48,9		

*Data kindly supplied by Ye. I. Studenikina.

growth (Table 13) for each age froup of the zooplankton, then by using the relations given in Ref. 5 and 14, one can formulte the maximum rations, i.e., the maximum amount of food (in calories) that can be consumed by the corresponding zooplankton group.

TABLE 13. FUEL VALUE AND DRY SUBSTANCE CONTENT OF VARIOUS SPECIES OF ZOOPLANKTON (5)

Species	Calorific value of 1 mg of dry substance	% content of dry substance in the organism
Acartia clausi	5,6	12,6
Calanipeda aquae-dulcis	5,6	15,8
Centropages kroijeri	4,86	17,9
Synchaeta sp.	5	10,2
Podon polyphemoides	5,6	20,0
Balanus larvae	5	15,0

Benthos

Up to 180 species of zoobenthos are counted in the Sea of Azov. In the last few years, the dominant species have been Cerastoderma (Carium), Abra (Syndesmya), Hydrobia, Mytilaster, Corbulomya, Balanus, Nephthys, Nereis.

The principal ecological factors determining the character of distribution of the bottom fauna and subsequently considered in the model are the following:

(1) Salinity of the water

(2) Oxygen regime

(3) Status of ground

(4) Food availability

(5) Temperature regime

Tables 14-16 give information on the influence of the first three factors on benthos organisms.

TABLE 14. FAVORABLE SALINITY CONDITIONS FOR ZOOBENTHOS SPECIES OF THE SEA OF AZOV (salinity in 0/00)

Species	Tolerant	Optimum development conditions
Cerastoderma	7,5 - 30	8.5 - 10.5
Abra	9,9 - 25	9 - 10
Mytilaster	8 - 20	10 - 11
Corbulomya	9 - 17,5	10 - 11
Balanus	7.5	10 - 12
Hydrobia	5 - 17,5	7.5 - 9
Nephthys	8 - 30	10 - 12
Nereis	5 - 30	7 - 10

TABLE 15. LOWER OXYGEN THRESHOLD FOR THE MASS OF BOTTOM INVERTEBRATES OF THE SEA OF AZOV UNDER SALINITY CONDITIONS FAVORABLE TO EACH SPECIES

Species	Salinity 0/00	Lower oxygen threshold (ml/l of O_2)	Length of survival in oxygen-free water (hours)
Cerastoderma	10-20	0	33-58
Abra	10-15	0	96-168
Corbulomya	10-15	1,5 - 2,0	0 (18-34% per day die)
Hydrobia	10-20	0	150-170
Nereis	12-14	0	360
Mytilaster		1,5 - 2*	240-288
Balanus		3 - 3,5*	
Nephthys		1 - 2*	

*Experimental data for these species are lacking, the table gives data for the corresponding genus of hydrobionts.

TABLE 16. GROUND TYPES FAVORABLE TO THE LIFE OF BENTHOS ORGANISMS OF THE SEA OF AZOV

Species	Type of Ground					
	Stones	Shells	Sand	Mudstone	Liquid gray with no shelly admixture	Slurry
Cerastoderma	+	+	+	+	+	++
Abra	-	-	-	-	+	+
Corbulomya						
Hydrobia	-	-	-	-	+	-
Nereis	-	-	+	+	+	+
Nephthys	-	-	+	-	-	-
Mytilaster	+	+	-	+	-	-
Balanus	-	+	+	+	-	-

Note: ++ preferred types of soil.

Benthos organisms feed mainly on detritus and to a lesser extent on phytoplankton and bacteria. As a rule, animal food comprises a very minor part of the ration, since there are no predators among the bottom fauna of the Sea of Azov.

TABLE 17. COMPOSITION OF FOOD OF THE MAIN SPECIES OF BENTHOS IN THE SEA OF AZOV

Species	Type of food in % by weight			
	Algae	Animal Food	Detritus	Bacteria
Cerastoderma	2,0		97,7	0,3
Abra	15,4		84,3	0,3
Mytilaster	4,2		95,4	0,35
Nereis	12,0	1,2	86,5	0,5
Nephthys	0,4	0,7	98,0	

The temperature regime of a body of water determines the rate of many biological processes: growth, development, basal metabolism, nutrition, reproduction, etc. As the temperature increases to 25°, the rate of these processes increases, and as the temperature rises further, the vital functions of zoobenthos are depressed. The amount of food consumed is determined by the presence of feed and by the water temperature. To calculate the maximum rations, it is necessary to have information on expenditures on energy metabolism and coefficients of food utilization for growth and assimilability of the food, as given in Tables 18-20.

TABLE 18. OXYGEN CONSUMPTION Q BY BOTTOM INVERTEBRATES FOR THE SEA OF AZOV

Species	Temperature (°)	Salinity 0/00	Consumption of 0_2, m//h per 1 g of weight	Dependence of 0_2 consumption (ml/h) as a function of weight (w) in g at 20°C	
Cerastoderma	24	10-20	0,050	=0,105	0,63
Abra		10-15	0,08	=0,041	0,610
Corbulomya	19	10-15	0,068-0,076		
Mytilaster				=0,078	0,754
Hydrobia	19	10-20	0,072		
Balanus				=0,095	0,4
Nereis	25	12-14	0,06	=0,980	0,81
Nephthys					

TABLE 19. COEFFICIENTS OF FOOD UTILIZATION FOR GROWTH (K2) AND FOOD ASSIMILABILITY (u) FOR VARIOUS BENTHOS GROUP

Organisms	K2(for average population)	u
Mollusks (*Cerastoderma*, *Abra*, *Corbulomya*, *Mytilaster*, *Hydrobia*)	0.3-0.4	0.4-0.6
Crustaceans (*Balanus*)	0.3-0.4	0.4-0.8
Worms (*Nereis*, *Nephthys*)	0.54-0.73	0.64

To calculate the production of zoobenthos at the expense of nutrition, information is also necessary on the average fuel value of benthos invertebrates given in the table below.

TABLE 20. FUEL VALUE OF MAIN REPRESENTATIVES OF ZOOBENTHOS IN THE SEA OF AZOV (green weight)

Species	Fuel value, kcal/g
Cerastoderma	0,216
Abra	0,684
Corbulomya	0,240
Mytilaster	
Hydrobia	0,580
Balanus	0,486
Nereis	0,700
Nephthys	

In contrast to the zooplankton discussed in the preceding section, benthos information on periods and rates of reproduction and on fluctuations of various characteristics for age groups is much less complete.

In this connection, despite the fact that the lifetime of benthos organisms is only a few years (Table 21), no age division was introduced into the model. This rough approximation is substantially attenuated by the fact that the seasonal change of species is not related to age, but is determined by the aforementioned ecological factors.

TABLE 21. LIFETIME AND DATA ON THE REPRODUCTION CYCLES OF THE MAIN REPRESENTATIVES OF BENTHOS ORGANISMS IN THE SEA OF AZOV

Species	Lifetime, years	Data on reproduction character
Cerastoderma	5	3 times a year starting at age 2 years, most intensively by 3-4 year olds. In May, over 70% of individuals.
Abra	4	Starting with age 3 years, twice a year; in June and August-September.
Hydrobia		
Mytilaster	3	In March-April - individuals older than 2 years; in May-June - one year olds; in autumn - 2-3 year olds.
Corbulomya	1.5-2	In the first and second year of life, for 10-12 days: (1) from 16 to 20 June ($t > 17°$) (2) from 10 to 23 July (3) from July to August.
Balanus	8	Year round, most intensively at $t = 14\text{-}16°$ in May-June and October.
Nephthys	3	
Nereis	2-3	

In the seasonal dynamics of the biomass of bottom invertebrates in the Sea of Azov, an increase in population and biomass is observed from spring to autumn. The spring biomass usually amounts to 1/3 - 1/2 of the autumn biomass of the previous year. The decrease in biomass in the course of the winter season is chiefly due to the natural death rate of the individuals which reached their age limit. In particularly unfavorable years, the loss of benthos biomass from autumn to the following spring may reach 48-71%,[5] but on average, 40% of the zoobenthos biomass dies off.

TABLE 22. SEASONAL VALUES OF DAILY PRODUCTIVITY COEFFICIENT (P/B)

Species	P/B - coefficient (daily)			P/B-Annual
	Spring	Autumn	Average	
Cerastoderma	0,0018 ($t^{o} = 10^{o}$)	0,0064 ($t^{o} = 15^{o}$)		3,9
Abra			0,006	2,05
Hydrobia				
Mytilaster	0,005	0,014	0,09	3,22
Corbulomya				1,1-2,8
Balanus			0,0022	1-4,76
Nephthys			0,03-0,19	
Nereis			0,03-0,19	

Fish Populations

The Sea of Azov is inhabited by 104 species of fish. Since there is definitely no point in working out a separate model for each of these species, the following scheme was adopted: some of the populations were modeled individually, and the others were combined into a single unit for more approximate modeling. In accordance with this breakdown, we will present the necessary information on the ecology of the fish populations.

ROUND GOBY

The round goby is indigenous to the Sea of Azov and a typical representative of the saltwater Pontian faunistic complex. It is capable of tolerating a fairly wide range of salinity, occurring in both freshwater and waters with 18-20 $^o/oo$ mineralization. The optimum salinity interval for its reproduction is 10-13 $^o/oo$. The concentrations of the round goby in any given zone are also determined by other factors: nature of ground (it prefers dense, muddy, sandy and shelly grounds), content of oxygen dissolved in the water, water temperature, and composition and quantity of available food. The population's habitats do not remain constant owing to seasonal migrations.

Most round goby individuals reach an age of 3-4 years, and only some, 5 years.[6] The population structure of the round goby is determined by the proportions of the age groups, and primarily by the yield of its young. As a rule, the generation of the current year's young is the most numerous one (Table 23). With increasing age, the population of the age groups decreases, and by the 4th year the death rate reaches 95% (Table 24).

TABLE 23. CHARACTERISTICS OF THE ROUND GOBY POPULATION

Index	Periods								
	1957-1962			1963-1969			1970-1973		
Biomass, thousand tons	102,6			78,8			25,8		
Total population, billions	7270			4488			2173		
Area, percent of sea area	86			72			60		
Age groups	1+	2+	3+	1+	2+	3+	1+	2+	3+
Population of groups, $^o/o$	65	31	4	62	35	3	79	19	2
Length, mm	81	104	112	75	97	105	78	91	101
Weight, g	15	32	39	12	24	29	13	19	25

TABLE 24. CHARACTERISTICS OF THE DEATH RATE OF THE ROUND GOBY (%) IN THE COURSE OF A LIFE CYCLE (according to data for 1961-75)

Index	Years of Life			
	1+ - 2+	2+ - 3+	3+ - 4+	4+ - 5+
Total loss, including:	61,7	89,9	94,2	100
Fishing	14,8	17,4	14,9	5,7
Natural	46,9	72,5	79,3	94,3

The round goby reaches sexual maturity at the age of 2-3 years. The entire sexually mature part of the stock spawns. Approaches of the fish to the spawning grounds begin with the warming of the water in the coastal zone to 7°, which usually occurs in April, and the migration to the spawning grounds becomes massive in April-May, when the water temperature reaches 10-12°. Spawning begins in April and continues until the end of August, which corresponds to a water temperature from 10 to 25°. The spawning is heaviest in May-June at a water temperature of 15-18°. The roe is laid in several batches, as many as 5 to 6. The entire maturation cycle of the egg batch and its casting last 15-20 days. Between castings of the egg batches, the females travel to the spawning grounds and feed in the coastal band of the sea. The fertility of the round goby changes according to the size and age of the fish, amounting to an average of 1.5 for one-year olds, 2.2 for two-year olds, 3.0 for three-year olds, and 2.0 thousand eggs for four-year olds.

The reproduction efficiency of the round goby is determined by a combination of factors: content of oxygen dissolved in the water, sea state, silting of spawning grounds, consumption of fish eggs by predators, and status of nutritive base.[5,7] A very essential condition is the proportion of the sexes in the spawning stock.

After spawning, the round goby leaves the coastal zone and begins to pasture actively.

About 85% of the stock pastures in the northeastern part of the Sea of Azov. At the same time, it is the object of fishing. From 15 September to 1 December, up to 30% of the stock is caught. The round goby winters in the same area where it pastures in autumn.

The principal food items of the round goby are zoobenthic organisms - mollusks (87.8%), worms (4%) and bottom crustaceans (6.2%). The young feed mainly on bottom crustaceans - mysids, ostracods, copepods, etc., whose fraction decreases from 100% for a body length of 20 mm to 40% for a body length of 50 mm as the size of the individuals increases. The round goby becomes a typical benthophage after reaching a length of 5 cm, when the mollusks in its ration are already as high as 60%. Individuals over 7-8 cm in size feed mainly on various mollusks, which make up 75-90% of their ration. For a food factor of 22.5-23, the round goby population can consume up to 60% of the production of feed benthos on the water area of the Sea of Azov.

TABLE 25. VARIATION IN THE COMPOSITION OF THE FOOD OF THE ROUND GOBY WITH ITS SIZE (% of frequency of occurrence)

Organisms	2	3	4	5	6	7	8	9	10	11	12	13	14	15	16	17	18
Mollusks		27	38	51	71	75	80	82	84	83	83	85	82	81	67	83	87
Crustaceans	100	78	57	46	25	18	14	9	8	8	9	6	8	12	13	7	6
Worms			5	3	4	6	5	7	5	5	3	2	5	3	8		
Fish						1	1	2	3	4	5	7	5	4	12	10	7

The feeding intensity decreases with increasing size and age of the fish (Table 26) and substantially depends on the water temperature in the pasture regions.

TABLE 26. MEAN DAILY RATION OF THE ROUND GOBY AT DIFFERENT AGES (% of body weight)

One-year olds - 5.4	Two-year olds - 4.11	Three-year olds - 3.9

The minimum rations are observed in winter (hundredths of one percent), and the maximum ones, in summer (7.8-10.3% of body weight).

Azov round gobies are subjected to wide temperature fluctuations, from 0 to 28°. At a water temperature above 5-6°, they lead a mobile life, wandering in search of food. When the water temperature is below 5-6°, they become sluggish and practically stop feeding.

An intensive growth of the round goby is observed at the end of spring and the beginning of summer, and the growth slows down drastically in July-August. The growth rate of the round goby also changes with increasing age: it grows most intensively during the first years of life.

TABLE 27. LINEAR AND WEIGHT GROWTH OF THE ROUND GOBY

Sex	Parameter	Age, Years				
		0+	1+	2+	3+	4+
FEMALES	Length, mm	65	95	111	121	125
	Increase, mm	65	30	16	10	4
	Weight, g	3.4	14.5	21.7	33.8	36.8
	Gain, g	3.4	11.1	7,2	6,1	3,0
MALES	Length, mm	65	109	132	151	-
	Increase, mm	65	41	23	19	-
	Weight, g	3,5	26,1	41,5	51,8	-
	Gain, g	3,5	22,6	15,4	10,3	

ANCHOVY (Azov Type)

The anchovy is one of the most numerous fishes of the Sea of Azov, second only to the sardelle in population numbers. The mean annual quantitative indices of the anchovy stock fluctuate over wide limits: a population of 9 to 107 billion individuals and a biomass of 30 to 560 thousand tons. Such a wide amplitude in population and biomass variations is due to a clear-cut dependence of the anchovy's vital activity processes on external factors, primarily the temperature regime.

The Azov anchovy - Engraulis encrasicholus macoficus - is one of two subspecies of the European anchovy inhabiting the Azov-Black Sea Basin.[9] This is a typically marine, pelagic, heat-loving fish found at water temperatures from 6 to 28°. When cooled to 5-6°, it grows torpid and dies. For this reason, the anchovy inhabits the Sea of Azov only during the warm period of the sea, migrating to the Black Sea for the winter. Thus, the Azov anchovy is characterized by well-defined migrations, which constitute an adaptation to the temperature regime within the confines of its range.

The change in sea regime and the establishment of a new level of biological productivity, reduced in comparison with 1931-51, which have occurred in the last few decades, have caused corresponding changes in the size, biomass and structure of the anchovy population (Table 28).

All this - a large size of the stock, substantial fluctuations in numbers and biomass caused by the population's sensitivity to external conditions, and identified negative changes in anchovy stock due to the change in the sea regime - determines the important role of the ANCHOVY block in the SS.

TABLE 28. BIOLOGICAL CHARACTERISTICS OF AZOV ANCHOVY POPULATION

Indices		Periods											
		1931-1951			1952-1959			1960-1969			1970-1975		
		From	To	Av.	From	To	Av.	From	To	Av.	From	To	Av.
Biomass, thousand tons	Total, including	80	420	220	30	220	100	30	540	220	163	376	297
	young	20	140	60	10	50	20	5	110	40	6	108	51
Population, billions	Total, including	30	117	64	9	59	30	11	89	46	33	75	60
	young	12	56	31	1	45	14	3	42	21	3	64	18
Production in Sea of Azov during Apr-Oct thousand tons	Total, including	50	290	170	2	100	60	2	290	150	118	235	184
	young	30	170	70	3	60	25	7	130	60	10	110	56
Ratio of production to biomass (P/B coefficient)				0,78			0,64			0,67			0,62
Average population of age groups, %	0+		54,6			44,0			46,9			47,0	
	1+ - 4+		45,4			56,0			53,1			53,0	
Average body length, mm			69,4			75,0			69,2			80,4	
Average body weight, g			3,83			4,25			3,90			5,2	

We will describe the annual cycle of the anchovy, placing particular emphasis on the dependence of its vital activity processes on the variation in water temperature, which is its most important ecological factor.

The anchovy hibernates in relatively immobile assemblages, practically without feeding. As soon as the Black Sea waters begin to warm up, the anchovy becomes mobile and begins migrating in the direction of the Kerch Straits. The anchovy's migration through the straits into the Sea of Azov usually begins as the temperature passes 8°, although it can also begin at 6 (late March - early April) and, depending on the character of spring, last from 18 to 52 days. The mass movement of the fish through the strait, lasting an average of 22 days, is observed at an average water temperature of 10-15° and ends when the waters of the strait and adjacent regions of the sea warm up to 16-16.5° (most frequently in late April and the first 20 days in May). During the period of mass movement, 58-99.8% of the spawning population, or an average of 84.6%, penetrates into the Sea of Azov. During migration in the Black Sea and the zone of the Kerch Straits, the anchovy's feeding rate is extremely low.

After passing the Kerch Straits, the anchovy becomes distributed over the water area of the Sea of Azov. The anchovy's distribution is determined by the warming patter of the water and location of the isotherms: the fish avoids regions where the water is colder than 10-14°. In the second half of May, the anchovy is ually found over the entire water area of the sea; it also penetrates into Taganrog Bay, where its distribution is determined by the mineralization of the water to a greater extent than in the other regions of the sea: the anchovy avoids freshened regions (where the salinity is below 7-8 $^{o}/oo$).[6]

The process of prespawning pasturing occurs simultaneously with the distribution over the water area. The anchovy feeds actively, consuming phytoplankton and plankobenthos organisms (Table 29).

TABLE 29. COMPOSITION OF THE FOOD OF THE AZOV ANCHOVY
(% by weight of food particle)

Organisms	April-May	June	July	August	September
Zooplankton	35,7	39,8	60,9	46,3	33,6
Phytoplankton	19,5	31,0	31,3	18,9	48,3
Benthos	44,8	29,2	7,8	34,8	18,1

Since the anchovy feeds by filtering out food items present in the water, the organisms prevailing in its ratin are of species whose density in the pelagic zone is highest at that time. The food factor of the anchovy amounts to 8-11 weight units of feed per unit gain.[9]

Reproduction of the anchovy begins when the water warms up to 16-18° (usually in the second half of May). An intensive spawning of the anchovy can take place over a wide temperature range, form 18 to 24°. According to observational data, the most intensive spawning takes place in late May - June. In July, the amount of eggs in the plankton drops abruptly, and in August it is found only rarely.

Since all the anchovies mature at the age of one year, and their lifetime is short, the structure of the spawing population is determined by the productivity of two successive generations, one of which matures in the current year. According to long-term data, the age structure of the spawning population is as follows: one-year olds - 60.1%, two-year olds - 37.1%, three-year olds - 2.8%, four-year olds and older - 0.01%. The age composition of the spawning population undergoes substantial changes every year. Thus the relative population of one-year olds changed from 25.9 to 89.1% in the course of the last decade. The size-weight parameters of the population are also subject to a similar variability (Table 30).

TABLE 30. SIZE AND WEIGHT OF SPAWNING ANCHOVY POPULATION
(Based on June estimated data)

Year	Average lenght at age, mm				Weight at age, g			
	1+	2+	3+	4+	1+	2+	3+	4+
1967	80.0	98.5	109.7	125.0	5.3	8.2	10.6	16.4
1968	91.5	98.1	103.9	113.9	6.7	8.1	9.3	11.6
1969	82.4	97.8	106.7	117.3	5.1	8.3	9.3	13.3
1970	82.6	98.2	111.0	123.8	5.3	8.3	13.3	13.3
1971	88.7	97.0	120.9	128.5	6.3	8.0	11.9	20.0
1972	86.0	101.1	116.6	-	5.4	8.9	13.6	-
AVERAGE	86.2	98.5	110.0	123.3	5.8	8.3	11.3	15.7

Anchovy fry, feeding mainly on young copepods have a high growth rate: their length increases by approximately 1 mm in 24 h. By autumn, the young anchovies may already have grown to 65-75 mm. By that time, the feeding of the young is practically the same as that of sexually mature fish.

After completing its reproduction, the anchovy begins to feed intensively, and usually manages to accumulate considerable energy reserves in a short period of time.

Pasturing of the stock is determined by the status of the feed base and the length of time elapsed from the completion of spawning to the autumn cooling of waters of the Sea of Azov, when the migration of the anchovy to the 1st and 2nd regions of the sea and the exodus to the Black Sea through the Kerch Straits begin. The migration dates are determined not only by the temperature regime of the waters, but also by the fatness of the stock.

However, the influence of this factor has been inadequately studied and is slight in comparison with the importance of cooling of the water, and therefore in the modeling, the process of autumn migration may be assumed to be dependent solely on temperature. The water temperature varies from 9 to 15° during the period of the mass migration, which ends most frequently at 7-10°. It can be stated fairly definitely that as the temperature in the area of the sea before the straits drops to 15°, the process of accumulation of the anchovy in this region and its further migration through the strait begin.

The dates of egress of the young and sexually mature anchovy from the Sea of Azov differ. Observational data for the autumn migration of the anchovy are summarized in Table 31.

TABLE 31. DATES OF AUTUMN MIGRATION OF THE AZOV ANCHOVY THROUGH THE KERCH STRAITS

	Young		Sexually mature fish				
						Duration Days	
Dates	Start	Mass migration	Start	Mass migration	end	Total	migration
Earliest	19 Jul	16 Aug - 16 Sep	20 Sep	3 Oct - 19 Oct	1 Nov	28	3
Latest	28 Sep	13 Oct - 20 Nov	6 Nov	15 Nov - 3 Dec	9 Dec	62	35
Average	12 Aug	16 Sep - 19 Oct	10 Oct	19 Oct - 6 Nov	19 Nov	42	19

Fishing for the anchovy is done during the autumn migration and to a lesser extent at hibernation sites in the Black Sea.

Table 32 gives an idea of the average level of fishing and its fluctuations in different periods.

TABLE 32. REMOVAL OF ANCHOVY BY FISHING ACCORDING TO PERIODS OF FISHING DEVELOPMENT IN THE AZOV BASIN

Index		Period								
		1930-1940			1946-1955			1955-1973		
		From	To	Av.	From	To	Av.	From	To	Av.
Biomass, thousand tons		116	288	184,2	47	330	208,0	32	562	178,5
Reserve, thousand tons		32	324	122,4	26	400	168,0	16	545	143,4
Production	Total of portion of stock caught	63	242	158,4	22	290	138,4	30	292	123,0
		3,4	169	86,3	15	233	84,8	8	262	71,3
Catch	Thousand tons	14,6	83,1	48,8	3,5	80,5	45,3	5,9	141,7	62,1
	% of biomass	11,1	35,5	26,5	7,5	63,8	21,8	15,5	68,5	31,2
	% of total production	12	66	31	16	77	33	13	75	46

The structure of the catch of the Azov anchovy is determined by the character of its autumn migration. Each year at the start of fishing (October), the young and adult anchovies migrate simultaneously, causing substantial catches of young. At the present time, the fraction of young in the catches (in numbers of fish) amounts to an average of 24%.

Average death rate indices of the anchovy for the same "average" generation, including removal by fishing, shows that the highest natural death rate of the anchovy (about 50% of the numbers of the generation) is observed during the 3rd and 4th years of life, and the largest removal by fishing is observed during the 1st-2nd year of life (Table 33).

To estimate the natural death rate during the winter-spring period, use was made of material on the difference in the data of an absolute estimate of anchovy of the same generation in August and June of consecutive years without removal by fishing, expressed in % (Table 34).

SARDELLE

Sardelle - Clupeonella delicatula delicatula (Nordmann) - the most numerous species in the Sea of Azov, is a short-cycle fish. As a rule, its lifetime does not exceed 3-4 years, and only isolated individuals attain the age of 5-6 years. Fluctuations in generation productivity are well-defined, and strong generations surpass weak ones in numbers by a factor of over 10.

The quantities and biomass of the sardelle in the Sea of Azov have been determined from 1931 to the present time. During this period, numerous changes in sea regime occurred which were reflected in the status of the sardelle population (Table 35).

TABLE 33. CHANGE (%) IN THE RESTOCKING OF ANCHOVY DURING ITS LIFE CYCLE
(Based on data for 1932-72)

Index	Population of 1st year fish on 1 Sept	Remainder of 1st-year fishing season	Population of 2nd year fish on 1 Sept	Remainder of 2nd-year fishing season	Population of 3rd year fish on 1 Sept	Remainder of 3rd-year fishing season	Population of 4th year fish on 1 Sept	Remainder of 4th-year fishing season	Population of 5th year fish on 1 Sept	Remarks
Population of generation	100.0	87.9	70.8	54.2	27.6	27.4	2.0	2.0	0	
Removal		12.1	29.2	45.8	72.4	72.6	98.0	98.0	100.0	For entire observation series
Including:										
Fishing industry		12.1		16.6		0.2				
Natural loss			17.1		26.6		25.4		2.0	
Number of observation years	36	36	35	35	34	31	31	22	22	
Population of generation	100.0	87.9	69.0	40.6	24.1	23.1	1.7	1.6	0	
Removal		12.1	31.0	59.4	75.9	76.9	98.3	98.4	100.0	Series neglecting years with entries of Black Sea anchovy and in which the generations are not adequately considered.
Including:										
Fishing industry		12.1		29.4		1.0		0,1		
Natural loss			18.9		16.5		22.4		1.6	
Number of observation years	36	36	22	22	-	14	14	14	12	

TABLE 34. NATURAL DEATH RATE OF ANCHOVY FROM SEPTEMBER TO JUNE ACCORDING TO AGE GROUPS (%)

Years	0+ - 1+	1+ - 2+	2+ - 3+
1968-1969	45,0	42,5	66,6
1969-1970	18,0	17,0	77,5
1970-1971	17,3	23.0	-
1971-1972	14,2	18.3	72.0

TABLE 35. SARDELLE STOCK AND CATCHES ACCORDING TO PERIODS OF DEVELOPMENT OF AZOV FISHING

Years	Stock thousand tons	Catch	
		Thousand tons	% of stock
1930-1940	465	59,3	12,8
1945-1951	463	63.2	13.7
1952-1958	412	66.8	18.2
1964-1975	454	62.0	13.7

In the last two years (1974 and 1975), the sardelle biomass is at the lowest level for the observation period, i.e., 200-230 thousand tons.

In the sardelle population, three age groups with different ecological characteristics are distinguished: fry (up to 4-5 months), young fish (up to 2 years) and sexually mature individuals.

Hibernation of the sardelle - young and sexually mature individuals - takes place in central regions of the Sea of Azov at depths of 10 m or more. Fishing for the sardelle is usually carried out at that time. Fairly accurate data are available on the size of removal by fishing for 1931-75. Hibernation assemblages are usually formed in December, when the water temperature is 2-4°. The better the fish are prepared for hibernation and the lower the wind activity above the sea surface, the earlier and the higher the water temperature at which the sardelle concentrates in an assemblage. During cold winters, when the sea surface becomes covered with stationary solid ice, the sardelle is characterized by a high natural death rate.

In late winter and early spring, the hibernation assemblages begin to break up, indicating the start of spawning migration.

Spawners first begin to approach the spawning grounds at a water temperature of 4-5°. As the water warms up, the strength of the spawning run increases, reaching a maximum at 10-15° (second half of April - beginning of May).

The sardelle spawns in freshened regions of the sea (with a salinity up to 7-9%). However, its main spawning ground, where practically the entire population is reproduced, is Taganrog Bay.

Reproduction of the sardelle takes place over a fairly wide temperature range, from 6-8 to 25°. It is most intense in late April-May at a water temperature of 14-19°. The reproduction period of the sardelle lasts mainly from April to July.

The fertility of sardelle spawners varies over wide limits. In 1963-69, it ranged from 3.9 to 28.2 thousand eggs in fish of different size,[5] and in 1973-75, from 2.3 to 19.9 thousand. All of the eggs are usually cast forth in three batches.

In most cases, the development of sardelle larvae (less than 10 mm long) takes place in slightly saline water (1-7%). Large larvae are more euryhaline and live at a salinity up to 10-12%.

Data on the distribution of the Azov sardelle for the past decade and a half show that in spring, up to 80% of the population lives in water areas with a salinity up to 7-9%, in August - 9-14%, and in October - 10-13%.

The majority of the young fish remain within the confines of freshened zones of Taganrog Bay during the summer period.

The fastest growth rate characterizes the sardelle during its first year of life, when its size reaches 45-55 mm in the course of the vegetation period. The weight growth of the sardelle is appreciable during the first two years of life, particularly at the age of 2 years (Table 36). At the age of 4 years, the sardelle reaches a size of 80-90 mm and a weight of 6-7 g.

TABLE 36. QUANTITATIVE CHARACTERISTICS OF THE SARDELLE ACCORDING TO AGE GROUPS IN AUGUST

Years	Body length, mm				Body weight, g				Fat content, up to		
	0+	1+	2+	3+	0+	1+	2+	3+	60 mm	80-70	71 mm
1967	48	71	73	74	1.4	4.2	4.8	5.0	19.6	27.3	25.5
1968	48	66	71	77	1.2	3.4	4.1	4.9	23.3	23.8	20.6
1969	36	58	66	75	0.7	2.3	3.1	4.2	19.6	16.9	15.9
1970	46	63	68	73	1.1	3.3	4.0	4.6	8.5	23.8	24.1
1971	45	66	72	75	1.0	3.9	5.0	5.5	9.5	20.8	23.9
1972	47	62	72	77	1.0	3.2	4.1	4.7	17.9	22.2	18.5
1973	43	61	70	77	0.9	2.9	4.5	5.7	13.7	25.4	27.4
1974	40	59	68	78	0.7	2.6	3.6	5.7	13.5	22.4	18.6
1975	48	61	68	77	1.3	2.9	4.2	5.3	11.6	22.8	23.4
AVERAGE	45	63	70	76	1.0	3.2	4.2	5.0	15.2	22.8	22.0

The reproduction efficiency of the sardelle is determined by the population of the spawning school (see Table 37).

TABLE 37. CHARACTERISTICS OF THE REPRODUCTION EFFICIENCY OF THE SARDELLE AS A FUNCTION OF THE BIOMASS OF THE SPAWNING POPULATION

Generation	Biomass of spawners (thous. tons) B	Number of first-year fish (units) per spawner
High-yield	330	0.8
Medium-yield	$250 < B \leq 330$	1.3
Low-yield	$B \leq 250$	2.7

The preferred food during the summer-autumn periods includes water fleas and crustaceans, mysids and other zooplankton organisms.

The sardelle's ration is determined by the age of the individuals and the temperature regime of the body of water. The sardelle population is the chief consumer of the Azov zooplankton. The main food competitors of the sardelle are the Azov anchovy, the goby, friar, three-spined stickleback, as well as the young of other fish species (Table 38).

The sardelle's pasturing rate decreases with the autumn cooling of the seawater, and the fish assembles in small schools and moves to open regions of the sea. In late November-December, it concentrates in hibernation areas, where its hibernation assemblages are formed and are subjected to fishing.

All age groups of the sardelle are found in the catches, an appreciable part of which consists of young fish.

PIKE-PERCH

The pike-perch - Lucioperca lucioperca (Linn.) - is the most abundant predator of the Sea of Azov. The maximum biomass and size of its population was 260 thousand tons and 535 million, respectively (1933-34). At the present time, the population of the Azov pike-perch is in a depressed state (the biomass slightly exceeds 10.0 thousand tons, and the population, 9 million) due to a deterioration of reproduction and habitation conditions as a result of the anthropogenic activity in the basin.

The pike-perch stock level is determined by the yield of the generations and conditions of their habitation in the sea.

The maximum catches, observed in 1936 and 1937, reached 73.6 and 72.0 thousand tons, for a mean annual value of 31.9 thousand tons for the period

TABLE 38. COMPOSITION OF SARDELLE'S FOOD IN THE SEA OF AZOV
(Percent by weight of food particle)

Components	Month							
	Jan-Feb	March	Apr-May	June	July	Aug	Nov	Dec
Copepoda	75,2	58,9	62,6	17.6-45	13.3-58	50.4	47.9	83.3
of Cirripedia	0,1	0,1	-	10.5-68	6.0-11.4	2.2	-	-
Ostracoda	-	-	-	29,8	1.3	0,8	-	-
Cladocera	-	-	-	1,9	-	-	-	-
Mysidacea	18.9	17.6	15.4	19.2	62.5-48	6.9	21.9	16.7
of Crabs and Shrimp	-	-	-	0,1	6,6	0,4	-	-
Rotifers	1.8	23.2	21.0	2.4	5.1	6.0	-	-
of Mollusks	-	-	0,5	10.0-12.3	6.0-16.0	33.3	0,6	-
Phytoplankton	4.0	0.1	-	1.0	0.1	0.1-0.7	-	-

of the natural runoff regime of the Don River (up to 1952). In the last two decades, its largest catches did not exceed 15.0 thousand tons, and in the last few years (1973-76), 5 thousand tons.

The pike-perch is a semi-migratory fish which spends the major part of its life (except for brief reproduction periods and the period of fry development) in the subsaline regions of the Sea of Azov. The area of its inhabitation is bounded by the 11.5 °/oo isohaline, and the young and first-year fish usually prefer regions with a water salinity up to 10.5 °/oo.[5,6] Two stocks of pike-perch are distinguished in the Azov basin - the Don and the Kuban' stocks. Earlier, when the freshening of the sea was sufficient, the Don pike-perch inhabited mainly Taganrog Bay, and the Kuban' pike-perch favored the eastern part of the sea proper. In the last few years, as the salinity of the basin has sharply increased, a definite tendency has been observed on the part of the pike-perch, including the Kuban' stock, to dwell primarily in Taganrog Bay, from which it migrates to the spawning areas.

The pike-perch inhabiting the sea grows faster than the one in Taganrog Bay, owing to the long period of active feeding and the composition of the food organisms. Differences in the size and weight characteristics, particularly in average weight, between the pike-perch inhabiting the bay and the sea are detected as early as the age of two years, but most clearly manifested in fish 3-5 years old (Table 39).

TABLE 39. LENGTH AND WEIGHT OF PIKE-PERCH OF DIFFERENT AGES ACCORDING TO REGIONS OF HABITATION

	Taganrog Bay			Sea Proper		
		Weight, kg			Weight, kg	
Age	Length, cm	1945-1958	1958-1973	Length, cm	1945-1958	1958-1973
1	18	0,08	0,07	18	0,08	0,07
2	35	0,5	0,40	36	0,6	0,46
3	40	0,8	0,75	43	1,1	0,95
4	47	1,2	1,17	50	1,8	1,54
5	54	1,8	1,67	57	2,6	2,25
6	60	2,6	2,26	61	3,3	3,06
7	62	3,2	2,73	63	3,8	3,80
8	64	4,0	3,14	64	3,9	4,11
9	65	4,1	4,35	65	4,4	5,17
10	66	4,5	4,85	65	4,8	5,13
12	69	5,2		66	5,2	5,42

The growth of the pike-perch young takes place fairly uniformly with the seasons, and sexually mature individuals gain weight most rapidly during the autumn-winter period, when about 75% of the annual gain occurs. The largest gains among the first-year and young fish and the sexually mature pike-perch are observed at 23-18°, 18-12° and 5-18°, respectively.

The lifetime of the pike-perch reaches 16 years, but because of elimination due to natural causes and heavy fishing, fish more than 10 years old are seldom found in the population. Fish up to five years old predominate in the population in number and biomass (Tables 40, 41 and 42).

TABLE 40. PROPORTION OF PIKE-PERCH OF DIFFERENT AGE GROUPS (%) ACCORDING TO REGIONS OF HABITATION

	Age Group								
Region	0+	1+	2+	3+	4+	5+	6+	7+	8+ and older
Sea Proper	22	11	28	53	72	82	61	100	100
Taganrog Bay	78	89	72	47	28	18	39	0	0

TABLE 41. AGE COMPOSITION OF PIKE-PERCH CATCHES IN 1975

Age Group	2+	3+	4+	5+	6+	7+	8+	9+	10+	11+	12+ and older
Size of genera- tions, T%	13,4	30,6	17,6	9,3	2,9	15,7	5,0	2,0	0,5	1,4	1,6

TABLE 42. MEAN BIOMASS OF PIKE-PERCH AGE GROUPS (thousand tons)

Age Group	0+	1+	2+	3+	4+	5+	6+	7+	8+	9+	10+ and older
1926-1951	7,7	36,1	32,5	31,7	15,5	5,8	3,0	1,4	0,7	0,3	0,3
1952-1973	2,9	11,9	11,2	8,2	4,9	2,2	0,9	0,4	0,3	0,1	0,3

The pike-perch reaches its sexual maturity in 3 to 5 years. After maturing, the pike-perch participates in spawning every year. The maturation rate of the individual generations varies with the conditions of habitation and growth, and the population of mature fish may vary from 12 to 54% in the three-year age group and from 48 to 93% of the population of the generations in the four-year age group (Table 43).

TABLE 43. MATURATION RATES OF THE AZOV PIKE-PERCH IN 1958-75
(After T.M. Avedikova, 1975)

Age	1+	2+	3+	4+	5+	6+	7+	8+	9+
Population	1	34	70	90	97	99	100	100	100

The mature pike-perch engages in spawning migrations and enters rivers of the northern Azov coastal region, the Don, the Kuban', and limans on the eastern shore of the Sea of Azov, where it reproduces. The chief reproduction sites of the Azov pike-perch are the Don River and Chelbas, Beysug and Kuban' limans.

The run of the Don pike-perch begins in autumn, usually at the end of September. A small part of the population enters the lower course of the river, where it passes the winter. However, the majority hibernate in Taganrog Bay and in the eastern regions of the sea. After the Don ice breaks up, or even during the spring ice drift, the main run of the pike-perch begins, and it reaches its maximum intensity in April.

In the Kuban', the spawning run begins in late winter and early spring. The dates of the mass run depend on the time when spring begins.

Spawning of the pike-perch takes place at a water temperature of 8.5-24°, which determines its period and duration. The spawning of the Don pike-perch usually starts when the water has warmed to 12°, and that of the Kuban' pike-perch, 9-11°.

Mass spawning of the Don pike-perch takes place in the second half of April and early May at a water temperature of 12-15°, and that of the Kuban' pike-perch, in mid-April and early May at 12-19°.

The pike-perch is characterized by a fertility ranging from 82 to 2500 thousand eggs. Usually, an average-size female contains several hundred thousand eggs. The individual fertility of the pike-perch is highly variable with the age, size and weight of the individuals and is determined by the habitation conditions of the fish in each specific year (Table 44).

TABLE 44. AVERAGE FERTILITY OF THE PIKE-PERCH (thousand of eggs) (After A. Ye. Landyshevskaya, 1973)

	Size of Females, cm								
Years	30	35	40	45	50	55	60	65	70
1966-1969	114	163	229	315	430	584	661	660	
1973	103	136	181	309	392	377	617	-	

The survival rate of the pike-perch during the embryonic-larval period of development is considerably affected by the water temperature and salinity level of the spawning grounds. The eggs develop normally at a water temperature of 9.3° to 27.2°. The lower lethal temperature for pike-perch larvae is 6.0-6.5°. A sharp drop in water temperature from 17 to 7° causes the larvae to die. The upper lethal temperature for pike-perch larvae is 30-32°.

A water salintiy up to 3 ^{o}/oo is favorable to the spawning of the pike-perch and normal development of the eggs. The survival rate of the eggs during the development in water with a salinity of 3.4-4.5 ^{o}/oo is only 1.2%.

The seaward run from the egg-laying areas on the Don and from the limans of the Kuban' takes place when the individuals are 19 to 50 mm long in late May-June, and in smaller numbers in July. During the first period of habitation in the sea, the pike-perch takes up residence in the coastal zone, and in July-Septeber migrates to the open regions.

The character of feeding of the pike-perch in ontogeny changes from planktonic in the early stages of larval development to predatory in the following period of life. The young fish feed on tiny plankton organisms, chiefly Copepoda and Cladocera, then Mysidae. The plankton period of feeding ends when the pike-perch reaches a length of about 33 mm. From the age of one month, the pike-perch leads a predatory mode of life. As the growth continues, the fraction of fish food continuously increases. Thus, for young fish 41-58 mm long, fish food is already as high as 97.5%

The chief nourishment of the adult pike-perch is the goby (56.5-59.5).*

*The first figure refers to Taganrog Bay, and the second, to the sea proper.

The species composition of the pike-perch's feed items varies considerably with the season and the location - in the sea proper or in Taganrog Bay.

Thus, in the latter spring, the pike-perch feeds primarily on the sardelle (81%), and in summer and autumn, on gobies (65.7% in summer and 94.1% in autumn). In the sea in spring, it eats mainly the sardelle (53.4%) and gobies (43.1%), and in the autumn, primarily gobies (74.7% of the weight of a food particle).

There are seasonal differences not only in the species composition of the food consumed by the pike-perch, but also in the rate of feeding. In the sea, the highest rate is observed in spring and autumn (respectively 61.8% and 46.9% of feeding individuals, and in summer, 25.2%).

The annual ration of the pike-perch is estimated at 7 body weights, and the daily ration, 2-9% of the individual's weight.

The distribution of the pike-perch over a range is affected by both the advent of a given stage of the biological cycle and abiotic factors. The maturing pike-perch executes spawning migrations, and the young fish arriving from the spawning grounds adopt a range whose size is limited by the salinization level of the seawater. On the range, important factors determining the distribution of the pike-perch are the density and accessibility of food organisms and the oxygen regime. The pike-perch is not found in regions of the basin where the content of oxygen dissolved in water is less than 5-6 mg/l, and dies if the oxygen concentration drops to 2 mg/l.

Pike-perch fishing is done during the autumn-winter and spring seasons in Taganrog Bay and the Don.

STURGEONS

Sturgeons are the most valuable food fish of the Sea of Azov and are represented by three species: beluga, huso huso (Linn.), sturgeon, Acipenser guldenstadtii (Brandt), and starred sturgeon, Acipenser stellatus (Pallas), which are fairly similar in ecological characteristics.

Although sturgeons range throughout the Sea of Azov, their distribution in it is uneven. The young, whose areas are bounded by isohalines, stay mainly in Taganrog Bay and along the northern seashore, and also in the freshened coastal region of the Kuban' River. Adult individuals inhabit the entire sea. Most of the stock hibernates in the western part of the sea (3rd and 4th regions).

All three species of sturgeons are typically migratory, traveling to spawn in the middle and upper reaches of the Don and Kuban' Rivers. Before the runoff of the rivers was regulated, the size of the stock and large catches of sturgeons were maintained exclusively through natural reproduction. At the present time, because of the construction of dams, which have almost completely barred access to the reproduction areas of sturgeons, the spawning grounds of the Don and Kuban' have become largely inaccessible.

Because of the complete disruption of the conditions for natural reproduction of sturgeons, a system of fish breeding plants has been created in the Azov basin to ensure their reproduction.

Artificial breeding of sturgeons is being conducted at seven fish breeding plants, including three plants on the Don (Rogozhkino, Aksay-Don and "Vzmor'ye") and four plants in the Kuban' River basin (Temryuk, Achuyevo, Grivenskaya and Krasnodar). As shown by observational data, the efficiency of sturgeon breeding is high, and the size of the sturgeon stock in the Sea of Azov increases in proportion to the plants' production of young fish (Tables 45 and 46).

TABLE 45. VARIATION IN THE POPULATION OF AZOV STURGEONS WITH THE DEVELOPMENT OF FISH BREEDING

Years	Quantity of young fish produced (yearly average)		Increase in sturgeon population in the sea	
	Millions	%	Thousands	%
1964-65	7.3	100	185	100
1967-69	13.4	184	354	191
1970-72	15.3	210	466	252
1973-75	27.0	370	736	400

TABLE 46. PRODUCTION OF YOUNG STURGEONS BY FISH BREEDING PLANTS OF THE DON AND KUBAN'

Year	Quantity (millions				Weighed portion (g)		
	Beluga	Sturgeon	Starred sturgeon	Total	Beluga	Sturgeon	Starred sturgeon
			Don plants				
1967	1.38	2.44	2.74	6.36	4.46	2.8	2.6
1968	1.74	2.48	2.80	4.32	3.55	2.81	1.54
1969	1.0	3.0	2.81	6.81	1.97	1.57	1.25
1970	0.04	4.35	3.37	7.77	3.7	2.39	2.28
1971	1.71	4.62	1.62	7.95	3.		
1972	0.45	4.44	3.09	7.96	3.5	2.6	1.6
1973	1.21	3.49	3.07	7.78	3.9	2.6	1.7
1974	0.55	5.56	3.51	9.62	3.0	1.0	1.7
			Kuban' plants				
1970		2.17	4.3	6.47		3.9	2.1
1971		1.86	5.97	7.83		3.7	2.2
1972		1.39	4.22	6.61		3.4	2.21
1973		3.93	8.59	12.52		3.7	2.8
1974		6.85	11.67	18.52		3.1	2.38

Table 46 presents data on the production of spawners and young fish by Don and Kuban' fish plants, used in the modeling.

The populations of all species of sturgeons have a similar structure. The presence of this structure, which is more complex than that of the fish populations discussed above, is due to a long lifetime, late maturation (Table 47), and the fact that sturgeons do not reproduce annually; the intervals between spawnings last 4-5 years. Therefore, the sexually mature part of the stock is divided into the spawning population and a reserve, i.e., individuals not particpating in spawning in a given year. Although the effect of natural reproduction is very slight and there is no point in considering it in the model, it is necessary to distinguish the spawning population in order to describe ecological characteristics such as the spawning migration.

The data of Table 47 reflect the structure of the stock (in % by weight and population) for each species of sturgeons.

TABLE 47. STRUCTURE OF THE STOCK OF STURGEONS

Species	Time of advent of sexual maturity (average number of years)	Young fish	Spawning populations	Reserve
Beluga	12	30*/60	17/9	53/31
Sturgeon	9	28/62	31/12	41/26
Don Starred Sturgeon	8	27/60	30/13	43/27
Kuban' Starred Sturgeon	7	28/58	33/19	39/23

*Note: Numerator - in % by weight of total stock:
Denominator - according to the number of individuals.

Table 48 summarizes data on average weights of individuals in different age groups of sturgeons, used in the modeling.

TABLE 48. AVERAGE WEIGHTS OF AGE GROUPS OF STURGEONS (kg)

Species	Average weight of young in Taganrog Bay	Average weight of young in the sea	Average weight of adult individuals
Beluga	2,2	2,7	95
Sturgeon	3,4	3,5	16
Don starred sturgeon	2	4	8,5
Kuban' starred sturgeon	2	2,05	7,5

Sturgeons are characterized by a mixed feeding type (predators and benthophages). Table 49 contains data on the sizes of rations and feeding efficiency of sturgeons.

TABLE 49. COMPOSITION OF STURGEON FOOD (in % by weight of food particle), YEARLY AVERAGE

Species		Type of Food: Fish — Round goby, Benthophilus, monkey goby, knipowitchia goby	Type of Food: Zoobenthos (mysids, shrimps, crabs, kerophiids, Cumacea, mollusks, chironomids, polychaetous worms)
Beluga	fry	3.1	96.9
	young	97.6	2.4
	adult	98.52	1.48
Sturgeon	fry	1.1	98.9
	young	57.65	42.35
	adult	61.72	38.28
Starred sturgeon	fry	-	100
	young	43.57	56.43
	adult	34.18	65.82

Sturgeons poorly tolerate high temperatures, and kills are observed at 25°. Sturgeon fishing is carried on in three fishing regions: (1) Azov-Don, (2) Azov-Kuban' and (3) Azov-Ukraine.

It is well known that adult individuals and young fish are found in the catches. Data on the percentage of young in the catches are given in Table 50.

TABLE 50. PERCENTAGE OF YOUNG IN CATCHES (average for 1970-72)

Region	Starred sturgeon	Sturgeon	Beluga
Kuban'	28.2	68.5	40.3
Don	27	30	33

We will now turn to a brief presentation of data on spawning migrations and pasturing of the young of individual species.

To reproduce, the beluga enters mainly the Don River, and only a small portion of the run enters the Kuban' River. The beluga run to spawn earlier than other sturgeons, and the first sexually mature individuals appear in the Don as early as January, when the water temperature is 0.1-1.0°. The spawning run is stretched out, and several waves are observed. The heaviest run is noted in March-April at a water temperature of 6-10°. During the entire period of spring migration, 29% of the spawning beluga population runs to spawn, while the majority (71%) of spawning individuals run to spawn during the summer-autumn run, which begins in June and reaches its peak in September. This beluga will spawn in the spring of the following year after hibernating in the Don. The production of fry from fish breeding plants in the Don and Kuban' Rivers is carried out during the months of June-August. As a rule, the seaward run of the young ends at the end of August. The young belugas pasture in Taganrog Bay for one year, then migrate to the sea.

Like the beluga, the sturgeon travels to the Don to reproduce, and only isolated individuals wander into the Kuban'. The start of the sturgeon's spawning run is observed in March at a water temperature of 1-3°, and the sturgeon enters the Don en masse in April, at a water temperature of 9-15°. In spring, 82-90% of the sturgeon's spawning stock goes to spawn, and the remainder goes during the autumn run from the beginning of September, with a maximum during the end of September and the first 10 days of October.

After spawning, the spawning population runs into the sea. The young sturgeons stay in Taganrog Bay for up to 4-5 years.

The spawning migration of the starred sturgeon takes place later than those of the other sturgeons. The Don portion of the run enters the Don at a temperature of 5-9°, and the maximum of the run occurs at 12-16° (which corresponds to the end of April-May).

The Kuban' sturgeon goes to spawn in may at a temperature of 8-12°, and its maximum run is observed in June at 18-25°. The seaward run of starred sturgeon young in the Don and Kuban' begins at the end of May and is heaviest in June-July. It ends in the Kuban' in August, and isolated specimens of the young remain in the mouth of the Don until November. In Taganrog Bay, the young pasture for 4-5 years.

BREAM

The bream, Abramis brama (Linn.) is a freshwater fish and is also a valuable and abundant benthophage among semi-migratory fishes. During the maximum development of Azov fishing, among valuable fishes, its catches were second only to those of the pike-perch and reached 46.4 thousand tons (1936), the average catches for the period of the natural regime of the Don River being at the 20-thousand ton level. After the runoff of the rivers became regulated, owing to the deterioration of the reproduction conditions, the size of its populations decreased sharply, so that the catches were reduced almost 6-fold. In the last 20 years, they have been practically at the same level, 2.5-3.0 thousand tons.

Fluctuations in the catches of the bream, like those of the pike-perch, are determined by the yield of its generations and its habitation conditions in the sea.

The size of bream generations is determined by the water supply of the spawning grounds (mainly floodplains) and the spring temerature regime.[5,6] After the Don River became regulated, the floodplains were flooded very seldom (3 times in the last 25 years), and this led to a sharp decline of their quality. All this, coupled with the salinization of the sea, has caused a low level of bream reserves and catches during the present period.[14]

Among semi-migratory Azov fishes, the bream is the least resistent to water salinity. Its young prefer regions with a salinity up to 7-8 $^{o}/oo$, and sexually mature individuals, up to 10.5 $^{o}/oo$. During sea freshening periods, the range of the bream amounted to 10.1 thousand km^2, or 30% of the water area of the basin, and in some years (1930-35), up to 70%. During the last decade, the bream has not been found beyond the confines of Taganrog Bay, and with increasing salinization, its range contracts toward the central and eastern parts of the bay. During the present period, the bream inhabits the eastern part of Taganrog Bay, covering only 3-5% of the water area of the sea.

The salinization of the basin and the associated decrease in range lead to a reduction of the reserve and growth rate, decline in the quality of the spawning population, and other negative biological aftereffects.

For the indicated reasons, the depression of bream reserves in the last 20 years has become permanent (Table 51), and the growth rate of fish of the same age has been cut almost in half (Tables 52 and 53).

TABLE 51. FREQUENCY (%) OF YEARS WITH DIFFERENT LEVELS OF BREAM RESERVE

Period	Level of reserve, thousand tons						Number of observations
	up to	100	150	200	250	300	
1930-1951	-	5	58	5	27	5	22
1952-1976	78	24	-	-	-	-	25

TABLE 52. AVERAGE WEIGHT OF BREAM (g) IN THE 5th AND 6th YEARS OF LIFE IN DIFFERENT PERIODS OF SALINIZATION OF THE SEA

Years of growth	Salinity °/oo	Age Groups	
		Five-year olds	Six-year olds
1935-1938	9,8	882	1275
1955-1958	12,1	688	872
1973	12,6	650	740
1974	12,9	650	720

TABLE 53. RATE OF WEIGHT GROWTH OF THE BREAM (g) DURING ONE-TIME REGIME OF THE AZOV SEA (Data of T.M. Avedikova)

Period	Age									
	1	2	3	4	5	6	7	8	9	10
1934-1952	10	122	371	527	712	927	1146	1402	1953	1620
1955-1975	12	130	400	526	646	751	831	1009	1123	1261

In the period of the natural runoff regime of the rivers, the lifetime of the bream was as long as 20 years, and 17-year old specimens used to be found in the catches. A considerable rejuvenation of the bream population has now occurred, and fish older than 10-12 years are rarely found, this being clear from the example of the 1975 spawning population (Table 54). The maximum size of the bream during the present period does not exceed 51 cm, and its weight, 3.5 kg.

TABLE 54. AGE COMPOSITION OF SPAWNING BREAM POPULATION IN 1975
(Data of G.P. D'yakova, 1975)

Age, years	3	4	5	6	7	8	9	10	11	12
Size of generations, %	0,9	21,4	34,4	19,7	19,5	3,1	0,5	0,1	0,2	0,2

The distribution of the bream over the area is determined, in addition to the salinity, by the biological cycle of the fish, and also by the nutritive base. The sexually mature beam pastures in spring, summer and fall, and with the advent of autumnal cooling, the stock begins to concentrate in the eastern part of Taganrog Bay and areas of the Don before the straits. A certain part of the population, and when the latter is low, sometimes a significant part, may enter the Don delta in November-December and remain there to hibernate.

The spawning migration of the bream into the Don begins during the first ten days of February, and the mass run lasts from the second ten-day period of March to the beginning of May. Usually, two heavy approaches are distinguished: at the end of March and in mid-April. The bream spawns at a water temperature of 11-24°, usually from mid-April through the end of July, and massive spawning takes place at a water temperature of 14-18°. After spawning, the spawners migrate to Taganrog Bay, where they pasture.

The majority of bream individuals reach sexual maturity at the age of 3 years.

The fertility of the bream, like that of other fishes, varies widely with the size, weight and age of the females and ranges from 42 to 605 thousand eggs, with an average of 154 thousand. Spawning takes place in two batches, the second batch being spawned 10-15 days after the first and amounting to 1/4-1/5 of the breeding performance. In the last few years, because of the limited number of bream spawning areas, partial or complete resorption of the eggs in the females has been frequently observed. This has a highly unfavorable effect on the size of the generation being born, as well as on the next reproduction and population, since females with resorbed eggs do not participate in the following year's spawning.

The development of bream eggs last 10-11 days at a water temperature of 11-16°, 6-7 days at 18°, and 2-3 days at 23°.

The survival rate of bream eggs depends to a large extent on the duration of flooding of the floodplains, and also on the spring temperatures: marked temperature fluctuations, particularly lows of 6-7°, results in a mass destruction of the laid eggs.

After the resorption of the yoke sac, the hatched larvae begin to feed on zooplankton. On reaching a length of 2.5-3.0 cm, the bream young partially switch to feeding on bottom organisms. The bream becomes a typical benthophage when its length reaches about 10 cm.

A mass migration of the young to Taganrog Bay takes place from mid-June until the end of July. The average size of the individuals changes from 22-25 cm for an initial weight of 0.24-0.42 g to 70 mm for a weight of 5.2 g at the end of the mass migration. The bream young which have migrated to Taganrog Bay first occupy regions adjacent to the outer delta of the Don, as well as coastal regions, spreading over the entire water area of the eastern bay by autumn.

In Taganrog Bay, the bream feeds on benthic organisms, consuming bottom crustaceans (mainly ostracods), worms, and mollusks. The young bream (1-2 years old) sometimes consumes appreciable amounts of planktobenthos forms, mainly mysids.

The bream's competitors in feeding include: during the freshwater period of life - the young and sexually mature individuals of fishes of litte value inhabiting the river, and during the marine period of life - gobies, sturgeon young, roaches, etc.

The catching of bream is based on fishing in its assemblages in Taganrog Bay during the autumn and spring periods, and also in the spawning population in the Don. Catches in the Don constitute 60-80% of the annual take.

ROACH

The Azov roach, Rutilus rutilus (Heckeli) is one of the most important food fishes of the Azov basin. In size of the population and catches, among semi-migratory fish, the roach is only behind the pike-perch and bream, and in the last few years has been only second to the pike-perch. The maximum roach catches occurred in 1935-36 (23.5 and 18.1 thousand tons), the averages for the period from the early 1930's were close to 5 thousand tons, and only in the last few years (173-76) have the takes been low, at the level of 1-2 thousand tons.

The roach is a gregarious fish, widely distributed over the Sea of Azov. However, its chief concentrations are observed in the eastern half of the sea and Taganrog Bay. Of greatest importance in its reproduction is the Azov-Kuban' region.

Of all semi-migratory fish, the roach is the most resistant to water mineralization. The upper limit of favorable salinity for its first-year young is 11 $^{o}/oo$m fir sexually mature fish, 12 $^{o}/oo$, and the highest fish density is usually observed inzones with a salinity of 9-10 $^{o}/oo$.[5] In this connection, and also in view of the extensive measures to develop the Kuban' limans, where most of the roach spawning takes place, the size of its population in the sea was at a high level up until the early 1970's. It dropped sharply only in the last five years because of unsatisfactory salt conditions in the Kuban' region of the Sea of Azov. In addition, as the average salinity of the Sea of Azov increased, a definite trend was observed whereby the area of the roach contracted and the main roach concentrations shifted from the eastern part of the Sea of Azov into Taganrog Bay (Table 55). The maximum size of the roach exceeds 50 cm, and its weight is 3.5 kg. The maximum age under present conditions does not exceed 9 years, but fish older than 6-7 years are very rare in the population. Dominant in age group populations are one and two-year olds, and in biomass, three and four-year olds (Table 56). By the age of two years, the population of the generations decreases by 30% owing to natural loss, and by the age of three years, by another 10%. When fishing is involved (at the age of 3-4 years), the natural death rate amounts to less than 10%, and removal by fishing amounts to 23 to 44%.[14]

TABLE 55. DISTRIBUTINS OF FOOD ROACH (%) IN RELATION TO THE SALINITY LEVEL OF AZOV SEA WATERS

Year	Salinity °/oo	Sea	Bay	Year	Salinity °/oo	Sea	Bay
1965	11,1	95,9	4,1	1970	11,7	77,3	22,7
1966	10,9	90,0	10,0	1971	11,8	40,5	59,5
1967	11,3	92,5	7,5	1972	12,3	30,2	69,8
1968	11,1	93,1	6,9	1973	12,6	45,0	55,0
				1974	12,8	16,4	83,6

TABLE 56. STRUCTURE OF THE POPULATION OF THE AZOV ROACH

		Age Groups, %						Average level	
Period	Index	1	2	3	4	5	6	Millions	Thousand tons
1932-	Population	55,9	22,2	14,0	6,4	1,4	0,1	464	-
1953	Biomass	7,4	16,0	37,2	30,0	8,4	1,0	-	222
1953-	Population	56,7	23,1	13,2	5,6	1,3	0,1	761	-
1972	Biomass	9,0	20,0	34,1	27,2	8,3	1,2	-	328

The roach characteristically engages in spawning and pasturing migrations, and therefore its distribution over the range in the Azov basin depends on the season, population status and nutritive base. During the autumn-winter period, particularly in February, the roach moves from open regions of the sea and bay into the coastal zone, from which the sexually mature portion of the population begins to migrate toward the spawning grounds.

The Azov roach becomes sexually mature at the age of two to three years, when about 83% of the females and 94% of the males mature.

The spawning population of the roach is represented by 2-6-year olds, and 3-4-year old fish usually predominate (Table 57). The ratio of the sexes in the spawning population is close to 1:1.

TABLE 57. AGE COMPOSITION OF SPAWNING ROACH POPULATION

Period	Population of age groups, %				
	2	3	4	5	6
1945-1968	1,9	44,1	39,4	12,6	2,0
1969-1975	0.9	57,6	35,2	5,4	0,7

The entry of the roach into limans takes place at a water temperature of 3-10° from the end of February to May, and is massive in March - early April. Spawning of the roach begins when the water warms up to 8-10° and is observed from the end of March to mid-May, and massive spawning takes place at a temperature of 12-14° (April - beginning of May). After spawning, the roach spawners migrate into the sea. The fertility of the females varies from 2 to 200 thousand eggs (average, 50 thousand eggs). In some of the fish, particularly those remaining in limans, resorption of the reproductive products takes place.

The optimum conditions for spawning and egg development are as follows:

(1) Water temperature in the spawning areas, 12-14°; no marked daily fluctuations of this temperature.

(2) Salinity of water no higher than 3 ‰, since a 3-5 ‰ mineralization of water causes a marked loss of the developing eggs.

(3) Saturation of water with oxygen in the spawning areas not under 35%.

(4) Absence of strong wind waves, which cause the water to become turbid.

Infringement of even one of these conditions causes a marked decrease in the number of hatching larvae, sharp temperature fluctuations being particularly harmful. Thus, lowering the temperature from 12.7 to 9.3° causes an unproductive generation, and lowering it to 3-5° leads to the complete loss of the laid eggs. The duration of egg development depends on the water temperature and amounts to 13 days at 8.7° and 1 day at 15-16°.

The yield of roach young is greatly affected by the temperature during the period of embryonic-larval development, and also by the availability of food to the larvae during the period of change to active feeding, and the presence of predator and competitor pressure in the breeding areas. The size of the spawning population is not a decisive factor in the formation of the size of a new generation.

In contrast to the sexually mature fish, which immediately after spawning leave the limans for the sea, the young remain in the breeding areas. Usually, their migration to the sea begins in June, and after reaching a maximum in July, ends in August.

The size and weight of the migrating individuals are 21-37 mm and 140-800 mg, respectively; at the end of summer, they may be 2 to 3 times as much. Roach fry which have entered the sea initially dwell in the shallows of the coastal zone (at a depth of less than 1 m), and subsequently also migrate to Taganrog Bay; the rate of this phenomenon has sharply increased in the last few years.

The roach in ontogeny feeds on various complexes of food organisms. Thus, larvae in the early stages of development consume zooplankton (rotifers, copepods, cladocerans), and in later stages switch to feeding on crustaceans. In feeding, the roach young in limans now dominate benthic forms of chironomid larvae. When they reach the sea, young of the current year consume bottom crustaceans, worms, and mollusks, and from the age of two years, switch to feeding exlusively on mollusks.

The feeding rate of the roach is substantially affected by the water temperature in the region of habitation. The fish feeds most actively at a temperature above 15°, so that during the summer season (May-August), up to 90% total ration required by the roach during one year is consumed. In spring (April) and autumn (October-November), 5-7% of the total amount ration is consumed.

The roach becomes edible at the age of three years, when it reaches 14-16 cm. Data on its average weight are given in Table 58. It is caught in September-December and February-April, when it approaches the coastal zone and executes spawning migrations. Until recently, the main fishing region was the Azov-Kuban' region, where up to 70% of the annual catch was taken.

TABLE 58. AVERAGE WEIGHT OF ROACH OF DIFFERENT AGE GROUPS (g)

Period	Age Groups		
	3	4	5
1945-1969	185	210	280
1973-1975	110	130	160

OTHER FISHES

It goes without saying that the characteristics of the other 97 unmentioned fish species of the Sea of Azov will not be cited here. What we are interested in is to consider in some way, for modeling purposes, the total influence which other fishes exert on the populations of edible fishes and on the ecosystem as a whole, with the understanding that many populations cannot and should not be considered. The classification of a population in the OTHER FISH class was decided on the basis of reported data[3-8] and expert estimates based on the following system of criteria:

C1. The average size and biomass of a population should not be smaller in order of magnitude than the size and biomass of the population selected for "individual" modeling.

C2. The commercial significance of a population (if the fish in question has any commercial significance at all) should be much less than that of the population discussed in Sec. 7.1-7.7.

C3. A given population should be in trophic or competing relationships with the populations of the "main" fishes, and these relationships should be significant for the latter.

C4. It is necessary to have either quantitative estimates of the vital activity parameters of the fishes, or at least fairly precise qualitative notions permitting the formulation of plausible hypotheses concerning the significance of such parameters.

Each of the selected populations must satisfy C2 and C4 and either C1 or C3.

From the multitude of fish species in the Sea of Azov, eight populations were selected - five fish species hibernating in the Black Sea (referred to below as the "Black Sea species") and three species dwelling permanently in the Sea of Azov (the "Azov species").

Black Sea fishes:

(1) Friar, Atherina nochon pontica (Eichwold)

(2) Three-spined stickleback, Gasterostens aculeatus (Linn.)

(3) Black-Azov Sea migratory herring, Alosa kessleri pontica (Eichwold)

(4) Azov Sea herring, Alosa caspia tanaica (Grimm)

(5) Red mullet, Mullus barbatus ponticus (Essipo)

Azov Sea fishes:

(6) Percarina, Percarina domendofii

(7) Syrman goby, Gobius syrman (Nordmann)

(8) Goby-knipowitschia, Knipowitschia longicandati (Kessler)

It is possible that if necessary, this number of populations can be increased later on.

Table 59, compiled on the basis of Refs. 6, 7, 8 and expert estimates, give the principal biological characteristics of the above species. Here and in all the remaining Tables 60-62, a large proportion of the data were obtained by means of expert estimates.

TABLE 59. PRINCIPAL BIOLOGICAL CHARACTERISTICS OF FISHES (1-8) BASED ON DATA OF NATURAL OBSERVATIONS AND EXPERT ESTIMATES

Species	Average biomass (thous. tons)	Average popula-tions (millions)	Average weight (g)		Length (cm)	
			Adults	Young	Adults	Young
Friar	30-60	8000	6,0	1,5	8,0	5
Three-spined stickleback	1	200	2,5	0,5	6	1,5
Sea herring	12	4000	141	3,6	22,4	6,7
Azov Sea herring	0,35	20	48	5,5	15	4,5
Red mullet	1,75	70	10,7	5,3	14,5	5,0
Percarina	8	30000	2,5	0,7	4,5	1,2
Syrman goby	7	2	17,0	3,6	14,5	6,0
Goby-knipowitschia	0,1-0,3	12	0,3	0,17	2,8	2,0

TABLE 60. CERTAIN PARAMETERS ADOPTED IN MODELING (number of five-day period)

Start of spawning	End of spawning	Entry from Black Sea	Departure for Black Sea	Start of spawning run	End of stages in breakdown of spawning period		
25	49	19	66	19	36	42	49
18	42	19	66	19	24	42	-
19	45	14	69	14	27	35	45
19	32	14	70	14	25	32	-
28	37	17	71	17	30	36	-
28	43	-	-	16	28	35	43
25	36	-	-	16	25	36	-
27	42	-	-	16	28	35	42

We will enumerate the principal effects of the selected populations on the ecosystem.

Friar - one of the most abundant fishes of the Sea of Azov, serves as food for the pike-perch, herring, and is also a feeding competitor of the anchovy, sardelle, and young of the goby.

Three-spined stickleback - consumes the eggs and larvae of the pike-perch and roach, is a feeding competitor of the young and larvae of valuable fish breeds as well as sexually mature planktophages.

Black-Azov Sea migratory herring - is a competitor and to a lesser extent, consumer of the young of valuable fish breeds as well as planktophages.

Azov Sea herring - serves as food for the pike-perch and is also a feeding competitor of the young of the pike-perch, roach, golden shiner, and sturgeons during the period of their feeding on planktobenthos.

Red mullet - is a food object for sturgeons and gobies and to a lesser extent, anchovy.

Percarina - is a competitor of the young of valuable fish breeds and to a lesser extent, a consumer of their larvae as well as a food object for the pike-perch.

Syrman goby - eats the sardelle and anchovy, serves as food for the pike-perch and sturgeon and is a feeding competitor of the round goby.

Knipowitschia goby - serves as food for edible fishes and competes in feeding with planktophages.

Tables 60, 61 and 62 give data on the feeding, breeding and regions of habitation of the fishes modeled in the unit.

It is evident from the data cited that our knowledge of the vital processes of the above fishes is very limited.

TABLE 61. FEEDING AND BREEDING CHARACTERISTICS

Species	Feeding Spectrum: Zoo-plankton	Phyto-plankton	Benthos	Fishes	Spawning: Fertility	Time	Place
Friar	+	-	+	-	Av. 592	May-Aug	coastal zone, 7 $^{0}/_{00}$
Three-spine stickleback	+	-	-	+	782-1381	end March end April	Kerch Straits, Kuban' estuaries
Sea herring	+	-	+	+	Av. 49000	April-mid August	Don R. in June-partly in Taganrog Bay
Azov Sea herring	+	-	-	-	12000-39000	April-early July	lower course of Don
Red mullet	-	-	+	+	3650	end May end June	southern part of Sea, Kerch Straits
Percarina	+	-	+	+	up to 3000	end May-early August	eastern part of Taganrog Bay
Syrman goby	-	-	+	+	Av. 820	May to June	Taganrog Bay, coastal zone
Knipowitschia	+	-	-	-	274-804	Mid-May-August-September	Taganrog Bay

TABLE 62. CHARACTERISTICS OF REGIONS OF HABITATION AND MIGRATION

Species Season	1	2	3	4	5	6	7	8
Winter	Black Sea	Black Sea	Black Sea	Black Sea, Kerch Straits	Black Sea	Eastern and Central parts of Sea of Azov	Central part of Sea of Azov	Eastern part of Sea of Azov
Spring Summer	Coast of Sea of Azov, Sivash	Sea of Azov, Kuban' limans	Taganrog Bay, Don River	Taganrog Bay, lower part of Don, Kuban' limans	Southern part of Sea of Azov, Kerch Straits	Taganrog Bay	Coast of Sea of Azov, Taganrog Bay	Taganrog Bay
Autumn	Coast of Sea of Azov	Coast of Sea of Azov	Northeastern part of Sea of Azov	Northeastern part of Sea of Azov	Southern part of Sea of Azov	Eastern part of Sea of Azov, Taganrog Bay	Sea of Azov	East Coast of Sea of Azov

We have beome acquainted with the life of the ecosystem of the Sea of Azov. Before turning to its modeling, it will be useful to recall that it is desirable to obtain a model, not of the system in general, but of a problem in the system. Only then can the model be expected to prove really useful, and in particular necessary for solving a specific problem.

What problems of the Sea of Azov are of most interest to us? Do they exist at all? yes, they unquestionably do, and furthermore, are of vital importance.

A considerable portion of the catchment basin of the Sea of Azov is located in a zone of insufficient humidification, where the coefficient of runoff from the territory of the catchment is equal to 0.13. For this reason, the river runoff is very limited and amounts[14] to an average of 41 km^3 (according to other data,[2] 43.4 km^3). The bulk of the runoff is due to two rivers - the Don and Kuban' (27.9 and 13.9 km^3, respectively). The exceptional variability of the Don River runoff with time (52 km^3 in 1942 and 11.8 km^3 in 1950) causes large fluctuations of the total water reserves of the basin (25% availability - 50.7 km^3; 75% - 33.0 km^3).

The river runoff of the Azov Basin is used for the needs of industry, agriculture, power engineering, water transport, municipal water supply and fisheries. The Sea of Azov is the closing link in the utilization of the water. It follows from general ecological considerations[8] that the effects of anthropogenic action in the basin should accumulate in the ecosystem of the Sea of Azov. This is indeed the case.[1]

We will examine in more detail the mechanism of the pressure exerted on the ecosystem of the Sea of Azov by the continental part of the basin and will attempt to determine the extent to which the ecological system is stable to this pressure, and the conditions and planning prospects for the development of the national economy on the territory of the basin.

The principal negative effects exerted at the present time by the continental part of the basin on the marine part should be assumed to be the following:

(1) Irreversible removal of a considerable part of the runoff. At the 1975 level, the total water consumption in the basin was already 23 km^3, and the irreversible consumption, 15 km^3, or about 35% of the river runoff norm. Despite the planned measures of efficient utilization of water in industry, heat and power engineering and agriculture, the water consumption, including nonrecoverable consumption, will continue to grow at a rapid pace. In 1980, the total planned water consumption will be 33 km^3, and nonrecoverable, 20 km^3; in 1985, 38 and 22 km^3, respectively, and in the 2000, 60 and 38 km^3, i.e., by the end of the century, practically all of the runoff will be irretrievably consumed by participants in the hydroeconomic complex. Of these, the largest water consumer is irrigation (total water consumption in 1975, 9.22 km^3; nonrecoverable, 8.69), and the rates of its presumed growth are the most substantial (in the year 2000, 27 and 25.5 km^3). The industry, heat and power engineering, and population of towns and urban-type settlements consume quantities of water comparable to irrigation (in 1975, 10.65, and in the year 2000, 21.22 km^3 is anticipated), but the fraction of nonrecoverable water consumption is much smaller (in 1975, 2.24 km^3, and in the year 2000, 5.09 km^3). The remaining sectors of the hydroeconomic complex (fisheries will be discussed separately) make a comparatively small contribution to the nonrecoverable removal of water.

(2) Seasonal leveling of runoff. In 1952, the Tsimlyansk storage reservoir, one of the largest in the USSR, was built in the lower course of the Don, and in 1975, the filling of the Krasnodar storage reservoir on the Kuban' was completed. The seasonal leveling of the runoff sharply reduced the frequency, area and duration of the flooding of floodplain spawning grounds in the tailraces of the hydrosystems (Table 63).

TABLE 63. MEAN MONTHLY RUNOFF OF THE DON RIVER BEFORE AND AFTER CONSTRUCTION OF TSIMLYANSK HYDROELECTRIC POWER PLANT (Village of Razdory)

Month	1881-1951			1953-1971		
	Flow rate m^3/sec	Runoff km^3	Runoff in % of annual	Flow rate m^3/sec	Runoff km^3	Runoff in % in annual
I	286	0,8	2,9	405	1,1	4,9
II	412	1,1	4,0	557	1,3	5,9
III	951	2,5	9,1	727	1,9	8,6
IY	2730	7,2	25,7	1347	3,5	15,8
Y	3600	9,6	34,4	1247	3,3	14,9
YI	899	2,3	8,3	767	2,0	9,0
YII	373	1,0	3,6	650	1,7	7,7
YIII	289	0,8	2,9	601	1,6	7,2
IX	244	0,6	2,2	599	1,8	6,7
X	241	0,6	2,2	612	1,6	7,2
XI	271	0,7	2,5	610	1,6	7,2
XII	243	0,6	2,2	411	1,1	4,9

The above table illustrates the radical changes in the annual runoff of the Don River. As a result of these changes, the flooding frequency of spawning grounds of the Lower Don dropped from 84 to 18% years, the area, from 95 to 30 thous. ha, and the duration, from 49 to 12 days.

(3) Reduction in the breeding areas of migratory and semi-migratory fishes due to the difficult access of spawning grounds. This effect is also a result of the construction of dams, and its impact on sturgeons is particularly strong. Thus, 80% of the spawning grounds have proven practically

inaccessible to the sturgeon, over 95% to the beluga, and 50% to the starred sturgeon.

(4) Change in biogenic and mineral runoff. A change in the qualitative composition of the waters flowing into the sea.

After the regulation of the Don River runoff, the biogenic river runoff decreased substantially. The proportions of different biogenic elements in the runoff, to which the ecosystem was adjusted, changes. Since modern methods of purification of waste waters from industrial plants and return waters of irrigation systems are inadequate, and the self-purifying capacity of rivers is limited, a certain amount of pollutants fall within the ecosystem of the sea.

Thus, the negative effects of the continental part of the basin on the Azov ecosystem are very appreciable. At the same time, the ecosystem is distinguished by an extremely low inertia of development and stability to external forces. This is due to the following factors:

(1) Exceptionally small dimensions of the sea (see above).

(2) Short period of chemical and biological cycles.

(3) Minimum variety of species, resulting in a particularly high degree of potential vulnerability of the ecosystem.

(4) Intensive water exchange with the Black Sea, permitting rapid introduction into the Azov ecosystem of representatives of Black Sea flora and fuana in the presence of conditions favorable to them in the Sea of Azov.

Under the prevailing conditions, the ecosystem of the sea has been thrown out equilibrium, and the changes taking place in it may be estimated as unfavorable. Catches of fish, particularly of valuable breeds, have decreased. The bioproductivity of the most valuable species of ichthyofauna has shrunk from an average of 90 thousand tons for 1927-51 to 20 thousand tons. The total catches of migratory and semi-migratory fishes have now dropped to an extremely low level, 5-10 thousand tons.

The extremely rapid development of negative aftereffects of anthropogenic reduction of the river runoff and its annual leveling renders particularly important the problem of examining the fundamentally new phenomena directly in the sea and their relationships. We will try to trace the direct and more remote aftereffects of the change in runoff regime.

One of the chief factors responsible for the unique fish productivity of the sea should be considered a low water salinity, thanks to which the populations of saltwater and generatively freshwater fishes have been able to utilize the food resources over practically the entire water area of the sea.

The average long-term salinity of the Sea of Azov during the 1912-51 period was 10.6 $^{o}/oo$. This average level correspond to an equilibrium between the large masses of Black Sea salt water arriving through the Kerch Straits and the continental runoff. The water exchange between the Black and Azov Seas is mainly determined by the wind conditions in the Kerch Straits, and hence as the river runoff decreased, the equilibrium should have been disturbed. The anthropogenic reduction of the river runoff coincided in time with the climate-caused depression of the total humidification of the basin, leading to an appreciable intensification of advection of Black Sea waters with an accompanying yearly accumulation of about 60 million tons of salts in the Sea of Azov. By 1976, the average salinity of the sea had increased to 13.8 $^{o}/oo$, and in Taganrog Bay, to 10.8 $^{o}/oo$

(versus 6.5 $^{o}/oo$ in 1912-51). Changes in the salinity field of the Sea of Azov are illustrated in Figure .*

The fastest and most noticeable consequence of such salinization of the sea has been a sharp reduction the areas of saltwater and relicit species, amounting to up to 10% of the sea area and 5% of the sea volume. The vacated ecological niches are rapidly snapped up by Mediterranean immigrants.

The latest studies[11,12] have made it possible to establish a number of new characteristics, whose appearance and development had never before been directly or indirectly correlated with the transformation of the river runoff. They include:

(1) Accentuation of the salt stratification and hence, temperature stratification of the water masses of the sea.

(2) Accelerated sedimentation of suspended organic matter and its accumulation in the bottom sediments of the sea.

(3) Increase in the size of bacterial populations of the bottom, caused by an increase in the mass of organic substrate.

(4) Increase in the biochemical consumption of oxygen by the surface layer of the ground.

(5) Stable formation of anaerobic or similar situations in the bottom layer. So-called oxygen kills are observed almost constantly in the summertime.

(6) Large-scale death of benthos and benthic fishes due to oxygen kills. Obviously, this promotes the phenomena described in items (2), (3), and (4).

*Translator's note: Number of figure missing in the original text.

(7) Self-pollution of the sea as a result of oxygen deficiency. This involves a periodic production in the Sea of Azov of toxic products due to anaerobic decay of soil organic matter (hydrogen sulfide, methane, phenols, carbolic acids, etc.).

(8) Reduction in the potential capacity of the Sea of Azov for self-purification involving the removal of organic pollutants.

(9) Transformation of the qualitative composition of the organic matter of the Sea of Azov.

(10) Slowing down of biogeochemical cycles of the main biogenic elements. In comparison with 1956-60, by 1971-75 the average rate of nitrogen turnover had decreased from 4.3 to 1.9 cycles/year, and that of phosphorus turnover, from 12.1 to 0.7 cycles/year.

The net result of the above transformations of the chemical aspects of the sea has been a sharp decrease in the amount of primary organic matter synthesized therein. In the last five years, the annual phytoplankton production has been in the range of 13-20 million tons, vs. a natural norm of 34 million tons. As a result, a curtailment of production is also observed in the higher links of the trophic pyramid.

The principal chains of the cause-effect relationships formed in the sea as a result of the anthropogenic reduction of the river runoff are illustrated by the diagram shown in Figure .*

*Translator's note: Number of figure missing in the original text.

The data presented in this figure make it possible to draw an important conclusion, i.e., the reduction in river runoff leads to not partial, but total damage of the ecosystem of the sea, detectable at the most diverse levels of its organization. Also visible on the diagram is the coordinating role of salinity change in the dynamics of all new processes taking place in the sea.

Thus, the Azov ecosystem has already been thrown out of the state of equilibrium and in now in some intermediate state. The problem of the Sea of Azov is one of the directions of further anthropogenic activity within the confines of the Azov Basin with due regard for these undesirable changes.

Serval alternative approaches are possible:

(1) Consider as necessary measures that would provide for the restoration of conservation of natural conditions, to halt the negative processes taking place in the sea and restore the Azov ecosystem as much as possible (for example, construction of the Azov Dam).

(2) Aim at the elaboration and creation of a set of natural conditions and economic measures that would create in the Azov Sea an "artificial" ecosystem that is sufficiently productive from the standpoint of fishery (for example, transformation of the sea into a "nursery" of sturgeons with artificial breeding).

(3) Treat the changes in the Azov ecosystem as a natural consequence of a highly efficient utilization of the water for other needs in the continental part of the basin.

(The negative significance of the rearrangement of the ecosystem taking place in the sea must not be exaggerated. The importance of the Sea of Azov in fishing will undoubtedly decrease if no steps are taken, but the salinization of the sea has no negative effects on such species as the anchovy, sardelle, etc.).

At the same time, however, one should realize that such control can be adopted only if it is certain that such a rearrangement will not lead to a complete degradation of the ecosystem and destruction of the natural object.

Within the framework of each of these approaches, a number of variants of specific measures are possible that can both preclude each other and prove mutually complementary. Approaches that effectively reconcile these three points are possible, as are fundamentally new views of this problem. In any event, it should be recalled that the problem of the Sea of Azov cannot be considered separately from the general problem of utilization of the water resources in the Azov Basin. At the present time, there exist several projects for diverting the runoff from other regions. In the preparation of general long-term plans, a diversion of the runoff from the Volga has bee proposed in volumes that by the end of this century would increase from 5 to 20 km^3/year. However, in view of the continuing drop in the Caspian Sea level, the Volga itself requires runoff assistance. In this situation, diversions of part of its waters to the Azov Basin create the necessity of appropriate compensations in the same amount and Volga's replenishment with the runoff of northern rivers. Specific proposals for such major hydroeconomic measures are already in the stage of constructive discussion. Thus, the problems of water distribution in the Azov Basin are exceeding the scope of their territorial boundaries and becoming a part of the overall program for transforming the river runoff of the European part of the USSR. There is still another extension of the problem on a country-wide scale, i.e., an economic one: the comparative rates of economic development of the regions included territorially in the Azov Sea Basin depends on all the resources, in particular, the water resources. It should also be noted at this point that the fishing economy is more closely determined by the necessary set of natural conditions than are most industrial and agricultural sectors.

Nevertheless, there exist anthropogenic actions in the Azov Sea Basin whose positive effect is unquestionable. They should be carried out as rapidly and effectively as possible.

They include primarily the construction of purification installations, the design of recycling water supply systems and latest waste water purification systems for plants now under construction and those being reconstructed, the creation of irrigation systems in which the evaporation loss would be minimal, and steps toward utilizing the water transport and preventing the pollution of waters with petroleum products. All these measures are stipulated in the Resolution concerning measures to prevent the pollution of the Black and Azov Basins (Pravda of 4 February 1976).

In any event, to select the control of a natural-technical system as intricate as the hydroeconomic complex of the Azov Basin, it is necessary to be able to predict with an adequate degrēe of reliability and detail the state of the Azov ecosystem for different variants of anthropogenic activity. However, the complexity of the processes taking place in the sea and their interdependence are such that no scientific group is able to predict the reactions of the ecosystem on the basis of only qualitative or basically qualitative ideas. To obtain even one prediction variant, it is necessary to perform many calculations, and an effective prediction implies that different paths of the system have been obtained, each of which is random to some degree. That is to say, a new tool for obtaining predictions is required. Selected to be such a tool was a mathematical model of the Azov ecosystem, a model realized in the form of a set of computer programs. And, although strictly speaking, the solution of the Azov problem requires a general model of water utilization in the Azov Basin, the model of the Azov ecosystem is its principal part, which simulates the processes taking place in the most complex and closing link of the water consumption of the Azov Basin.

2. Method of Modeling of Water Exchange Between Different Regions of the Sea and of the Associated Change in the Concentration of Solutes and Suspensions

The solution of the problems listed above requires the creation of a mathematical model of the entire ecosystem of the Sea of Azov. In this section, we will consider only one but very important part of this model - a model of water exchange between different regions of the sea. Its importance is due to the fact that water exchange determines to a considerable degree the changes in the concentration of solutes and of the phytoplankton, zooplankton, etc. inhabiting the water mass. These changes are very substantial for the ecosystem as a whole.

The most accurate and universal means of solving such problems involves the use of hydrodynamic equations for calculating the currents in a body of water, and the subsequent calculation, by means of the turbulent diffusion equation, of the dynamics of concentrations of the substances on the basis of the flow pattern obtained. This equation is

$$\frac{dx}{dt} = - \operatorname{div}(x \cdot \vec{u}) + \operatorname{div}(E, \operatorname{grad} x) \quad (1)$$

In practical calculations, exact differential relations are replaced by their finite-difference analogs, and the computations (usually done with a computer) are performed for discrete instants of time on a discrete grid approximately the body of water.

The necessity of changing to discrete time and space steps when describing the dynamics of concentrations of a substance in a body of water by exact hydrodynamic equations renders competitive the methods of description of this dynamics whereby the discreteness, although usually fairly rough, is established in space and time. If instead of the vertices of the grid one represents individual regions of the body of water, and the currents in the latter are described in terms of water exchanges between its neighboring regions, the finite-difference analog of the turbulent diffusion equation can be integrated as a relation describing for each region the balance of the substance entering it from neighboring regions (or from the outside) and carried out neighboring regions (or participating in certain chemical transformations). The basic idea, which we wish to repeat once again, consists in the fact that models based on balance relations should never be compared with exact hydrodynamic models. Both types of models describe, perhaps with different degrees of accuracy, the same physical laws of the real world.

Let us turn to a more detailed description of the calculations of the concentration dynamics of a substance in a body of water. Let the latter be divided into n regions, which may be assumed internally homogeneous in the concentration of this substance. The following notation is introduced:

x_i^t - concentration of sbustance at time t in region of number i;

v_i^t - volume of region i at time t;

y_i^t - entry of the substance into region i at time t;

q_{ij}^t - volume of flow from region i to region j at time t;

K_i - decay coefficient of the substance.

The equation for the concentration dynamics of the substance is

$$x_i^{t+1} = [x_i^t(V_i^t - \sum_j q_{ij}^t) + \sum_j q_{ji}^t x_j^t + y_i^t - K_i V_i^t x_i^t]/V_i^{t+1} \quad (2)$$

$$i = 1, 2, \cdots, n$$

The terms of the right member of Equation (2) have a clear physical meaning:

$x_i^t v_i^t$ - amount of substance in region i at time t;

$x_i^t \sum_j q_{ij}^t$ - amount of substance carried out of the region to neighboring regions;

$\sum_j q_{ji}^t \cdot x_j^t$ - amount of substance entering region i from neighboring regions;

y_i^t - inflow into region i from the outside;

$K_i v_i^t x_i^t$ - consumption of substance in region i caused by chemical decomposition.

In conformity with the two terms in the right member of the turbulent diffusion equation (1), the quantities q_{ij} are assumed to consist of two terms:

$$q_{ij} = q_{ij}^{I} + q_{ij}^{II}$$

The first term corresponds to the water exchange between regions i and j, related to dominant currents, and the second terms describe diffusion or random disturbances relative to the dominant currents durint the selected time step.

Accordingly, $q_{ij} > 0$ and $q_{ij} = 0$ only for regions with no common boundary. Since the second term in Equation (2) describes the interpenetration of water at the boundary of the regions, we have the conditions $q_{ij}^{II} = q_{ij}^{II}$, i.e., the second terms are the same for oppositely traveling currents. A different condition, $q_{ij}^{I} \cdot q_{ji}^{I} = 0$, holds for the first terms, i.e., at least one of these two terms is equal to zero. This is a reflection of the fact that the directional flow between two contiguous regions can take place in only one of two possible directions.

The equation of concentration dynamics (2) makes it possible to compute the concentrations x^{t+1} only if the values of all the variables in the right member of the equation are known. The values of concentration x^t in the preceding step are assumed to have been computed or specified as initial conditions. The values y^t of inflows of the substance into the regions of the body of water are exogenous factors and should be specified. The decay constants K_1 of the substance may be different for different regions of the body of water because of possible differences in physicochemical conditions of the region, and should also be specicified exogenously. The remaining values of the volumes v_i^t, v_i^{t+1} of each of the regions and flows q_{ij}^t depend on the hydrological regime of the body of water. They may also be either specified or computed as a result of the application of a special procedure describing the hydrology of the body of water.

In accordance with these various possibilities, formula (2) can be used for different purposes. If the situation in the body of water is sufficiently stable, one can calculate the steady state of the concentrations, assuming that the quantities entering into formula (2) remain unchanged when the substitution $t \to t + 1$ is made. This leads to the relation

$$x_i = x_i(1 - \frac{1}{V_i} \sum_j q_{ij}) + \frac{1}{V_i} \sum_j q_{ji} x_i + y_i - K_i x_i \qquad (3)$$

$$i = 1,2, \cdots, n$$

Simple transformation reduce the system of equations (3) to the standard form

$$Ax = 6,$$

where A is a square matrix of order n with coefficients

$$A_{ij} \begin{cases} K_i + \frac{1}{V_i} \sum_j q_{ij} & \text{for} \quad i = j \\ \\ - \frac{1}{V_i} \sum_j q_{ij} & \text{for} \quad i = j \end{cases}$$

and y is a column vector with components y_i.

The steady state of the concentrations of the substance in the body of water is obtained as the solution of the linear system

$$x = A^{-1} y;$$

hence, if the volumes of flow q_{ij} between the regions of the body of water are specified or estimated in some manner, and the concentrations of the substance may be considered to be in a steady state, then from a given inflow (removal) y of the substance one can compute the distribution of its concentrations in all the regions of the body of water, the dependence of vector x, or steady-state concentrations, on vector y, or losses of the substance, being linear.

The second method of using Equation (3) consists in computing the nonstationary concentrations x. The nonstationary values of volumes v_i^t and flows between regions q_{ij}^t can be computed with the aid of a suitable hydrological model. For a shallow body of water characterized by a predominance of level fluctuations due to the raising and lowering of water by the effect of wind, this can be done by means of a model analogous to the one used for simulating the hydrological regime of the Sea of Azov.

In this model, a time step of 5 days was chosen. It was assumed that to the 5-day average of the wind velocity vecotr there corresponds a certain slope of the water surface, which to a first approximation was assumed to be an ideal plane. These assumptions were based on data from natural observations and level fluctuations of the Sea of Azov.

The sequence of the calculations in the model is as follows: first, the average levels of each of the regions are calculated from the average wind velocity vector above the water area of the sea. From the level of the region, its volume v_i^{t+1} is calculated. Comparison of v_i^t and v_i^{t+1} shows what additional (or excess) amount of water is required by region i. From the relative arrangement of the regions, one determines from where this amount of water enters this region. Also considered are inflows of water with river runoffs and from other sources, and also the balance of evaporation from the sea surface and precipitation on the latter.

A systematic study of the hydrometeorological regime of the Sea of Azov began in 1922. Up to that time, only irregular measurements of the hydrometeorological characteristics of this sea had been taken from several coastal stations, as well as sporadic measurements of water temperature and salinity in the open part of the sea. By the early 1930's, the network of hydrometeorological stations and posts conducting regular measurements numbered 31 observation points. the data of hydrometeorological observations during the period from their inception to 1935 were classified and correlated in Ref. 15. During World War II, systematic observations in the Sea of Azov were discontinued, but as early as 1947, all formerly active stations and posts began systematic observations. At the same time, hydrological and biological studies in the open part of the sea were resumed.

In 1949, in connection with projects to regulate the runoff of the Don and Kuban' Rivers, a number of scientific and planning institutes carried out additional studies that made it possible to prepare forecasts of possible changes in the hydrological regime of the sea.

Observations made up to 1959 were classified and correlated in the Hydrometeorological Handbook for the Sea of Azov.[16]

In addition to the results of measurements of hydrometeorological characteristics, this handbook presents conclusions of topical investigations conducted under special programs. As a result, the handbook constitutes a complete and conprehensive description of the hydrometeorological regime of the sea.

At the present time, systematic observations of hydrometeorological characteristics such as atmospheric pressure, wind speed and direction, temperature of air and water, absolute and relative humidity, amount of precipitation, duration of solar radiance, etc. are being conducted at thirteen weather stations arranged in a fairly regular patter along the entire coastline. For measurements in the open part of the sea, the Azov

Scientific Research Fishery Institute, which is the chief organization engaging comprehensive investigations of the Azov ecosystem, conducts four cruises per year: in April, July, August and October. The research ship takes water and ground samples at 33 points arranged in a fairly regular pattern over the water area of the sea. The water samples are taken at two or three levels, depending on the depth in the region of the sampling site. If the preliminary analysis performed on the spot aboard the ship indicates the presence of a temperature stratification or a bottom deficit of oxygen, additional samples are taken at 0.5-m intervals from the water surface to the bottom.

Under laboratory conditions, the samples are subjected to a thorough chemical and biochemical analysis. In particular, such indices as total mineralization, dissolved oxygen content, iron content, pH analysis, alkalinity, concentrations of nitrogen and phosphorus in organic and inorganic state, silicon content, etc. are determined.

In addition to taking the samples, the expedition ship also measures the wind speed and direction, air and water temperature at various levels, atmospheric pressure, current speed and direction by means of independent printing current meters, and water transparency by means of a Secchi disk. These measurements and observations do not exhaust the entire range of studies performed on the expedition ship. During each cruise, special studies aimed at more thorough and comprehensive investigations or certain individual ingredients of the ecosystem are carried out. The programs of these additional observations are prepared by considering the suggestions of specialists who investigate and simulate the Azov ecosystem for the purpose of a more accurate description of the key components or processes taking place in the Azov ecosystem.

REFERENCES

1. A.B. Gorstko and F.A. Surkov. Mathematics and Problems of Conservation, Moscow, 1975.

2. A.M. Bronfman. The present hydrological-hydrochemical regime of the Sea of Azov and its possible variations. Trudy azNIIRKh, Issue 10, 1972.

3. A.B. Gorstko and F.A. Surkov. Dynamic model of the functioning of water communities of the Sea of Azov, In: "Methods of Systems Analysis in Problems of Rational Utilization of Water Resources." International Institute of Applied Systems Analysis, Austria, 1974.

4. A.B. Gorstko and F.A. Surkov. Dynamic model of functioning of water communities in the Sea of Azov, In: "Simulation and Ecology." Nauka, Moscow, 1975.

5. A.B. Gorstko, et al. The "Sea of Azov" simulation model, In: "Methods of Systems Analysis in Problems of Effective Utilization of Water Resources." Moscow, 1976.

6. V.G. Dubinina and Yu. M. Gargona. Fisheries of the Azov Basin under conditions of intensive utilization of water resources. Trudy VNIRO, Issue 103, 1974.

7. N.I. Revina, S.P. Volovik and N.K. Fil'chagin. Status of the reserves of Azov food fishes (gobies, anchovies, sardelles) and their possible changes in the presence of certain water management measurements, Tr. azNIIRKh, Issue 10, 1972.

8. M.K. Spichak. Hydrological regime of the Sea of Azov in 1951-57 and its influence on certain chemical and biological processes. Tr. AzNIIRKh, Issue 1, 1960.

9. N.F. Taranenko. Population dynamics of the Azov anchovy. Tr. AzCherNIRO, Issue 24, 1966.

10. E.N. Altman and D.M. Tolmazin. Method of calculation of currents and water exchange in the Kerch Straits. Okeanologiya, Vol. 10, Issue 3, 1970.

11. A.M. Bronfman. Salinity of the Sea of Azov and its forthcoming changes. Izvestiya Severo-Kavkazskogo nauchnogo tsentra Vysshey shkoly. Seriya Yestestvennyye nauki, No. 1, 1973.

12. A.M. Bronfman, G.D. Makarova and M.G. Romova. Present climate-caused changes in the composition of organic matter in the Sea of Azov. Izvestiya AN SSSR, seriya geografiya, No. 6, 1973.

13. A.P. Zhilyayev. Calculation of level fluctuations of the Sea of Azov. Okeanologiya, Vol. 12, Issue 1, 1972.

14. A.B. Gorstko. Mathematical modeling and problems of utilization of water resources, RGU, 1976.

15. Hydrometeorological Handbook for the Seas of the USSR, Vol. 3, Issues 1, 2, 3, Gidrometeoizdat, Leningrad, 1937.

16. Hydrometeorological Handbook for the Sea of Azov, Gidrometeoizdat, Leningrad, 1962.

CHAPTER 2

BRIEF CHARACTERIZATION OF FACTORS AFFECTING THE FORMATION OF THE CHEMICAL COMPOSITION OF LAKE BAIKAL WATER

(Material pertaining to the US-USSR cooperation in the area of "Mathematical Modeling of Lake Ecosystems)

GENERAL CHARACTERISTICS OF THE LAKE

The basin of Lake Baikal is located almost at the center of Asia, in a very rugged mountain province of the south of Siberia - the Baikal region. The characteristics geomorphological feature of the region are medium and high mountains extending over 1500 km in the southwest to northwest direction, and an alternation of ridges and trenches, the largest of which is filled with waters of the lake.

Baikal is the oldest and deepest intracontinental body of water in the world. The formation of the Baikal trench began about 30 million years ago. The watershed area of the lake is 0.54 million km^2, and the area of the lake itself, 31.5 thousand km^2. The length of the lake is 636 km, maximum width 79 km, minimum width 25 km, maximum depth 1620 m, and volume of the water mass, about 23 thousand km^3. The trench of Lake Baikal is divided into three basins, of which the middle one is the deepest; it is separated from the southern basin by the Selenga shallows, in the region of which the largest tributary, the Selenga River, flows into the lake. The runoff of the Selenga amounts to about 50% of the total runoff into the lake.

Baikal concentrates approximately 4/5 of the total surface water reserves of the USSR. However, the importance of the lake does not end there. During the past approximately 1 million years, when this body of water was formed in it present boundaries, some species properties arose in the waters of the lake: low solute content, high transparency, low temperature and high saturation with dissolved oxygen.

Baikal's biological community is specific and closely balanced. In the course of its evolution, its organisms have adapted to conditions varying little with time, and have reacted very sensitively to changes in these conditions. Suffice it to indicate that Baikal organisms of the open deepwater parts of the lake do not dwell in the shallow regions near the delta, which are subjected to the action of the river runoff.

PROSPECTS FOR THE ECONOMIC DEVELOPMENT OF THE BAIKAL REGION

In planning the basic aspects of the development of the territory adjacent to Baikal, a lake that is a unique water reservoir on the earth, an inadmissible approach would be one in which the desired rapid progress in economic development might lead to a change in the quality of the water and atmosphere. This basic principle - to preserve the lake's ecosystem, the result of processes that took thousands of years - is used in formulating all the special requirements for developing the economics and changing the size of the population in the region, and intensifying the monitoring of the environment.

The organization and implementation of management measures in the Baikal Basin will be accomplished in the near future with consideration for setting the lake region apart as an area with special levels of requirements as regards the problems of conservation and reconstruction of the environment.

Important elements of this concept include a gradual change to a directed control of the environment and simultaneous improvement of its quality.

The increased amount of attention given to the basin of Lake Baikal in the past 10 to 15 years has been related to a certain inevitable confrontation of attempts to combine the principles of conservation of the lake's natural properties with the possibilities of development of various areas of the region. In this connection, a series of resolutions were passed by the government, various ministries, Academy of Sciences, Hydrometeorological Service and other organizations.

The planned development of the industrial-territorial complex in the lake basin up to the year 2000 will be coordinated mainly with the individual regions - in the basin of the middle course of the Selenga River, on the itinerary of the Baikal-Amur highway under construction in the north. These limitations are determined by the aforementioned necessity of preserving the purity of the lake's waters.

Considering the further industrial development in the Selenga River Basin, it was deemed appropriate to design plants with a circulating water supply and to centralize the repurification of the waste waters.

The total volume of capital investments in the development of production facilities in the basin of Lake Baikal during the period from 1971 through 2000 will amount to over 10 billion rubles, approximately 6% of which will be spent on measures to protect the purity of the water resources and other natural facilities.

As an estimated level, during the next 30 years, a 4 to 5-fold increase in the volume of gross industrial production, 3-fold increase in the volume of agricultural production, and 1.5-fold increase in timber production are envisaged. The expected size of the population will increase by a factor of 1.5 during the same period.

DEVELOPMENT OF BAIKAL AS A RESORT AREA

Considerable shifts in the utilization of recreation resources are planned for the Baikal region. The presence of favorable types of weather will permit a vigorous growth of many aspects of tourism in this region. Also promising is the development of medical treatment in sanatoriums and of resorts and recreation, based on mineral sources and state parks.

A 1971 government resolution stipulates a broad development of recreation and treatment areas as well as foreign tourism on the shores of Baikal. At the present time, during the navigation season, over 100 thousand people visit the lake. It is predicted that by the year 2000, the flow of visitors will be 2.5 million per year, including 100 thousand foreign tourists. It is planned to create six natural parks with an area of 150-300 thousand hectares each, mainly in the southern and middle parts of the lake's basin.

The planned expansion of rest areas will cause an increase in the population's employment and will attract visitors to tourist services, rest houses, etc. Modern construction of numerous boarding houses and campsites in such tourist centers as peschanaya Bay and other places will also be required. These measures and processes will inevitably lead to an increased role of so-called unorganized and inadequately organized residential and industrial sewage systems. Thus, the requirements for their purification and isolation from the lake will be raised.

Specialists in recreational development are already pointing out the difficulties involved in the water supply and utilization of waste, since the self-purifying capacity of the rivers flowing into the lake is practically nil and their discharge is low.

Factors hampering the development of the Baikal area such as the seismicity of the regions and the potential danger of specific diseases (tick encephalitis, etc.) must also be considered.

On the whole, it may be hoped that intelligent efforts and sound measures to prevent the undesirable influence of the anthropogenic factor will permit a positive solution of the problem of combining conservation and economic development in the Baikal region.

BASIC FEATURES OF THE CLIMATE FROM THE STANDPOINT OF FORMATION OF CONCENTRATION FIELDS OF SUBSTANCES IN THE ATMOSPHERE

The formation of the climate in the Baikal depression and adjacent territory is determined by the large-scale transport of the air masses, thermal conditions of the lake, mountain relief, and other local factors.

The humidification of the basin is related to the westward transport of the air masses. During the warm part of the year, the cyclonic activity is activated here, resulting in 80-90% of the total annual precipitation, including 50% in July-August alone. In winter, a powerful anticyclone which blocks westerly winds develops in the lake region.

The distribution of precipitation above the lake is nonuniform and varies from 200 to 1200 mm for individual regions. The average long-term total precipitation for the water area is about 400 mm per year. The largest amount of precipitation falls on the southern shore of the lake; in the region of the Selenga shallows, it is most commonly in the range of 300-400 mm per year. Approximately 15% of the total precipitation is due to evaporated local moisture.

The nonuniformity of the annual distribution of precipitation coupled with the characteristics of the temperature regime and dissected topography accounts for the fact that rainfall floods are the main phase of the rivers' water regime. They occur from May to September, the period when 80-90% of the annual runoff is formed. In the wintertime, the rivers are low.

The distribution of impurities in the atmosphere and in the surface layer of the lake is greatly affected by the temperature regime and the wind direction and speed.

Stable and strong temperature inversions, often with a complex multi-stage structure, are very frequent above the lake, especially during the warm season. During these periods, the self-purification of the air reservoir is minimal, since the impurities concentrate in local regions. In situations where breeze and mountain-valley circulations interact in the Baikal trench, the impurities penetrate intensively in the direction of both the dry land and water areas. During these periods, pollutants become distributed over small areas of the territory and retain relatively high concentrations. Subsequently drawn into the local wind system, they may spread over considerable distances.

FORMATION OF CURRENTS IN THE LAKE

The chief source of motion of Baikal's water masses are the winds in its basin. In limited areas, an appreciable influence is exerted by inertial jets formed by large inflows. Above the water area of the lake and particularly above the central and southern parts, the northwesterly type of wind fields predominate during the course of the year (frequency, 31%). Strong winds of southeasterly direction are frequently observed near the eastern shore of southern Baikal. Another characteristic feature of the entire region is the simultaneous presence of northwesterly wind currents on the western shore and southwesterly ones on the eastern shore.

The frequency of winds of different velocities is approximately the same for all directions during the annual cycle. The wind speed is in the 5-10 m/sec range most of the time, but it may reach 16-20 m/sec during the spring-summer period.

Wind-generated currents form several types of circulation of water masses in the lake.

Large-scale cyclone-type circulations cover all three parts (basins) of the lake, the number of such circulation being 6-7. Inside, mesoscale eddies and secondary circulation, particularly in regions with a heterogeneous bottom and shore, exist along the coastal macrocirculations.

Insofar as it has been studied, the wind regime above Baikal makes it possible to estimate the duration of water-lowering (raising) circulation processes in the lake at 40 to 80 hours.[18]

Currents are observed in the lake everywhere, including deepwater areas. The current speed has an annual variation; it increases with an intensification of the winds after the lake is cleared of ice in May-June, declines during the summer period of scarce winds, and increases during the autumn storm period.

The horizontal structure of the current fields is fairly complex, particularly in the coastal regions.

The average speed of large-scale circulations is around 2-3 km per day (2.3-3.5 cm/sec) during the navigation season and 1-1.5 km per day (1.1-1.8 cm/sec) during the ice period, but individual large-scale gusts can be an order of magnitude higher. The gusts last an average of 20-30 h.

Among other circulatory formations, the highest frequency is displayed by eddies 1-2 km in size. Late in autumn, in the presence of strond wind and when the temperature stratification is practically absent, eddies from 6-7 to 5-10 km occur.

Hydrochemical surveys made in the coastal strip revealed finer turbulent structures 0.5-1 km in size. It is possible that these eddies have a local character related to the inhomogeneity of the shoreline.

A characteristic feature of currents in the 8-10 km shore strip is their practically identical direction over the entire thickness of the layer from the surface to the bottom.

However, within this area there exist several characteristic features in the transport of the water masses. The current speeds at a distance of 0.4-0.6 km from the shore are 1.5-2 times lower than at 1.5-2 km. Slight eddylike circulations of different types and sizes frequently appear in this strip. The transport in the strip up to 1.5 km is much less than in the zone located at a distance of 1.5-3 km. Steady and strong alongshore currents begin to appear at approximately the same distance (1.5-2.5 km).[25]

At a distance up to 2-3 km, the current speed is 1.5-2 times lower than at 3-5 km from the shore.

In the deepwater part of the lake, the observed maximum of current speeds ranges from 25 to 50 m, then the speeds slow down, and below 100 m toward the bottom become almost homogeneous in magnitude and direction. According to observations in southern Baikal during the open period, the average current speeds for the navigation season are in the 12-18 cm/sec range at a depth of 15 m and 4-8 cm/sec range at 50 m and lower. The speeds increase everywhere from summer to autumn.

The vertical structure of the current speed profile is determined to a considerable degree by the temperature stratification of the water masses.

When the latter is constantly present, the speed values averaged over several days and the directional stability decrease from the surface to the thermocline layer. Below the latter, they increase, then the speed decreases smoothly with depth.

In deepwater parts of the lake, according to the character of the vertical distribution of currents, the upper (dynamically active), deep and bottom zones are distinguished. The upper zone covers 0.3 of the depth, and contains high values of maximum speeds and an inhomogeneous distribution of average values during periods of temperature stratification. In the deep zone, the currents are more stable and change little with time and in speed. The bottom zone (without the layer of bottom friction) is characterized by a certain increase in current speeds.

During the cold season, the currents remain, but their speed is much lower. A major part of the time (60%), the speeds under the ice are less than 2 cm/sec. On the western shore, they were observed during 30-45% of the observation time, and on the eastern shore, speeds above 2-3 cm/sec were not observed. In winter, in areas located far from the shore, speeds of 5-9 cm/sec were recorded that remained almost constant in magnitude and direction for up to 5-12 days.

The vertical current speed profile in the upper 3 m layer under the ice is characterized by very low values. Below 3 m, the speed increases, then decreases somewhat in the area of the first thermocline layer (at approximately 25 m), reintensifies, then decreases again. At the bottom, the current speed increases slightly.

In the southern Baikal at the 15-20 m level, a cylonic circulation similar to the one observed during the navigation season was observed in winter.

TRANSPORT OF MATTER IN THE LAKE

As was indicated earlier, the main transport of water masses in the lake takes place in the upper layer, whose thickness amounts to approximately 0.3-0.4 of the lake's depth.

Observations of the distribution of water temperature, aquatic organisms and certain substances in the water of the lake showed that during all seasons, local formations (separate water masses) exist according to one or several indices. The dimensions of the heterogeneous structures amount to 0.5-1 to 5-10 km, but "spots" of smaller size, distinguished by means of hydrochemical indices, were also found.[18,22]

The coefficients of horizontal turbulent exchange (K), calculated from data on currents and dimensions of heterogeneities of hydrochemical and hydrobiological fields, are of the order of 10^2-10^5 cm^2/sec.

In the near-shore zone of southern Baikal, for eddies 0.5-1 km in size, they were found to be 10^4-$5 \cdot 10^4$ cm^2/sec, and at a depth of 13 m, 350 m from the shore, $5 \cdot 10^2 - 6 \cdot 10^3$ cm^2/sec.

Data obtained after studying the distribution of fluorescent matter in the shore zone showed values of $10^2 - 10^3$ cm^2/sec; according to observations of another tracer, for the summer-autumn period, $(3-5) \cdot 10^4$ cm^2/sec, and for winter (across the flow), 10^3 cm^2/sec.

The average values (K) for the November-December season on the Selenga shallows were found to be in the $(2-8) \cdot 10^4$ cm^2/sec range for eddies of approximately the same size.

A study of the structure of current fields in southern Baikal showed that macroturbulent eddies in the shore strip have an anisotrophic character which decreases with increasing distance from the shore. The isotropy remains only in small formations up to 100 m in size.

It was also found that the mean daily exchange coefficients are highly variable and do not always obey the accepted laws in the case of large-scale macroturbulent eddies.

According to the water temperature and optical characteristics of the water masses, a near-shore zone of deepwater Baikal having a width of 1-2 km is distinguished in the lake. Extending through it are turbid floodwaters, and it contains the highest values of gradients of the indicated parameters.[23,24] The permanent differences manifested here between the values of many indices indicate the existence of a transverse component of the velocity of the alongshore cyclonic circulation, directed toward the shore in the surface layers and having a value of 10^{2} - 10^{-3} cm/sec for the warm period.[20] The velocity of the reverse process (horizontal turbulent diffusion) at the boundary between the near-shore zone and the waters of the open lake has approximately the same value, but on the average, the transport processes have a stronger influence on the distribution of impurities.

The pulling of the surface waters of the lake toward the shores by the transverse component of the alongshore flow interferes with the inflow of wash products from the shores and with the runoffs into the pelagic zone of the lake. These substances will dissolve slowly in a comparatively narrow strip and be transported over long distances. The localization of impurities in a comparatively small volume is most pronounced in summer and winter during periods of vertical stratification.

Analysis of data on the seasonal variation in water temperature and in the concentrations of chemical elements in deep layers of the lake makes it possible to assert the existence of a vertical circulation. The latter develops with particular intensity above underwater slopes in a near-shore strip 3 to 9 km wide. On the average, such circulations with speeds of 10^{-1} - 10^{-2} cm/sec are most frequent directed downslope.

According to hydrochemical data, the processes of ascent of water masses in the central part of the lake ($\sim 10^{-1}$ cm/sec) and descent near the shore promote the aeration of deep waters. These processes take place intensively in autumn, when the intensification of wind activity raises the horizontal current speeds, and the temperature stratification attenuates.

According to preliminary estimates, the substitution time of deep waters by surface ones is approximately 20 years at a rate of descent of 10^{-2} cm/sec.

A strong mechanism of vertical mixing of the water masses is thermal convection. Calculations of vertical thermal diffusivity showed a fluctuation of the values from unts to thousands of cm^2/sec during the course of a year. During the period of stable summer stratification, the diffusivity is equal to approximately 7 cm^2/sec, and during the autumn isothermy, over 1000 cm^2/sec.[23] The contribution of thermal convection to the vertical mixing is many times greater than that of turbulent diffusion. We calculated the average vertical turbulent exchange coefficient from data on current speed fields to be of the order of 10^2 cm^2/sec.

The highest values of the thermal diffusivity coefficient corresponds to periods of development of intensive convection in the lake and periods of spring warming and autumn cooling.

The combination of complex horizontal and vertical displacements of the lake's water masses as a result of steadily acting large-scale circulations and periodically forming smaller eddies related mainly to seasonal phenomena leads to the transport of waters in the upper layer from the center of the lake to the shores, their descent along the shore slopes into the bottom region, and ascent of deep waters at the center of the lake.[20]

WATER EXCHANGE BETWEEN INDIVIDUAL PARTS OF THE LAKE - WATER BALANCE

According to the data of the Limnological Institute, the water exchange accomplished by large-scale horizontal circulations within each of the three main parts of Baikal takes place most intensively in the upper 40% of the water mass.

Table 1 gives long-term average water balances of individuals parts of the lake for a year.[20]

The water balance of Lake Baikal, according to the calculation of the State Hydrological Institute based on observations for the period from 1901 to 1970 and Limnological Institute for approximately the same period, is presented in Table 2.[21]

BASIC ECOLOGICAL IMPORTANCE OF THE SELENGA REGION

In connection with the prospect of economic development of certain regions in the Selenga River basin, augmentation of the river load with treated waste as well as particles of soil cover washed into the river is a possibility.

The importance for Baikal of the chemical runoff of the Selenga and of the processes taking place in the river, especially its lower course, delta

TABLE 1. AVERAGE LONG-TERM WATER BALANCES OF PARTS OF BAIKAL IN ONE YEAR, km
(Verbolov and Shimarayev, 1972)

Elements of Balance	Northern part of lake	Central part of lake	Southern part of lake
	GAIN		
Inflow (surface and underground)	13.8	23.7	23.4
Precipitation	3.7	2.8	2.8
Inflow from neighboring part of lake (runoff)	-	13.9 (from northern part)	36.2 (from southern part)
TOTAL	17.5	40.4	62.4
	LOSS		
Evaporation	3.6	3.5	2.3
Outflow into neighboring part and Angara River	13.9 (into central part)	36.2 (into southern part)	60.1 (into Angara River)
TOTAL	17.5	39.7	62.4
Inflow when water level is raised*	20	20 from south 10 from north	10
Outflow when water level is lowered*	10	20 from north 10 from south	20
Volume of waters in part of trench	7020	9200	5450
Conventional time of water exchange (loss + wind tides) volume = years	225	132	66

*The longitudinal profile of the lake level was assumed to be the same as in a uninodal seiche.

TABLE 2. WATER BALANCE OF LAKE BAIKAL DURING THE PERIOD 1901-70

Elements of Balance	mm/year	m^3/sec	km^3/sec	%
(1) As calculated by the State Hydrometeorological Institute				
GAIN				
Surface inflow	1914	1910	60,28	
Precipitation	405	404	12,76	
Total	2319	2314	73,04	
LOSS				
Runoff through Angara River	1888	1884	59,46	
Evaporation	416	415	13,10	
Accumulation	15	15	0,48	
Total	2319	2314	73,04	
(2) After A.N. Afanas'yev				
GAIN				
Precipitation	296		9,29	13,1
Condensation on surface of lake	27		0,82	1,2
Inflow of river waters	1870		58,75	82,7
Inflow of ground waters	(68)		2,30	3,0
Total	2261		71,16	100
LOSS				
Runoff from lake	1916		60,39	84,8
Evaporation	331		10,33	14,6
Total	2261		71,16	100

and contiguous region of the lake, consists in the fact that the Selenga is a principal tributary which actively participates in the formation of the ecosystem of this body of water. The value of the Selenga delta region and of the shallow zone encircling it also lies in the growth and development of the Selenga whitefish young exclusively in this area. Initially, after its larvae have hatched, in April-May, the whitefish remains in the delta for 35-45 days, and in shallows, until mid-August. Hence, until the end of June, the whitefish young are under the direct action of the substances entering the delta with the river runoff and during the subsequent period are exposed to the influence of the waters diluted in the shallows. If the level of toxic pollutants in the water of the Selenga from April to August is an active one for fish, there is no doubt that it can have an even stronger influence on the remaining trophic links of the Selenga shallows.

An essential role in all seasons is played by the runoff of suspended matter and waters of the Selenga in the formation of bottom sediments of the shallows. The studies performed also indicate that the suspended material is affected by the processes of pollution and self-purification of the reservoir.

TEMPERATURE REGIME OF WATER IN THE SOUTHERN PART OF THE LAKE

Baikal is a cold-water lake with water temperatures changing little in the course of the year at depths of over 150 m. While in the surface layer of water in different seasons, the température ranges from 0.3°C in February to 15°C in August, starting at a depth of 150-200 m it is approximately constant at 3.3-3.9°C the year round.

At least 40-50 days pass after the ice of the lake breaks before the upper 20-meter layer of water warms up to 3.3-4°C and the spring homothermy sets in. In southern Baikal, it usually corresponds to the third ten-day period in June. At the start of the warming period (May - early June), the isothermal layer is thin and its water temperature low. During the first two to three weeks after the ice break, the water temperature in southern Baikal remains at the 0.5-1°C level in a layer of water only a few meters thick.

The summer warming of open waters of southern Baikal lasts from the spring isothery (end of June) to the middle and end of August. By that time, the surface layer of water has warmed up to 12-15°C, and occasionally higher.

During the period of summer warming, the temperature stratification of the water mass is well-defined, especially after long periods of calm. During this time, one distinguishes a layer of increased temperatures (epilimnion) with a low gradient of their decrease with increasing depth, an intermediate layer with a sharp temperature drop - the discontinuity or thermocline layer, and hypolimnion - a layer with lower water temperatures and small gradients of their decrease with depth.

At the start of the period of summer warming, the thermocline layer is established at a depth of only 2-5 m, and toward the end of August descends to 4-5 m in northern Baikal and 10-25 m in central and southern Baikal.[26]

BRIEF CHARACTERIZATION OF CLIMATIC CONDITIONS OF THE SELENGA REGION

Expeditionary studies in the area of the Selenga delta and shallows and observations at stationary weather stations in this region offer convincing evidence of the presence here of conditions and seasonal meteorological processes common for Baikal and its littoral atmosphere.

The climate of the delta area is continental, but, like on the entire shore, milder than in regions distant from the lake.

The mean annual air temperature is -0.7°C, the July temperature is +17.5°, and the January temperature, -21.1°. The duration of the period with air temperatures above 0° is 170-180 days.

The total annual atmospheric precipitation is 250-400 mm, and the mean long-term precipitation is about 315 mm. The major part of the precipitation occurs during the warm season. The maximum is observed in July and August, and the heaviest precipitation occurs in the second half of June.

Evaporation in the Selenga region changes appreciably from one year to the next. The total absorbed radiation is approximately 90 kcal/cm^2 year.

DISTRIBUTION OF SELENGA WATERS IN THE LAKE - INFLUENCING FACTORS

The Selenga is the most substantial tributary of Lake Baikal. The area of its basin amounts to 83.4% of the territory of the lake's water runoff, and the water runoff amounts to 50% of the total runoff into the lake. The Selenga waters flowing into the lake annually introduce an average of about 4 million tons of solutes and 2 million tons of suspended matter (75% of the annual inflow of salts and 70% of suspensions brought into the lake with all river waters).

The distribution of the Selenga waters in the lake takes place via a system of numerous delta branches (Figure 1).

The delta area is over 600 km^2, the outer edge being about 70 km long. During the period of highest water content in the river, approximately 30 branches are counted in the delta. During the period without ice cover, about 90% of the Selenga River runoff is carried from the north and

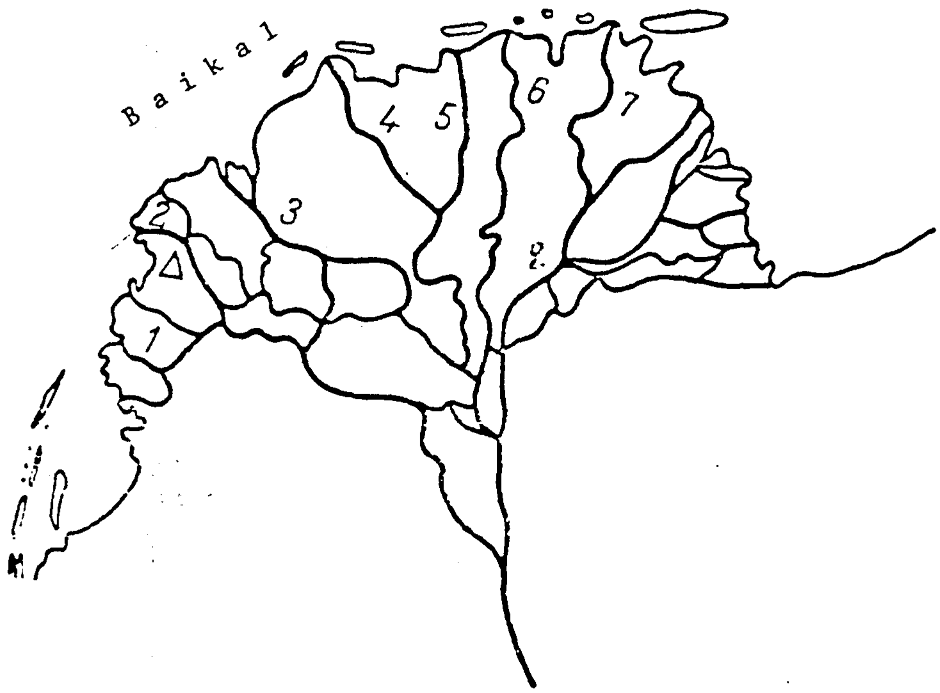


Fig. 1. Delta of Selenga River and its branches[10]

1 - Shamanka, 2 - Kharauz, 3 - Galutay,

4 - Srednyaya, 5 - Krivaya, 6 - Kolpinnaya,

7 - Severnaya, 8 - Lobanovskaya,

Δ - Kharauz weather station

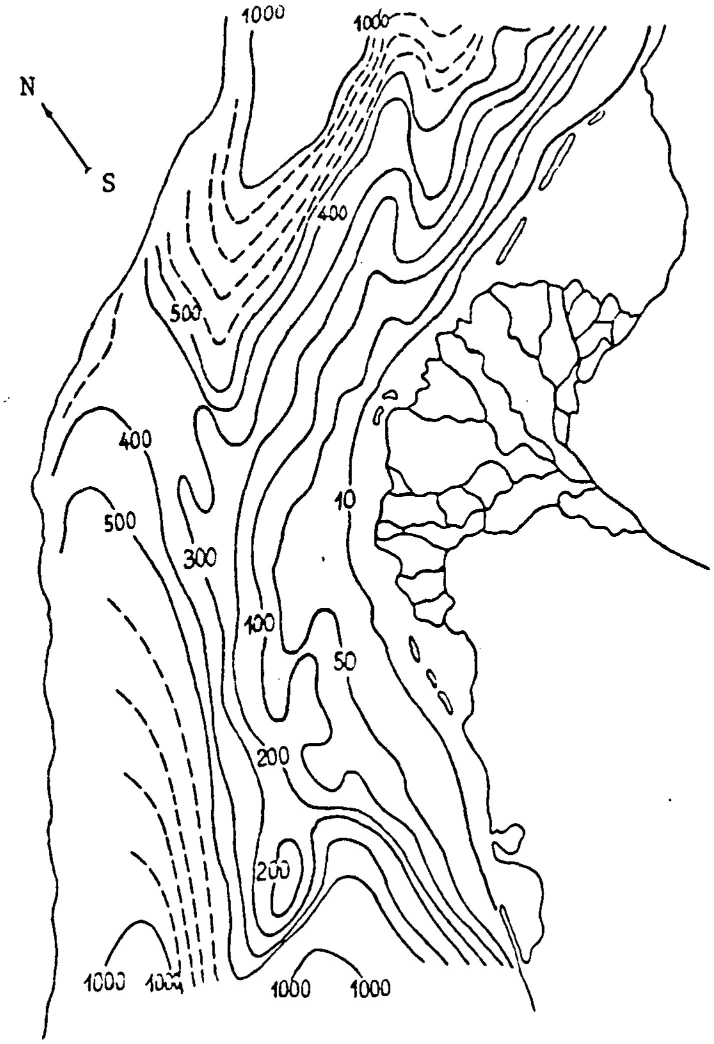


Fig. 2. Diagram of depths in the region of Selenga shallows[26]

southern parts of the delta through 8-10 main branches.* The entry of river waters into the lake through branches of the central part of the delta is insignificant.[8,9]

The largest navigable branch, Kharauz, located in the southern part of the delta, usually gives less than 20% of the total runoff, with the remaining large branches giving no more than 5-10%.

When the river discharges in the section before the delta are close to average (1500 m^3/sec), 50-60% of the runoff enters the southern part of the delta and 35-45% enters the northern part, of which 30% goes into Proval Bay. At discharges of 1500-2000 m^3/sec, the runoff is approximately evenly distributed between the southern and northern parts of the delta. If the discharges exceed 2000 m^3/sec, 50-60% of the runoff enters the lake through branches of the northern part of the delta.

In winter, 90-95% of the river waters located at the apex of the delta enter the lake through one branch.[3]

According to the data of hydrological observations, the penetration of river flows into the lake depends on the water content of the branches and speed of the flows at the exit to the lake. In the main branches, the speed of the currents most commonly fluctuates between 30 and 60 cm/sec. At an average speed of about 30 cm/sec in one of the main branches, the Selenga water extends over a distance of 3 km into the lake, expanding by a factor of more than 4-6 in this stretch. At the maximum speed of flow, 70 cm/sec, observed mainly during the passage of a flood, it extends over 9 km into the lake, and at the minimum speed, 6 cm/sec, over 0.3-0.4 km.

*According to some estimates, through 6-7 branches.

Further, distribution of the Selenga waters in the lake is very complex, and judging from available data, is explained in different ways by some of the investigators. This pertains primarily to the directions and magnitudes of water exchange between the individual parts of the lake, and hence, to the transport of the solutes and suspended matter present in the water.

The size of the water area over which the Selenga waters are distributed as a function of hydrometeorological conditions can apparently vary from tens to a thousand or more square kilometers. There are as yet no sufficiently precise comprehensive criteria to permit one to determine from generalized indices the boundaries of the zone of penetration of river waters into the interior of the lake. If, for example, the average current speed in the open lake, 5 cm/sec, is used as the only citerion for a contact boundary, the size of the area is about 500 km^2, with the principal direction of elongation of the zone along the northeastern shore.

During the period of flooding, when the flow of the Selenga water is heaviest, it can reach the western shore and, entering the system of macrocirculation currents penetrate into southern Baikal. At low discharges, the northward distribution of the Selenga waters into central Baikal is more probable. As is evident from the comparison, these data almost contradict the above conclusions that the river runoff is distributed over the branches as a function of the water content (see p.).

The formation of currents and zones of propagationof substances in the Selenga shallows, in addition to being affected by the penetration of river flows from the delta branches, is also dependent on the characteristics of the local wind field above the lake.

The principal directions of the wind in the region of the Selenga shallows are southwesterly and northeasterly. The wind of NE direction is observed with particular frequency on the western shore, opposite the Selenga delta. During the navigation season, the frequency of winds of these directions amounts to approximately 20% each. The highest wind speeds are usually observed slightly to the north of the delta.

As an example, Figure 3 (Table 3) shows the principal wind directions and average speeds recorded by observations on ships in June-August.

Owing mainly to the constancy of the wind directions (with the prevalance of northeasterly ones), horizontal currents which retain their direction the year round are created in the lake. One of them, the Selenga current, was observed back in the 1920's. According to the observations, in calm weather the waters of the Selenga flow into Baikal in two branches: to the northeast and southwest in the direction of the head of the Angara River. The main flow, hugging the western shore of Baikal, travels to the southwest in a band a few kilometers wide. The Selenga River waters, mixed with the lake waters, can be easily distinguished by their reduced transparency and color index, as well as hydrobiological and hydrochemical indices. It has been found that in the area of the head of the Angara River, the Selenga waters are observed to a depth of 5 m in summer and 20-50 or even 100 m in winter. The current speed in a stable flow in winter is 2.7 cm/sec.[26,27]

During SW winds, waters of the Selenga River are detected along the eastern and northeastern shore of the lake over 120-130 km. When the band is 3-5 km (occasionally up 7-8 km) wide, they occupy an area of 500-600 km^2 in the central part of the lake. In the presence of NE winds, the

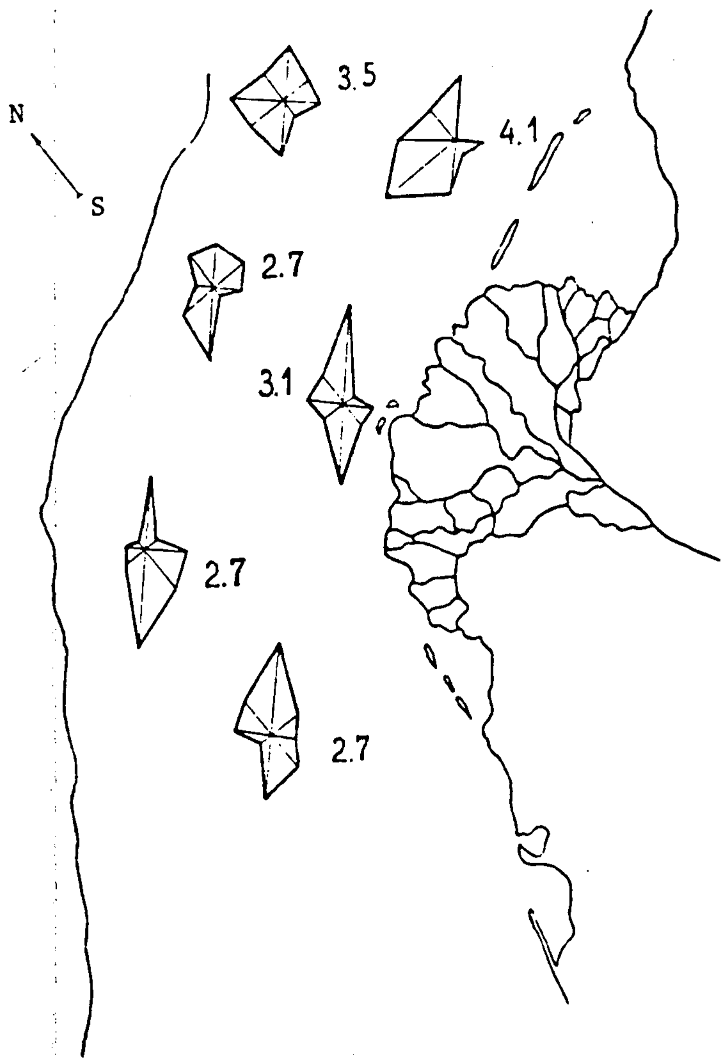


Fig. 3. Average wind speeds (m/sec) in June-August and wind roses on the Selenga shallows[16]

TABLE 3. AVERAGE WIND SPEED (m/sec) IN JUNE-AUGUST BASED ON DATA OF SHIP OBSERVATIONS ON THE SELENGA SHALLOWS, AND FREQUENCY OF WINDS OF DIFFERENT DIRECTIONS AND CALMS (in %)[16]

Stations	Average Speed	N	NE	E	SE	S	SW	W	NW	Calm
16	3,5	9,4	13,0	8,0	9,4	4,3	13,7	11,6	14,5	16,1
17	4,1	9,8	15,7	-	7,8	3,9	13,7	23,5	15,7	9,1
14	2,7	10,6	10,6	10,6	7,6	1,5	16,7	10,6	4,5	24,6
15	3,1	8,9	25,9	4,5	7,1	7,1	21,4	7,1	9,8	8,2
10	2,7	2,9	17,6	4,4	10,3	13,2	26,5	7,4	5,9	11,8
11	2,7	11,9	23,8	8,3	6,0	10,7	16,7	2,4	9,5	10,7

Selenge waters spread over approximately the same area to the south of the delta. Having a higher temperature and lower density, the waters of the Selenga River spread mainly through the surface layers of the lake to a depth of 10-20 m.

An essential role in the further mixing of the water masses is played by the vertical motion of the flows, which leads to an equalization of the properties of the water masses, formation of an epilimnion, thermocline, and hypolimnion. According to the data of the Limnological Institute, the contribution of the thermal convection mechanism to vertical mixing is many times greater than that of turbulent diffusion. A special role is played in the spring separation of shallows and estuaries by the formation of thermal bars.

In addition to the thermobar phenomenon, the thermocline present in the upper layers of the lake during 75-80% of the year is also important. By isolating waters of the most biologically active upper layer (epilimnion) from the main water mass, the thermocline raises the concentration of impurities inthe upper trophogenic zone of Baikal. Both of these phenomena promote the accumulation of impurities around the areas of the lake near estuaries. In the summertime, warm river waters containing matter not characteristic of the natural lake water background, spread mainly along the shores in a comparatively thin surface layer.

Hydrological observations made during the cold season lead to the assumption that the system of currents formed under the action of wind during the navigation season remains essentially unaffected for a long time. This is confirmed by studies made during the period of November-March. However, with time, the speed and stability of the currents may decrease.

It may be assumed that the mechanisms of transformation of currents consists in a steady transfer of energy from macroturbulent formations to smaller structures. This also leads to the conclusion that the role of such structures in the migration of impurities present in the water masses increases during the cold season.

As a result of the combined action of runoff and wind currents, the maximum area over which the Selenga waters differing in color were detected during the open season apparently amounts to 1500 km^2 in the portion of the lake adjacent to the delta.

According to the data of aerial visual surveys, a zone of heavier turbidity exists inside this region. During period of medium runoff, its area is no smaller than 150 km^2 at the outer edge of the delta and of approximately the same size in Proval Bay, located north of the delta.

In the shallow-water Proval Bay, whose total area is 150 km^2, the motion of the waters is chiefly determined by the wind active above the bay. The runoff current is manifested here only in the southern portion of the bay, into which empties the most heavily flowing of the northern tributaries of the Selenga River. The speed of the total current in the bay is 5-18 cm/sec less than in the adjoining open regions of the lake, but in the presence of strong winds, it values reach 60-65 m/sec. The water exchange of Proval Bay with the open lake under calm and weak wind conditions is slight and caused by the inflow of river waters.[1]

Studies on models of runoff currents of the Selenga and Angara Rivers and wind currents do not give definite answers concerning the spread of Selenga water.

One laboratory study of a hydraulic model of Lake Baikal* confirmed field observations of hydrochemical indices and turbidity, which indicated penetration of Selenga waters to the western shore.

The modeling revealed the development, near the northwestern shore in South Baikal, of a cyclonic circulation and a transit current promoting the transport of Selenga waters into the southern basin.

The time taken by the Selenga waters to reach the flow of the Angara amounts to an average of about a year and a half, according to calculations made with this model.[2]

Because of the characteristics of the wind regime of the Selenga region, the transport of waters to the north predominates in spring-summer near the southeastern shore, and to the south in autumn.

At the same time, the distribution of current speed fields with time remains complex. A sharp change in current directions can take place here in one or two days. The average current speeds during the navigation season in the central part of the shallows at a depth of 15 m are 15 cm/sec, and at 150 m, cm/sec. At a distance of 150 m from the lake edge of the delta, opposite one of the large estuaries, the speed in the surface layer in different parts of the stream was 7-19 cm/sec, and at a distance of 300 m, 13 cm/sec. Thus, it is apparent that in addition to alongshore currents with speeds of 20-30 cm/sec, a circulatory formation with low speeds, 2-10 cm/sec, exists in the central part of the region.

*According to field studies, 40% of the discharge of the Selenga River was supplied to the northern branches and 30% each to the central and southern branches.

During the winter season, currents to the shallows are attenuated and clearly observed only across from the active branches of the delta. No currents are observed at distances of 3 km.

During the ice period, in the region adjacent to the Selenga River delta, if currents along the shore are present, they are under 2 cm/sec. The speeds of deep current (below 150 m) during this period are more appreciable than those of surface currents. Speeds of 5-7 cm/sec or even 10 cm/sec have been observed, although 60% of them did not exceed 3 cm/sec.

In the northern part of the Selenga shallows, the current speeds are low in all seasons, and according to observations during the navigation season, they are of a pulsed character that duplicates the wind regime.[17]

It has been noted above that the surface currents on the Selenga shallows are marked by a considerable complexity and inhomogeneity.

Because of frequent changes in wind directions and sometimes even in the presence of stable winds, the current fields in the shallows may vary considerably during a short time interval. As an example, Figure 4 shows a current pattern recorded in the surface layer over the course of two days. Preservation of current fields as long as ten days was observed less frequently, despite the variability of the wind conditions. As a rule, currents of deepwater circulation are more stable and begin to be manifested in the shallow-water region at depths of over 40-50 m.

During the navigation season, the net transport of water masses in the Selenga shallows near the southeastern shore is directed eastward, and near the northwestern shore, westward. The average transport speeds for the entire cross section of the flow are 1-3 cm/sec, and lower in summer than in autumn (particularly in November-December). In the central region of

Fig. 4. Diagram of surface currents in the Selenga region in the presence of various winds[8]

1 - prevailing southwesterly wind (30 August 1972);

2 - prevailing northwesterly wind (31 August 1972);

3 - steady lasting northwesterly wind (8 September 1972)

the shallows, a turn of the current across the lake is observed (most frequently) in the upper layers.

The average duration of a current in a single direction, based on autumn data at a station located 7 km from the delta at a depth of 13 m, was 42 hours (maximum, 5 days), and at depths of 25 and 47 m, 45 hours (maximum, 7 and 5 days). The average current speeds at these depths were 28, 17 and 24 cm/sec. The macroeddies were 1-4 km in size, and the time of action (existence of the eddies) was 10-40 hours.[5]

WATER EXCHANGE IN THE REGION OF THE SELENGA SHALLOWS

The predominance in the Selenga region of SW, NE and in part, NNW winds makes it possible here to distinguish several types of water mass transport: the equilibrium type, in which one or several macroeddies are located between the southern Baikal and central Baikal circulations; wind tide type, whereby waters of southern Baikal intrude into the shallows over approximately 1/3 of the extent of the region or, coversely, 1/3 intrudes from central Baikal; and a transition state characterized by a high turbulence of the currents.

The duration of the intrusion of waters of southern or central Baikal into the shallows usually does not exceed 30-40 hours, and the return to the state (level) of equilibrium takes place in 1-1.5 hours. Calculations show that about 10 km^3 flows into the southern part of the lake when the water level is raised by the effect of wind, and 20 km^3 flows out into the central part when the water level is lowered. Observations established that during the annual cycle, water transport northward takes place near the eastern shore, and southward, primarily along the northwestern shore.

Tests on the model showed that under conditions of stormy winds directed along the lake, water exchange in the basins is approximately 3-4 times greater than between them through the Selenga shallows.

RUNOFF REGIME AND CHARACTERISTICS OF SUSPENDED MATTER OF THE SELENGA RIVER AND SHALLOWS

In comparison with other rivers of the lake basin, the Selenga river has the greatest turbidity. During the medium low-water level in May, the river waters may contain 350-400 mg of particles per liter, the average long-term concentration maximum in May being in excess of 100 mg/ℓ. The transparency of Selenǵa waters during the spring-summer period does not exceed 0.15-0.20 m and increases to 1.5 m by autumn.

The chief causes of the higher content of suspended and dragged material in the river water are the shower character of the rains and the intense management activity on the territory of the river's watershed. However, the rate of chemical denudation in the Selenga basin - 0.0021 mm/year - is less than for the basin of the entire lake - 0.0052 mm/year. The latter rate in turn amounts to approximately 1/2 of the average chemical denudation of the earth, equal to 0.01 mm/year.[12]

The annual distribution of the runoff of suspended matter (in % of the mean annual value) is irregular:

Winter	Spring	Summer	Autumn
1.2	23.2	57.8	17.6

The (mean long-term) particle size distribution of suspended detritus of the Selenga River is as follows (in %):

particles of size greater than	0.5 mm	3.2
from 0.5 to	0.2 mm	8.1
< 0.2 to	0.1 mm	9.5
less than	0.1 mm	80

In the last fraction, 75-90% of the particles are 0.05 mm in size.[11]

During the last decade (1965-74), the mean annual transport of suspended matter into Lake Baikal by the Selenga River, according to measurements in the cross section before the delta, amounted to 1.9 million tons, with extreme values of 0.8 and 3.8 million tons (in 1972 and 1973, respectively) in individual years of the period. Measurements of the runoff of suspended matter during previous extended time periods up to 1965 showed approximately the same values. For example, the average removal of suspensions in 1947-62 amounted to 2.3 million tons.

The coefficients of variation of the runoff of suspended matter during these two consecutive periods were practically the same: 0.52 and 0.54.

In terms of concentrations of suspended matter, it was determined that in 1947-62, the Selenga carried an average of 80 mg/ℓ into the delta, versus 62 mg/ℓ in 1965-74.

In the view of specialists of the Limnological Institute, the present regime of transport of suspended matter (which has been in existence for at least 30 years) substantially exceeds the mean annual runoff of suspensions into the lake during the entire period of formation of the deltaic cone in the Selenga delta, equal to 0.9 million tons per year.*

During the period of rainfall floods, 50% of the suspensions are composed of particles smaller than 0.01 mm and 40%, 0.01-0.05 mm. During the winter low-water period, the particle size is above 0.05 mm.

The average sedimentation rate in the region of the delta shallows is approximately 150 cm per 1000 years, which is 25 times faster than the

*The value was obtained from the age of the cone, 2 million years, its volume, 1.2 thousand km^3, and the density of the detritus, 1.5 g/cm^3.

average rate for the entire lake. The volume of deposits on the bottom of the lake has now reached 46000 km^3, i.e., the Baikal trench is now two-thirds filled with sediment.[12]

With increasing distance from the delta, the suspended material is sorted out, and the types of bottom sediments change from sands to clayed silt.

In the near-shore sands of the outer delta, over 75% consist of the 0.25-0.05 mm particle size fraction. This fraction and a finer one, 0.05-0.01 mm, predominate in the coarse silts (48%). In fine and clayed silts, approximately 60% consist of particles 0.05-0.005 mm in size.

The content of organic matter is lowest in sands, less than 1%, and maximum, 2.4%, in pelitic silts. In comparison with other regions of Baikal, the bottom sediments of the Selenga shallows are depleted or organic matter.

In the surface layer of the bottom sediments of the shallows, the closer to the delta, the more active the diagenesis of organic matter. As a result, the content of organic matter (in terms of organic carbon) increases from 0.35% at depths of 0-5 m to 2.5% at 100-250 m.[13]

Allochthonous organic matter is observed in bottom sediments at a distance of 3-5 km from the shore.

According to individual observations, the distribution of organic nitrogen in the bottom sediments of the shallows has a spotty structure. In the southern region near the delta, the relative concentration N_{org} equals 0.15-0.20%, and in the northern region, 0.05-0.15%.

The relative phosphorus content of the bottom sediments remains at approximately the same level, ~0.1%, over a wide range of depths (0-250 m).[13]

A large portion of the organic matter of bottom sediments of the surface layer is represented by readily hydrolyzable compounds.

It is difficult at the present time to draw conclusions regarding the annual dynamics of the chemical composition of the suspensions. An analysis of suspended substances sampled in May give the following results (in % of air-dried residue):[14]

C_{org} ~2; P - 0.1; Fe ~ 3; Mn ~ 0.05; SiO_2 ~ 60.

DISTRIBUTION OF SUSPENDED MATTER OVER THE SELENGA SHALLOWS

On the average, a complete exchange of the lake's waters can take place only in the course of over 400 years. However, owing to the existing system of circulation currents, the Selenga waters can reach the Angara River in 2-3 months. On the other hand, river waters flowing into central and possibly northern Baikal can remain in the lake for a long time.

In the deepwater region of the lake, water exchange is slow in comparison with the border regions, pelagic zone, and near-shore strip. As a result, in the open deepwater region of the lake, the water transparency can reach 40 m and decrease to 5-10 mm during the period of maximum plankton development.

Turbid waters of the Selenga River, particularly floodwaters, differ markedly in color and optical characteristics from the transparent lake waters. The zone of visible propagation of the Selenga water usually occupies a shore strip 1.5-3 km wide and crosses the 4-5 m isobath. At these depths, the water mass is always homogeneous according to optical observations.

At the same time, hydrochemical observations in the region of Selenga shallows in August-October detected currents promoting the transport of suspensions 20 km into the interior of the lake and along the eastern shore 60 km to the south and 20 km to the north. Most frequently, in summer, the water transparency in the region before the mouth, even far from the shores, is mainted in the 2-3 m range, and after storms it may decrease to a few centimeters. The southern branch, as the larger one, is traced to a depth of over 30 m (particularly in calm weather). The main index is the vertical homogeneity of the stream based on the water temperature and transparency. The northern stream apparently nmoves under the surface waters of Baikal.[10] According to certain observations, for example, of 20 July 1962, turbid river waters extended over approximately 50 km in the northern direction and 15 km (farthest distance) into the interior of the lake. The water transparency in the zone at the outlet of the branches was up to 2 m, and at a distance of 1-2 km, up to 9-17 m. In 1963-64, on the western shore of southern Baikal near the southwestern end of the Selenga shallows, in a region through which pass the dilute Selenga waters, the water transparency at a distance of 1-1.5 km from the shore ranged from 4-5 m in August-October to 18-21 m in June. In late May and early July, the transparency in this area was in the 8-14 m range.[26]

The very frequently observed sharp propagation boundary of the Selenga waters is related to the particular character of the turbulent diffusion processes involved and to the thermobar phenomenon arising at the interface of the shore waters and the colder lake waters.

The dilution in the strip is very indefinite, not more than 3-4-fold, the dimensions of the region being as follows: length, 10 km; width, 2 km; layer thickness, about 20 m. The turbulent diffusion coefficients, calculated for this layer for a speed of alongshore current of about 5 cm/sec, are $K_x \sim 10^4\ cm^2/sec$ and $K_x \sim 10\ cm^2/sec$. The clear-cut interface of the water masses and low dilution indicate that the course of the impurity propagation process cannot be described by the parabolic equation of turbulent diffusion.[18] The propagation of the impurity has a flow character with fairly well-defined boundaries.[18]

The content of suspended matter in the water of the Selenga shallows varies appreciably in the course of a year. As one moves a considerable distance away from the delta branches, the concentration of suspensions usually decreases by a factor of 10-15, and as a rule, reaches its maximum throughout the shallows in August-September.

In May-June, when the concentration of suspended matter in the Selenga River at the exit from the delta is most often only 23-26 mg/ℓ, the average concentrations of suspended matter in the region of the lake adjacent to the delta are also high in comparison with the mean annual values. At a distance of 1.5 km opposite the branches, the level of suspended matter is 13-20 mg/ℓ, and at a distance of 21 km 0.8-1.2 mg/ℓ.

During this period, the water temperature in the river and 21 km from the outlet of a branch is 12° and 4°C, respectively.

The high level of suspension concentrations in the water of the shallows in May-June is also characterized by a high degree of homogeneity from the surface to the bottom over a considerable distance from the branches, up to 7.5 km. The average concentration level at this boundary is 2-4 times the mean annual level. Tables 4-7 present data characterizing in detail the state of the aqueous medium in terms of the May-June parameters discussed.

TABLE 4. WATER TEMPERATURE INTERVALS IN LATE MAY - EARLY JUNE ON THE SELENGA SHALLOWS
(Based on observations in individual years)

Distance from delta, km	1,5	3	5	10	21	27
Depth, m						
0	10,0-12,5	3,6-5,9	2,8-4,2	2,1-3,2	2,6-2,9	2,0-2,8
5	6,0-10,3	3,2-7,4	2,7-6,6	1,9-3,5		
10		3,4-6,4	2,7-6,4	1,7-3,8		1,6-2,9
25		3,7-6,7	2,7-5,8	1,7-4,1	2,7-3,2	
50			2,8-4,2	1,7-4,8	2,7-3,4	
100					2,9-3,5	
200					3,5	
400					3,4-3,5	3,5
600					3,4-3,5	

TABLE 5. WATER TRANSPARENCY (m) IN MAY-JUNE ON THE SELENGA SHALLOWS
(Based on observations in individual years)

Distance from delta, km	0	1,5	3	5	7,5	10	21	27
Interval of values observed	0,5-1,2	0,5-2,5	0,8-5	1,5-7	2-10	8-12	15-22	15-22
Average	0,5	1,3	3	5	7	10	17	18

TABLE 6. CONCENTRATION OF SUSPENDED MATTER IN WATER (mg/ℓ) ON THE SELENGA SHALLOWS IN JUNE 1969; SURVEY OF ONE SECTION

Distance from delta, km		1,5	3	5	7,5	10	21	27
Depth, m	0	8	1,8	0,6	0,5	0,6	0,5	0,5
	5	10	1,8	0,7	0,5	0,5	0,5	0,6
	10		1,5	0,6	0,6	0,5	0,5	0,6
	25		1,5	0,6	0,8	0,5	0,5	0,5
	50			0,8		0,6	0,5	0,5
	200						0,6	0,5
	400						0,6	0,6
	600						0,6	

TABLE 7. CONCENTRATION OF SUSPENDED MATTER IN WATER (mg/ℓ) ON THE SELENGA SHALLOWS ON 18-20 JUNE 1971
(Concentration ranges and average of 5 sections)

Distance from delta, km	1-1,5		3-4		5		6,5-9		12,5		18-19	
	Concen-tration range	Aver-age	Concen tration range	Aver-age	Concen-tration range	Aver-age	Concen-tration range	Aver-age	Concen-tration range	Aver-age	Concen-tration range	Aver-age
Depth, m 0	5,9-22,6	12,3	0,7-12,3	5,6	3,3-8,3	5,8	1,0-2,2	1,3	1,2	1,2	0,9-1,0	1,0
10	5,4-9,7	7,6	0,5-10,7	5,3	2,4-7,6	5,0	0,8-4,1	2,2	0,8	0,8	0,8-1,0	0,9
25			0,3-3,7	2,4	2,3-2,7	2,5	0,9-1,9	1,4			0,9-1,2	1,0
50					2,6-3,1	2,6	0,8-1,6	1,2			0,9-1,4	1,1
100							0,8-1,2	1,3	0,7	0,7	0,7-2,0	1.3
200									0,6	0,0	0,6-1,0	0,8

REFERENCES

1. M.M. Aybund, V.P. Kratsov, Ye. N. Podozerov and Yu. B. Chegurov. Motion of waters in large bays and their water exchange with open parts of Lake Baikal, Trudy GGI, Issue 231, Gidrometeoizdat, Leningrad, 1976, p. 231.

2. V.A. Znamenskiy. Study of runoff and wind currents on a hydraulic model of Lake Baikal. Trudy GGI, Issue 231, Gidrometeoizdat, Leningrad, 1976, p. 231.

3. M.M. Aybund. Characteristics of runoff distribution in the Selenga River delta at different water contents. Abstracts of reports at Third All-Union Hydrometeorological Service Conference-Seminar on the Hydrology of Estuarine Areas of Rivers. Moscow, 31 March - 3 April, 1976. GOIN, 1976, p. 38.

4. V.W. Ioganson. Role of mountain forests in the formation of the runoff and water regime in the basin of Lake Baikal. Voprosy geografii, 102, pp. 115-121. Mysl', Moscow, 1976, p. 207.

5. V.I. Verbolov. Variability of water currents and temperature. Trudy Limnologicheskogo instituta Vol. 12 (32), Nauka, Lenigr. Sec., Leningrad, 171, p. 293.

6. M.N. Shimarayev. Certain features of long-term variation of hydrometeorological elements. Trudy Limnolog. in-ta Vol. 12 (32), Nauka, Leningrad, 1971, p. 293.

7. B.A. Bogoyavlenskiy. Natural boundaries of the Selenga River delta. Productivity of Baikal and anthropogenic changes of its character. Irkutsk, 1974, p. 320.

8. M.M. Aybund, A.I. Babkov and Ye. D. Yegorikhin. Results of study of surface currents in the Selenga region of Lake Baikal by means of aviation. Trudy GGI, Issue 205, Gidrometeoizdat, Leningrad, 1975, p. 131.

9. B.F. Lut. Basic features and genesis of bottom relief. Tr. LINa Vol. 12 (32). Nauka, Leningrad Sec., Leningrad, 1971, p. 293.

10. P.O. Sherstyankin. Dynamics of the waters of the Selenga shallows in early summer based on data of distribution of optical characteristics and water temperature. Nauka, Moscow-Leningrad, 1964, p. 193.

11. L.K. Vlasova. Runoff of suspended detritus of Baikal rivers. In: Bottom Sediments of Baikal. Nauka, Moscow, 1970, p. 160.

12. K.K. Votintsev. Chemical denudation in the Baikal basin and role of its products in sedimentation in the lake (pp. 64-68). In: Bottom Sediments of Baikal. Nauka, Moscow, 1970, p. 160.

13. I.B. Mizandrontsev. Chemical composition of ground solutions and waters of the bottom layer. In: Limnology of Near-Delta Areas of Baikal. The Selenga Region. Nauka, Leningrad, 1971, p. 293.

14. G.S. Goldyrev, L.A. Vykhristyuk and F.I. Lazo. Bottom sediments of the outer delta of the Selenga River, In: Limnology of Near-Delta Areas of Baikal. The Selenga Region. Nauka, Leningrad, 1971, p. 293.

15. V. Ya. Zyul'kina. Importance of suspended detritus and bottom sediments in the self-cleansing of Selenga River waters of volatile phenols. In: Productivity of Baikal and Anthropogenic Changes of its Character. Irkutsk, 1974, p. 320.

16. M.N. Shimarayev. Some characteristics of wind conditions above the surface of Baikal during the navigation season. Trudy Limn. in-ta Vol. V (XXV), Nauka, Moscow-Leningrad, 1964, p. 193.

17. I.V. Lebedev. Principal results of a study of the winter hydrological regime of the Selenga shallows of Lake Baikal. In: Raboty Irkutskoy gidromet. observatorii, Issue 5, Irkutsk, 1970.

18. V.I. Verbolov. Coefficients of horizontal macroturbulent exchange in the near-shore zone of southern Baikal. Tr. Limnol. in-ta 14 (34). Nauka, Leningrad Sec., Leningrad, 1970, p. 213.

19. L.A. Vykhristyuk. Organic matter and its transformation in bottom sediments. Tr. Limnol. in-ta, Issue 21 (41). Nauka, Siberian Sec., Novosibirsk, 1975, p. 287.

20. V.I. Verbolov and M.N. Shimarev. Water exchange in Baikal. Dokl. inst. geografii Sibiri i Dal'nego Vostoka, Issue 36, Irkutsk, 1972.

21. Z.A. Vikulina and T.D. Kashinova. Water balance of Lake Baikal. Tr. GGI Issue 203, Gidrometeoizdata, Leningrad, 1973, p. 268.

22. A.V. Znamenskiy. Concerning processes of internal water exchange and turbulence on Lake Baikal. Trudy GGI, 203, Gidrometeoizdata, Leningrad, 1973, p. 268.

23. V.I. Verbolovm V.M. Sokol'nikov and M.N. Shimarev. The hydrometeorological regime and heat balance of Baikal. Nauka, Moscow-Leningrad, 1965.

24. L.M. Galkin, V.M. Sokol'nikov and M.N. Shimarev. Distribution of floodwaters in southern Baikal. Tr. Limn. in-ta, Vol. 14 (34), Nauka, Leningrad, 1970.

25. M.M. Aybund. Results of full-scale studies of currents in southern Baikal. Tr. GGI, 203, Gidrometeoizdat, Leningrad, 1973.

26. M.M. Kozhov. An outline of Baikal limnology. Vostochno-Sibirskoye knizhnoye izdatel'stvo, 1972, p. 254.

27. V.M. Sokol'nikov. Currents and water exchange in Baikal. Tr. Limnol. in-ta SO AN SSSR, Vol. 5 (XXV). Moscow-Leningrad, Nauka, 1964.

28. L.M. Knyazeva. Present precipitation in the southern part of Lake Baikal. Tr. Bayk. Limnol. stantsii Vol. XV, AN SSSR, Moscow-Leningrad, 1957, p. 464.

APPENDIX C

RESULTS OF HYDRODYNAMIC AND DISPERSION CALCULATIONS FOR LAKE BAIKAL AND SEA OF AZOV

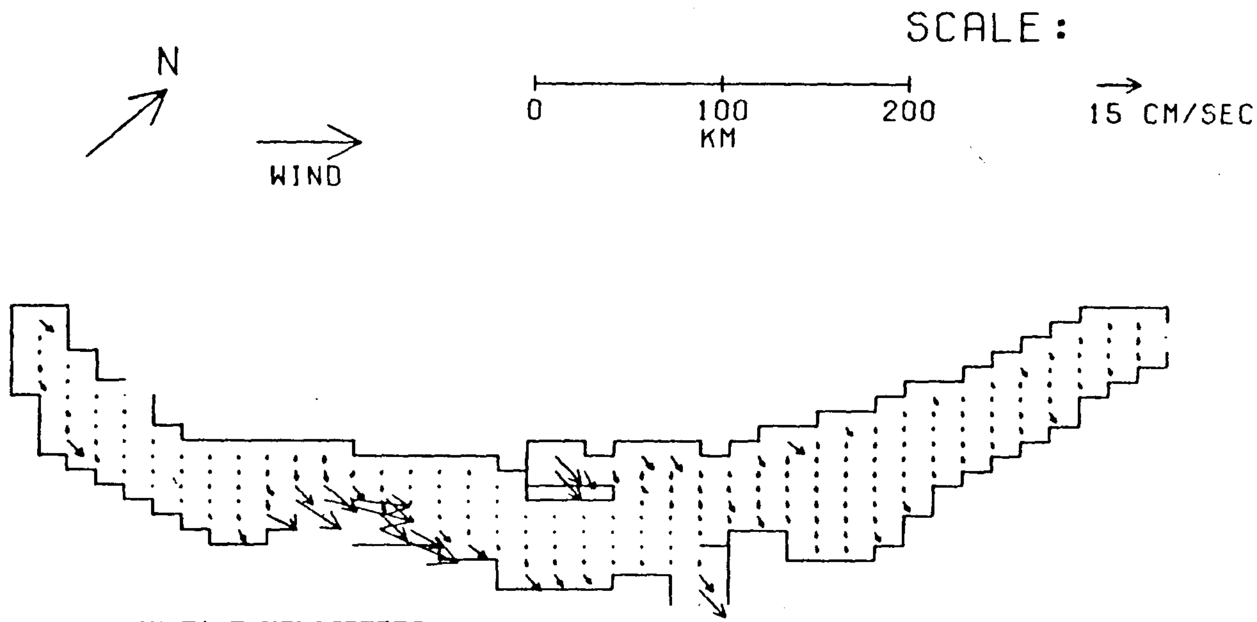
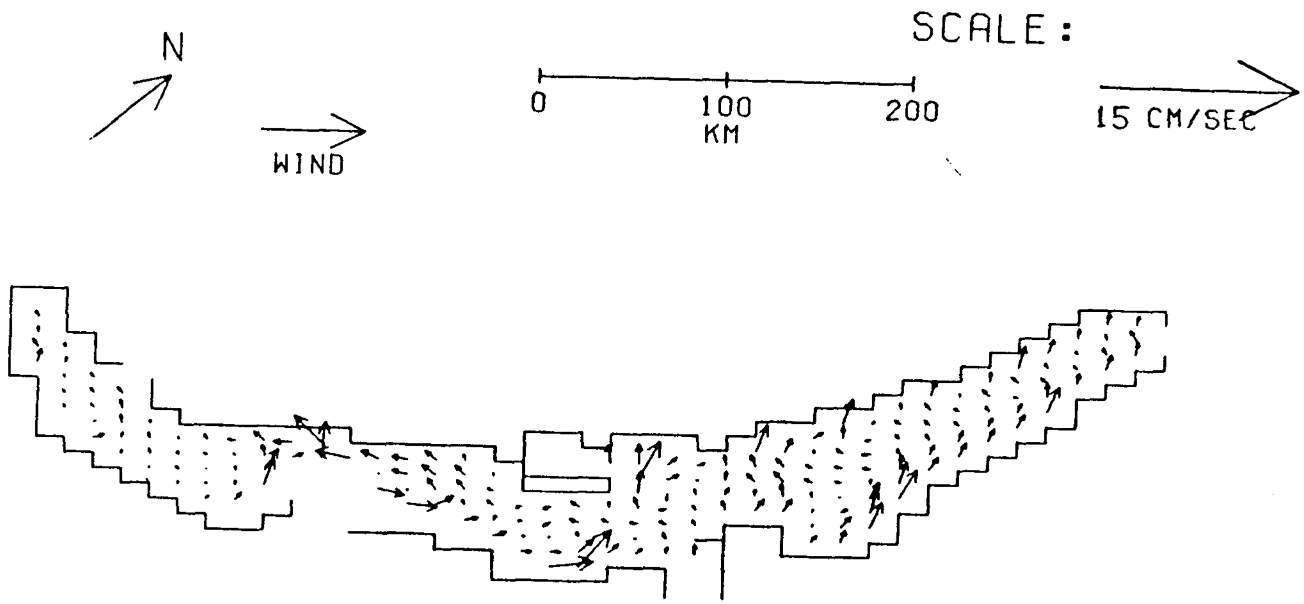
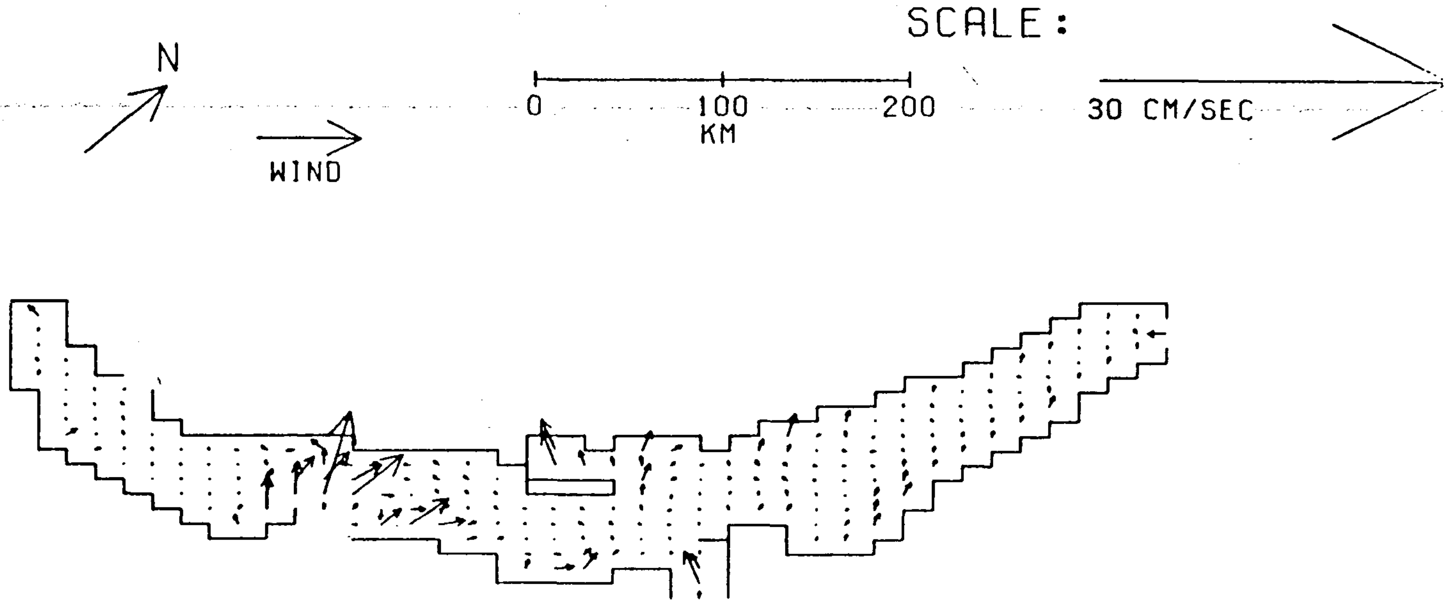


Figure C-1a. Steady-state hydrodynamic model calculation for Lake Baikal with southwest wind.



VELOCITIES AT 200 METERS

Figure C-1b. Steady-state hydrodynamic model calculation for Lake Baikal with southwest wind.



NEAR BOTTOM VELOCITIES

Figure C-1c. Steady-state hydrodynamic model calculation for Lake Baikal with southwest wind.

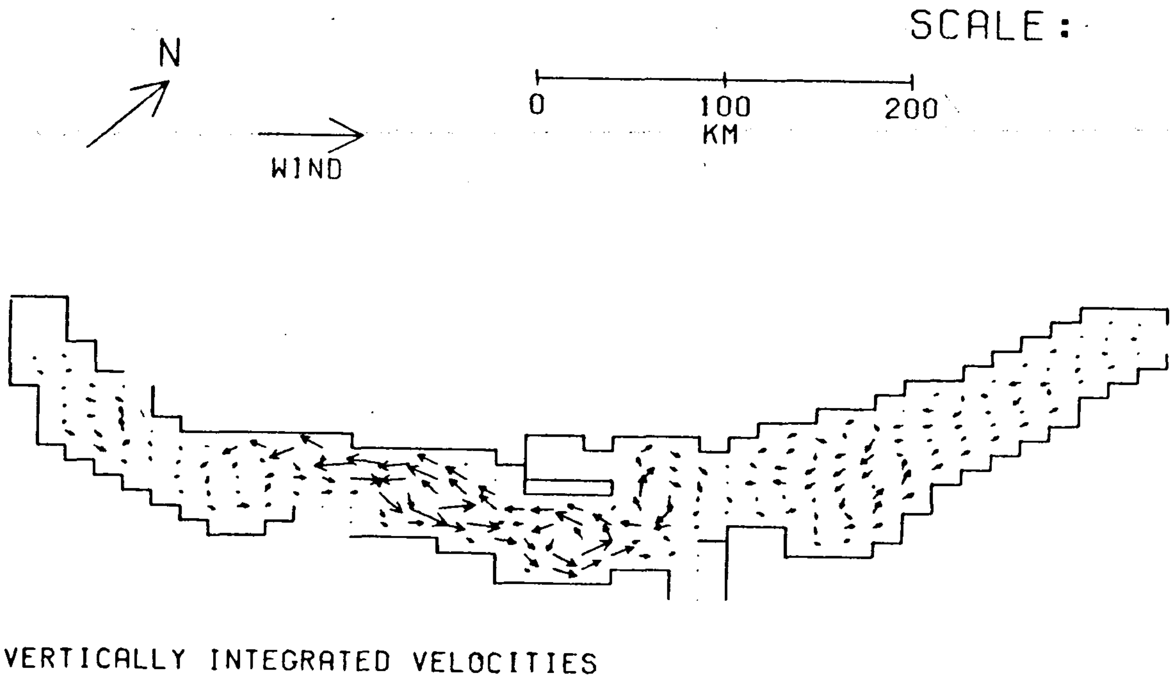
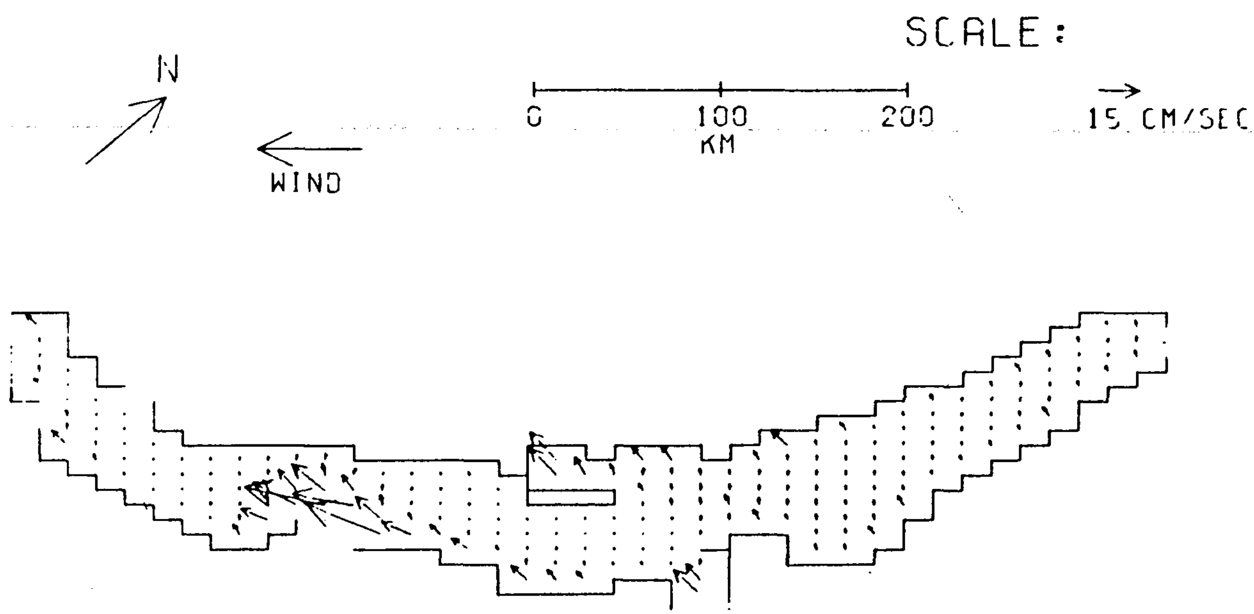


Figure C-1d. Steady-state hydrodynamic model calculation for Lake Baikal with southwest wind.



SURFACE VELOCITIES

Figure C-2a. Steady-state hydrodynamic model calculations for Lake Baikal with northeast wind.

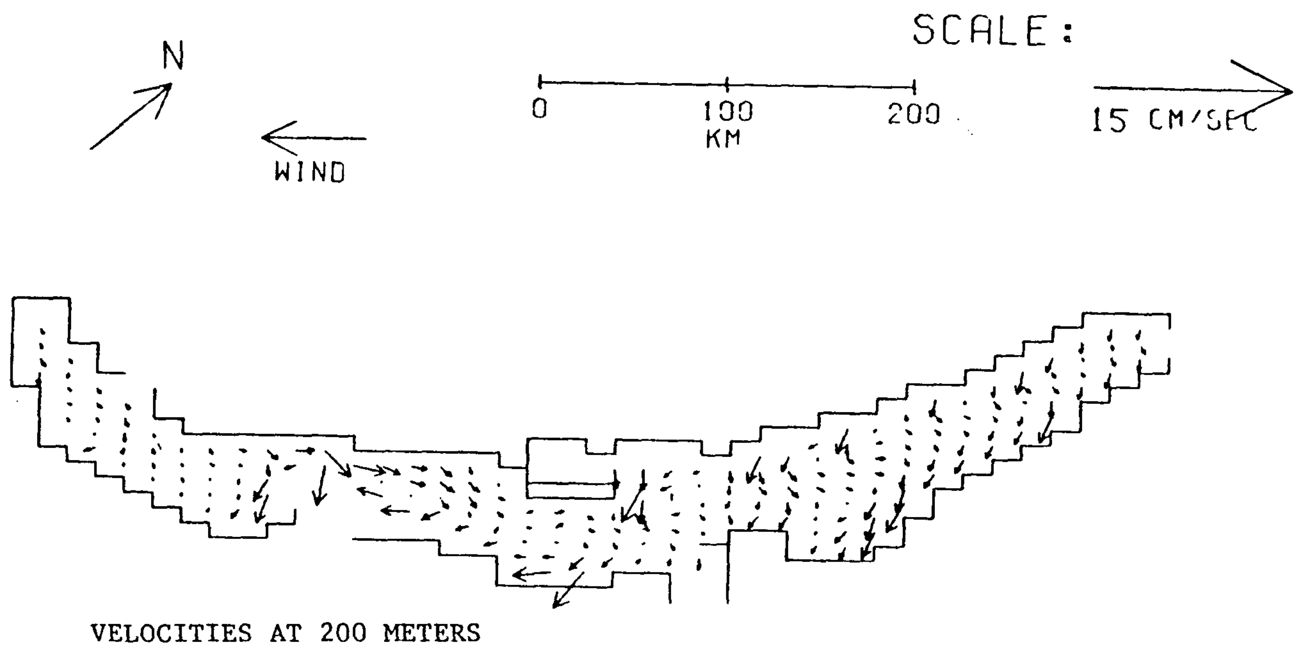


Figure C-2b. Steady-state hydrodynamic model calculations for Lake Baikal with northeast wind.

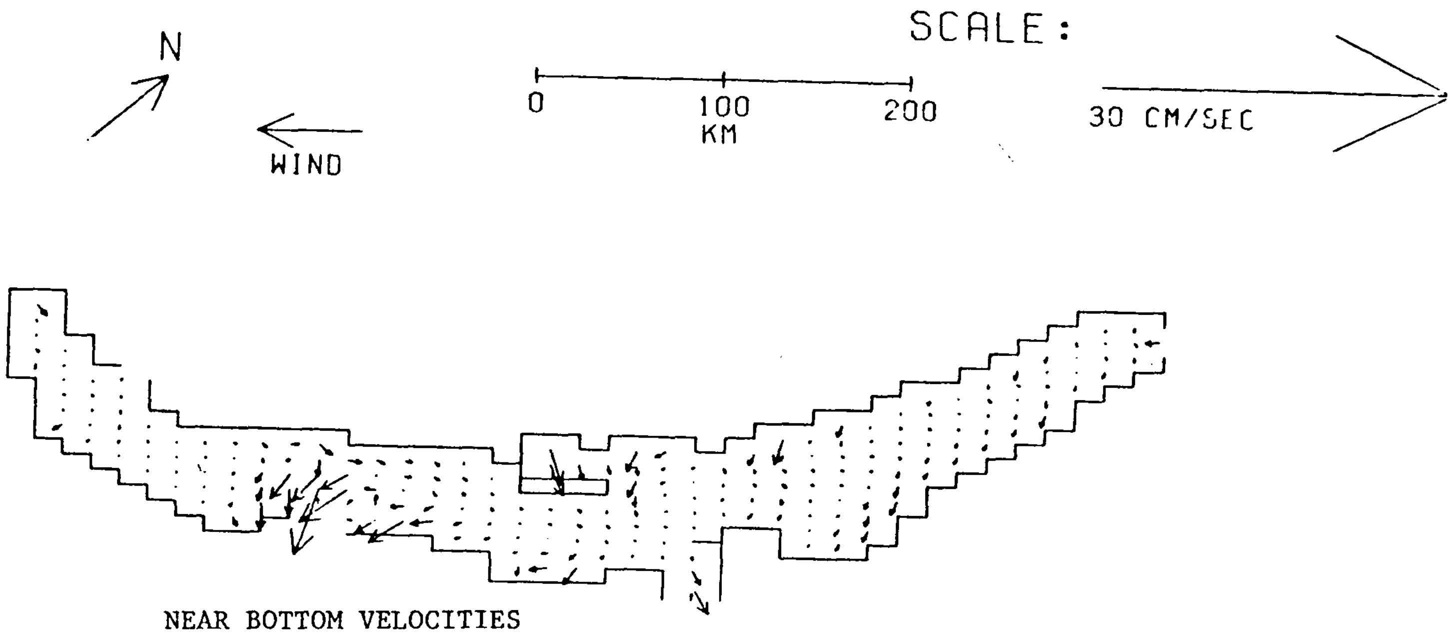


Figure C-2c. Steady-state hydrodynamic model calculations for Lake Baikal with northeast wind.

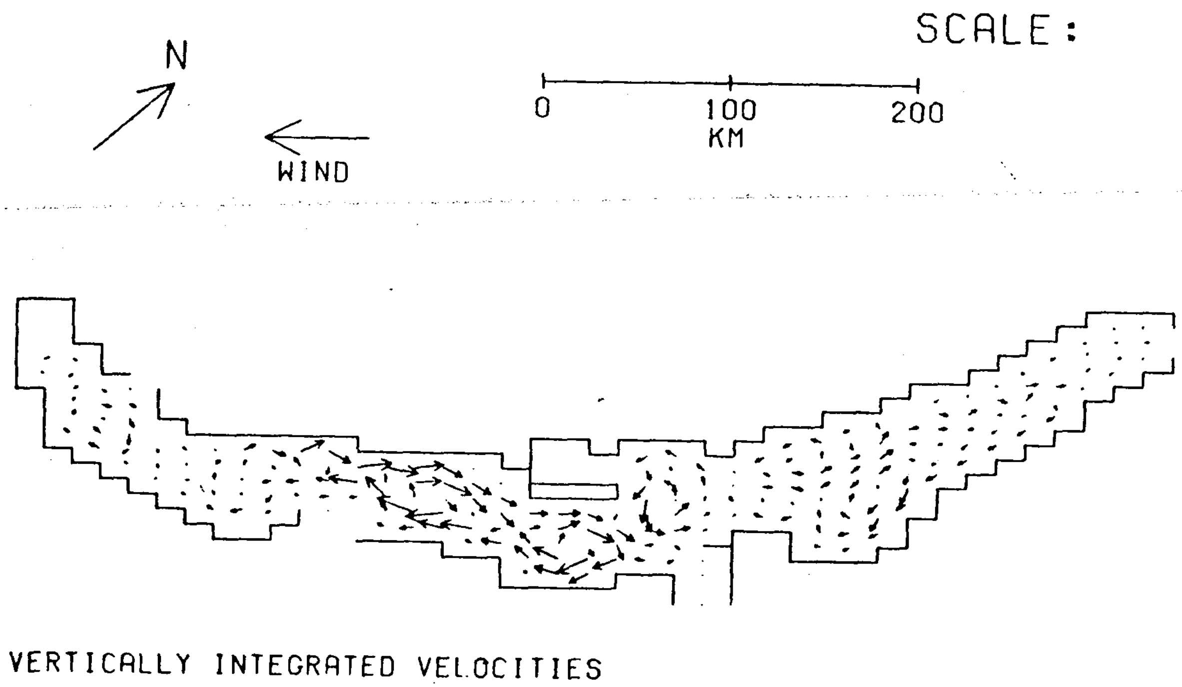


Figure C-2d. Steady-state hydrodynamic model calculations for Lake Baikal with northeast wind.

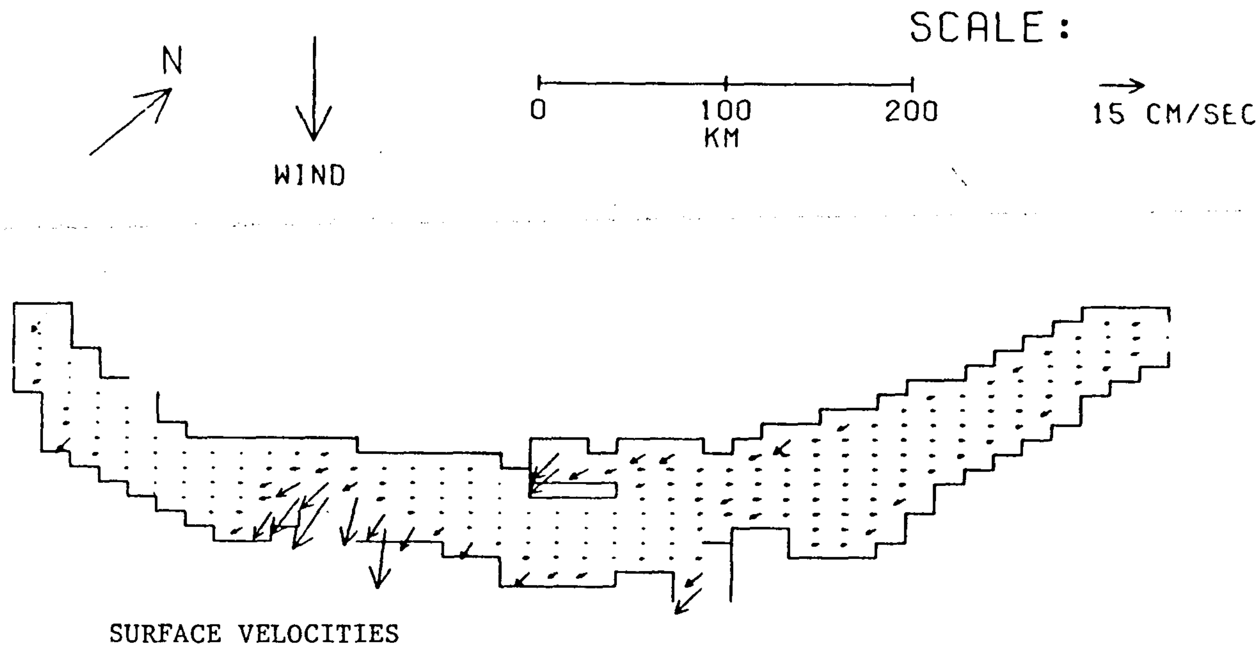


Figure C-3a. Steady-state hydrodynamic model calculations for Lake Baikal with northwest wind.

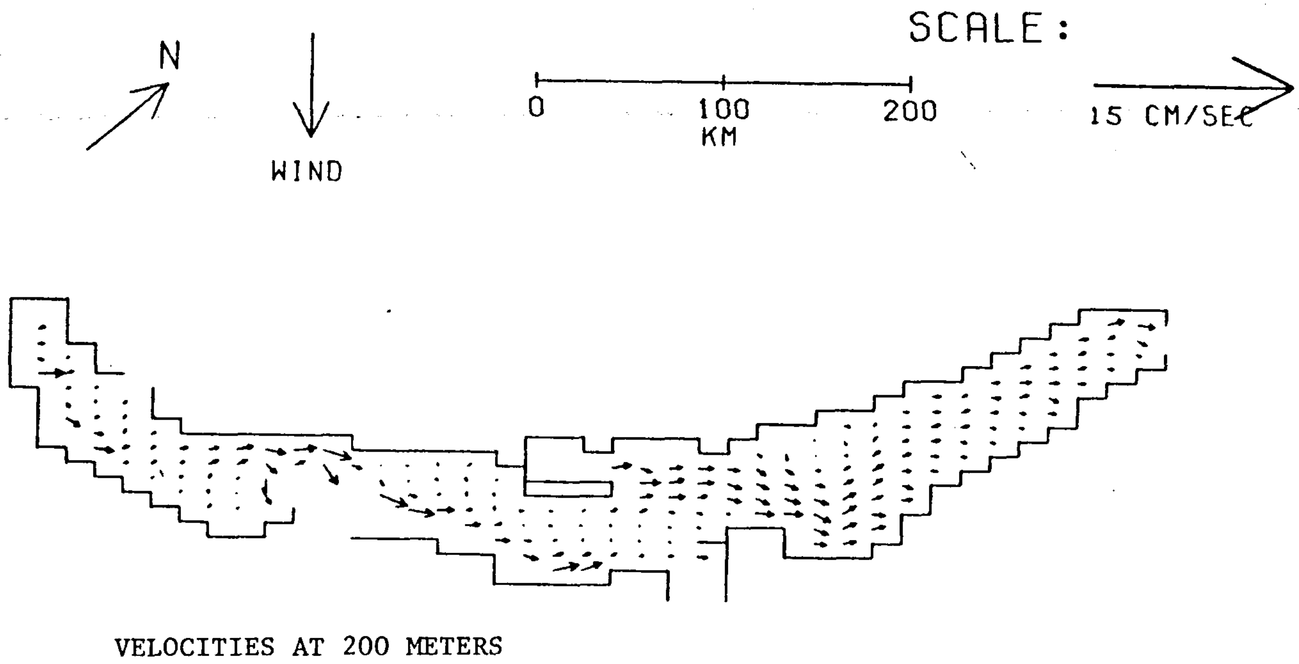
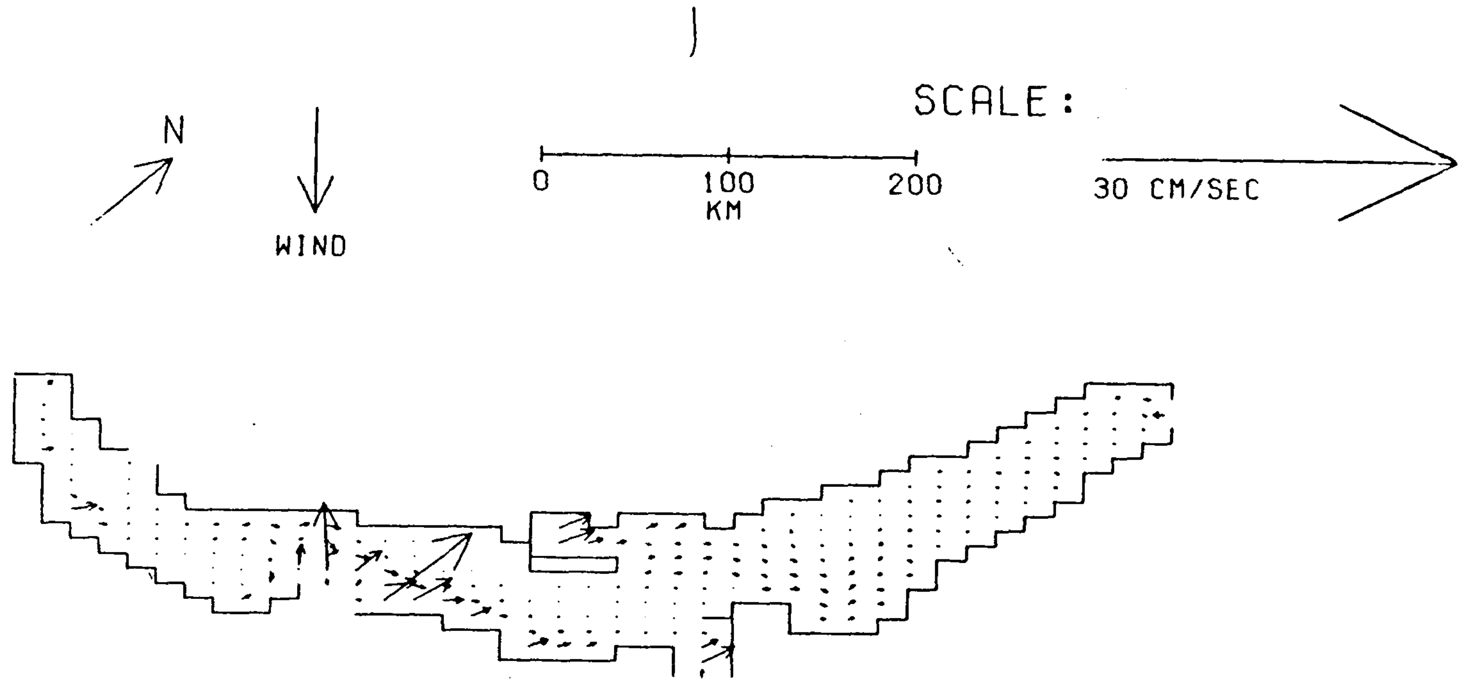


Figure C-3b. Steady-state hydrodynamic model calculations for Lake Baikal with northwest wind.



NEAR BOTTOM VELOCITIES

Figure C-3c. Steady-state hydrodynamic model calculations for Lake Baikal with northwest wind.

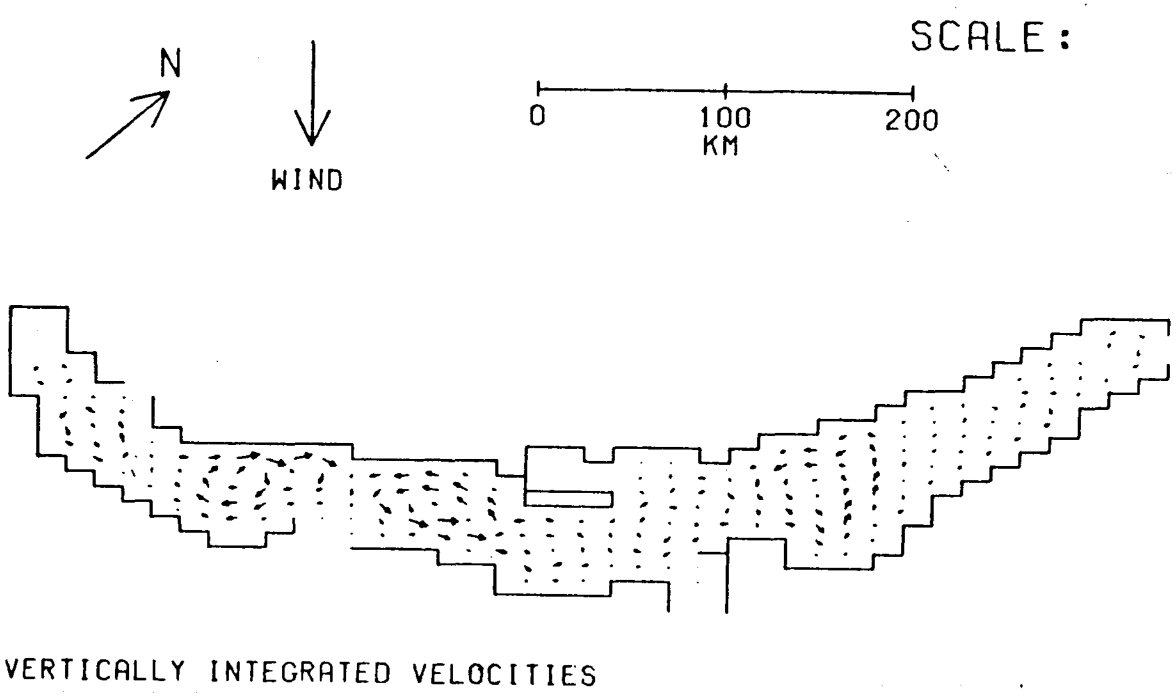


Figure C-3d. Steady-state hydrodynamic model calculations for Lake Baikal with northwest wind.

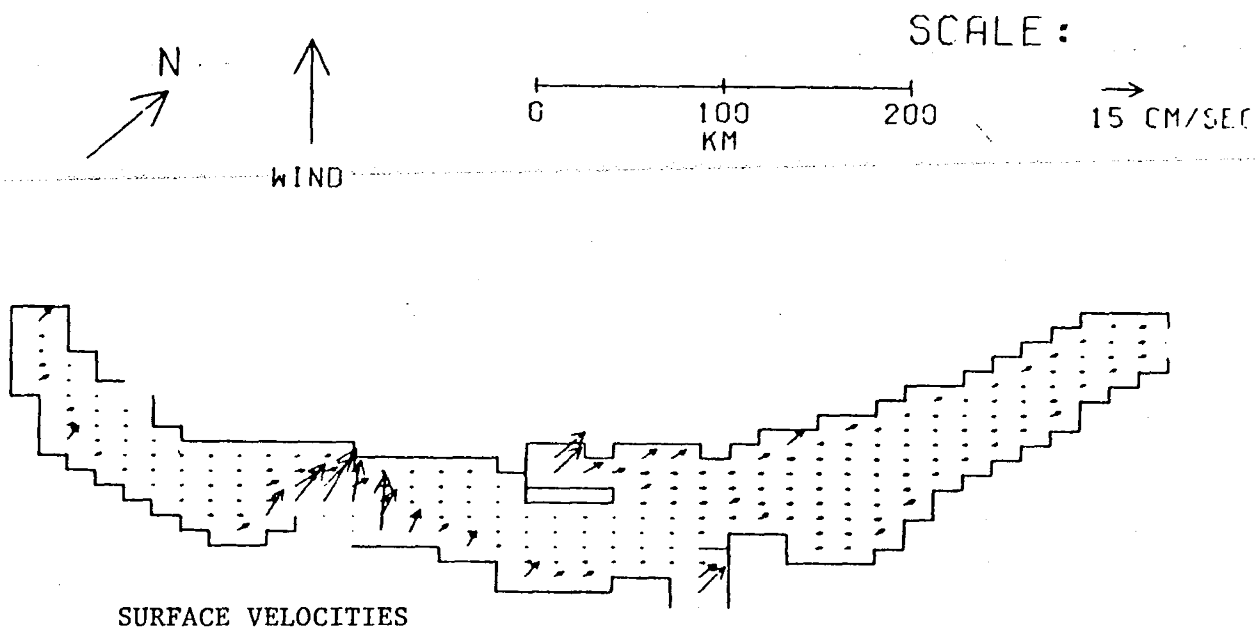
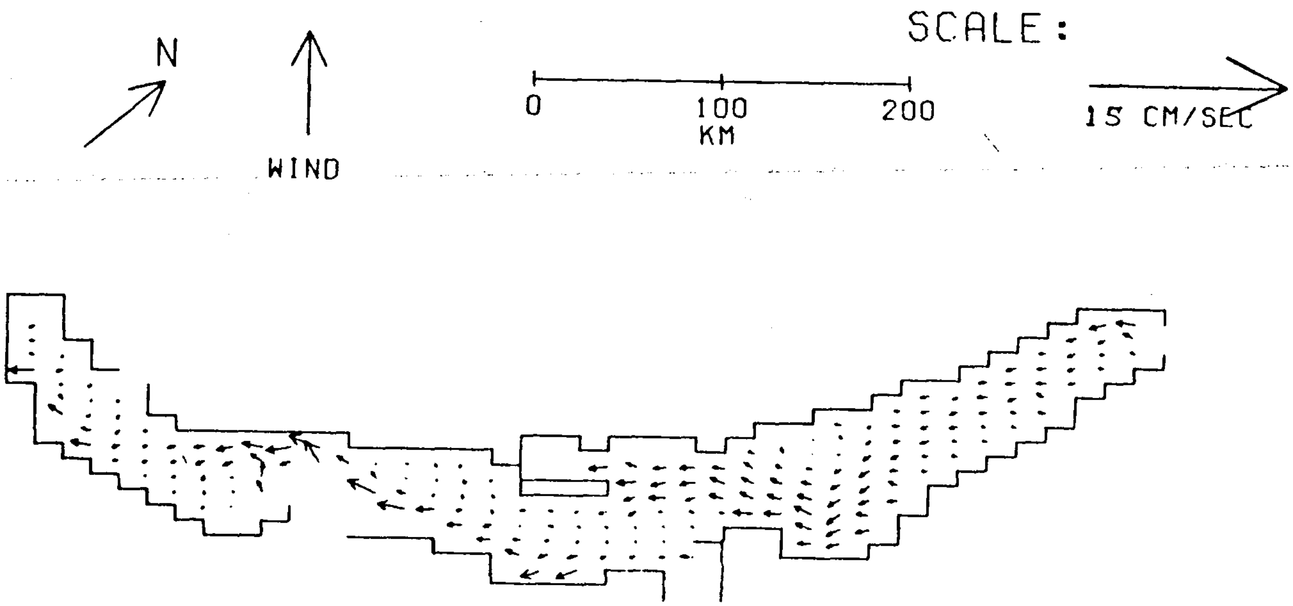
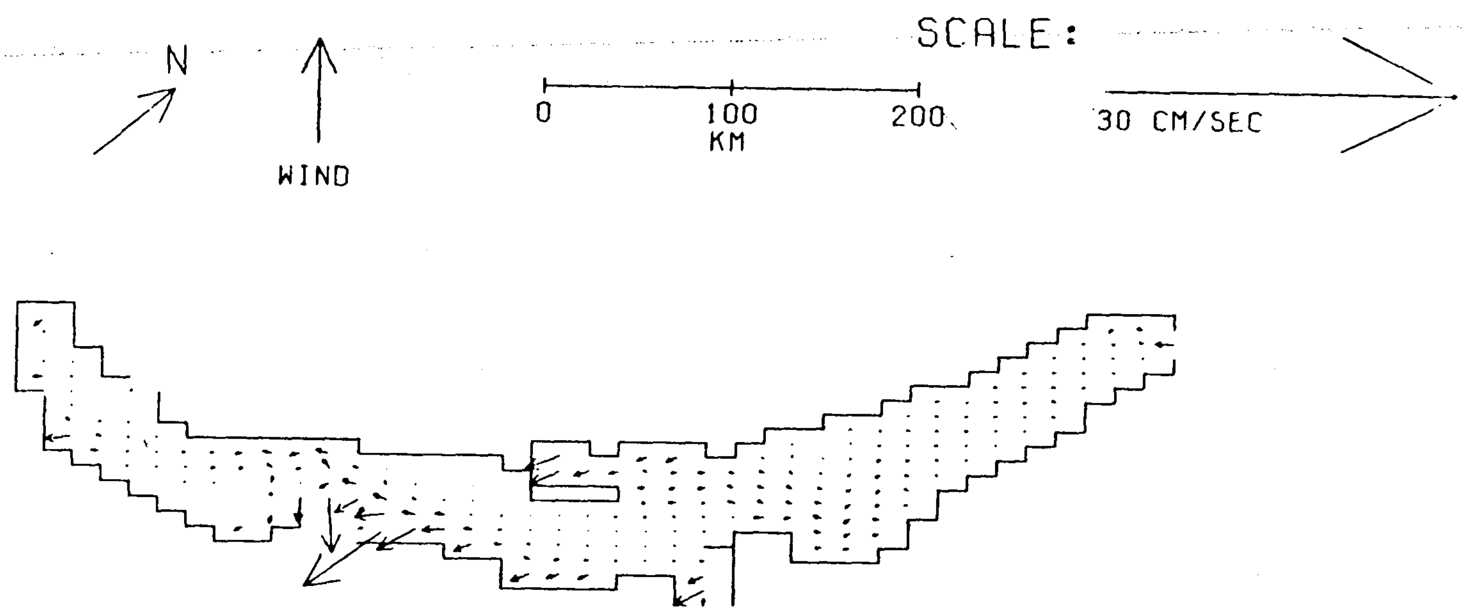


Figure C-4a. Steady-state hydrodynamic model calculations for Lake Baikal with southeast wind.



VELOCITIES AT 200 METERS

Figure C-4b. Steady-state hydrodynamic model calculations for Lake Baikal with southeast wind.



NEAR BOTTOM VELOCITIES

Figure C-4c. Steady-state hydrodynamic model calculations for Lake Baikal with southeast wind.

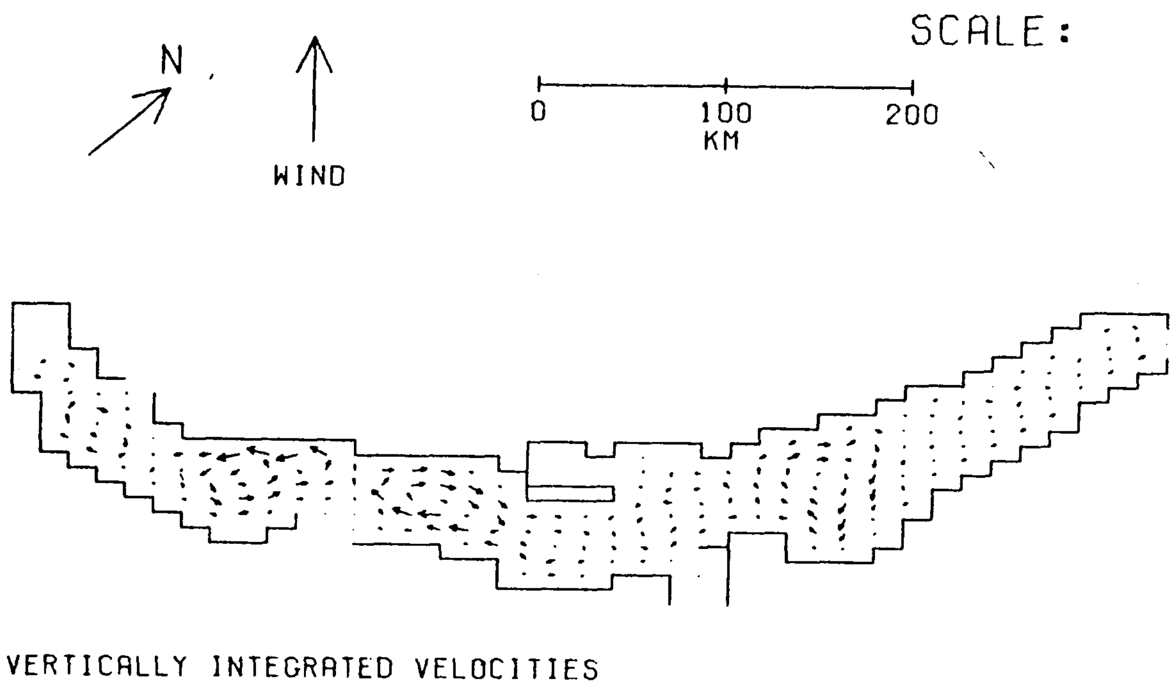


Figure C-4d. Steady-state hydrodynamic model calculations for Lake Baikal with southeast wind.

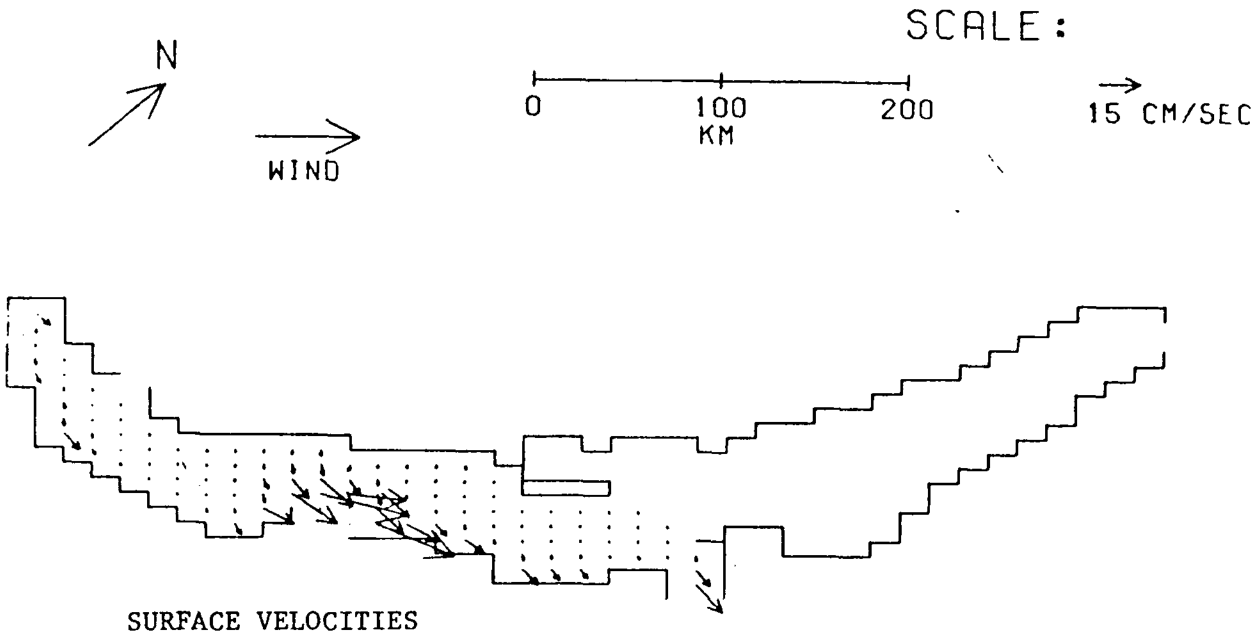


Figure C-5a. Steady-state hydrodynamic model calculations for Lake Baikal with southwest wind and northern basin ice covered.

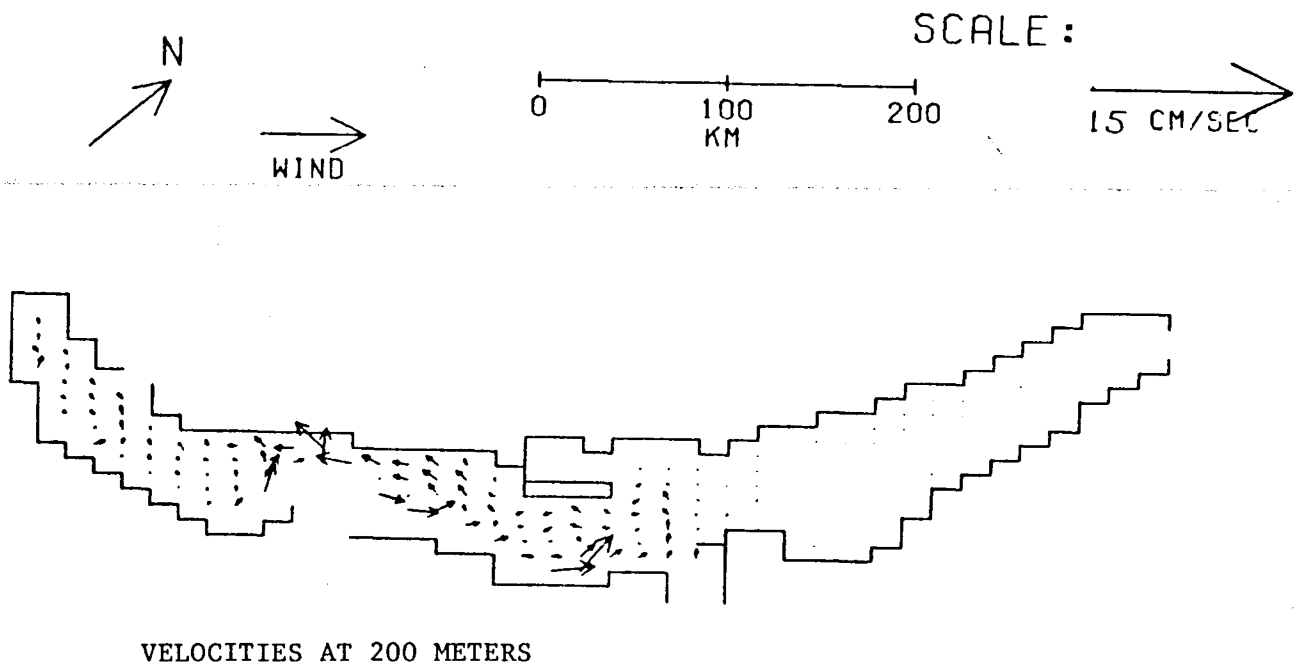


Figure C-5b. Steady-state hydrodynamic model calculations for Lake Baikal with southwest wind and northern basin ice covered.

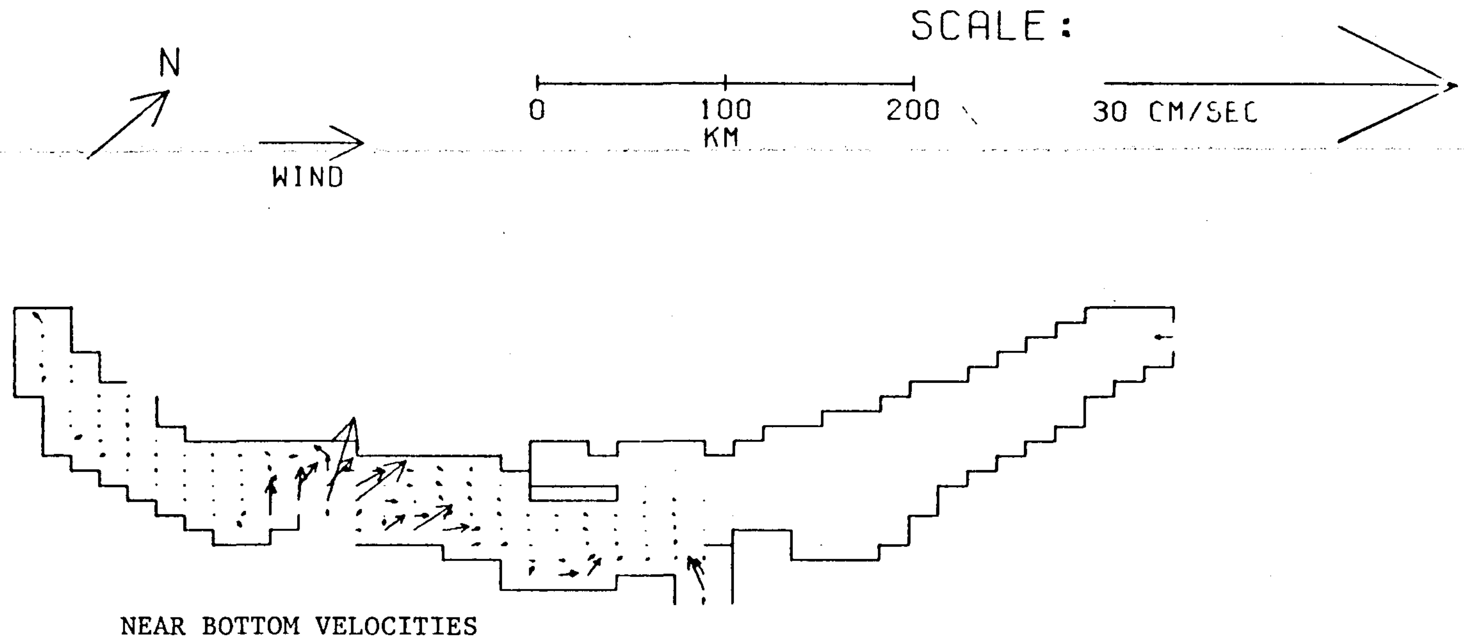


Figure C-5c. Steady-state hydrodynamic model calculations for Lake Baikal with southwest wind and northern basin ice covered.

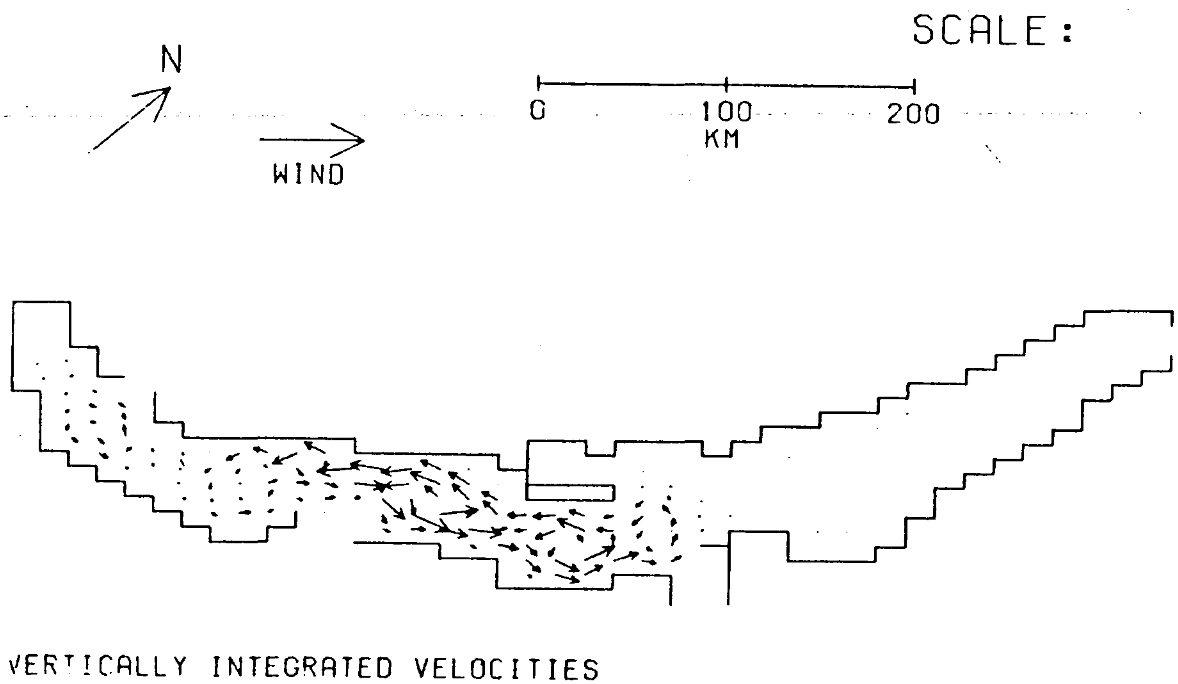
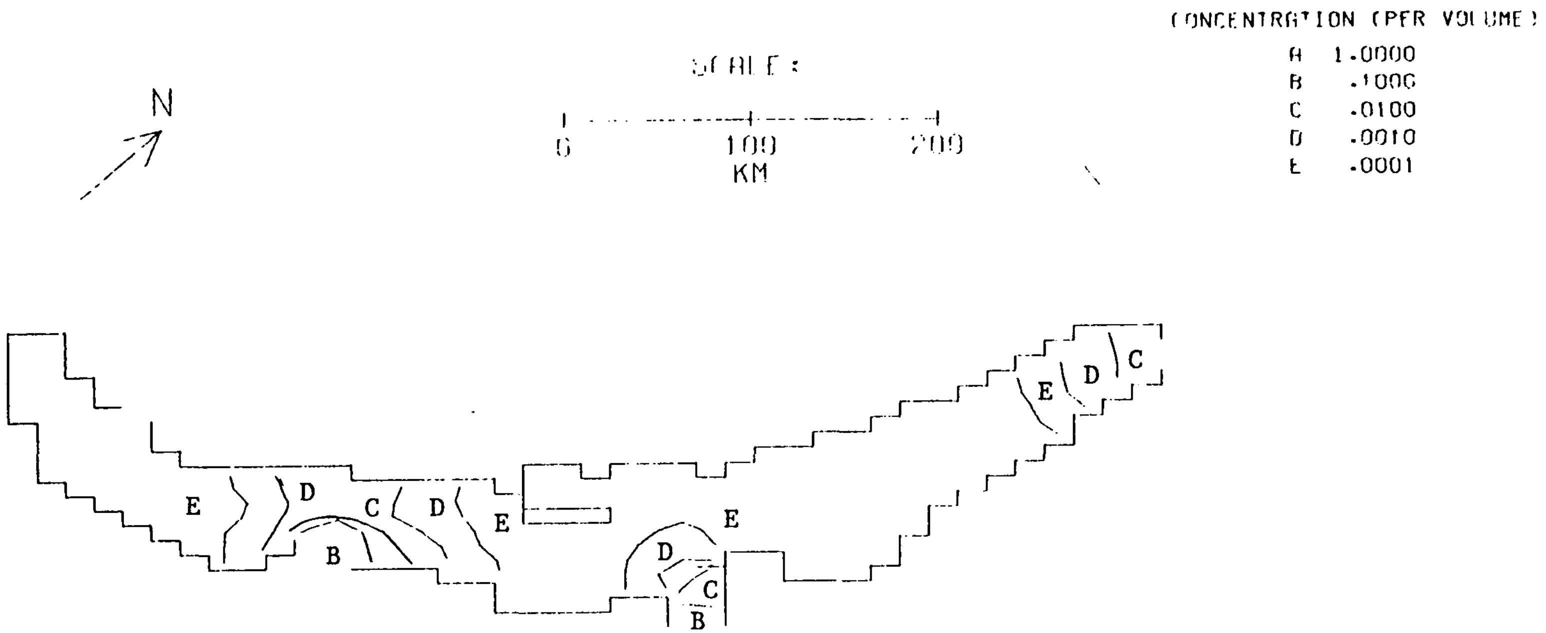


Figure C-5d. Steady-state hydrodynamic model calculations for Lake Baikal with southwest wind and northern basin ice covered.



SURFACE CONCENTRATIONS - NO SETTLING

Figure C-6a. Dispersion model calculation for Lake Baikal after 28 days with steady southwest wind.

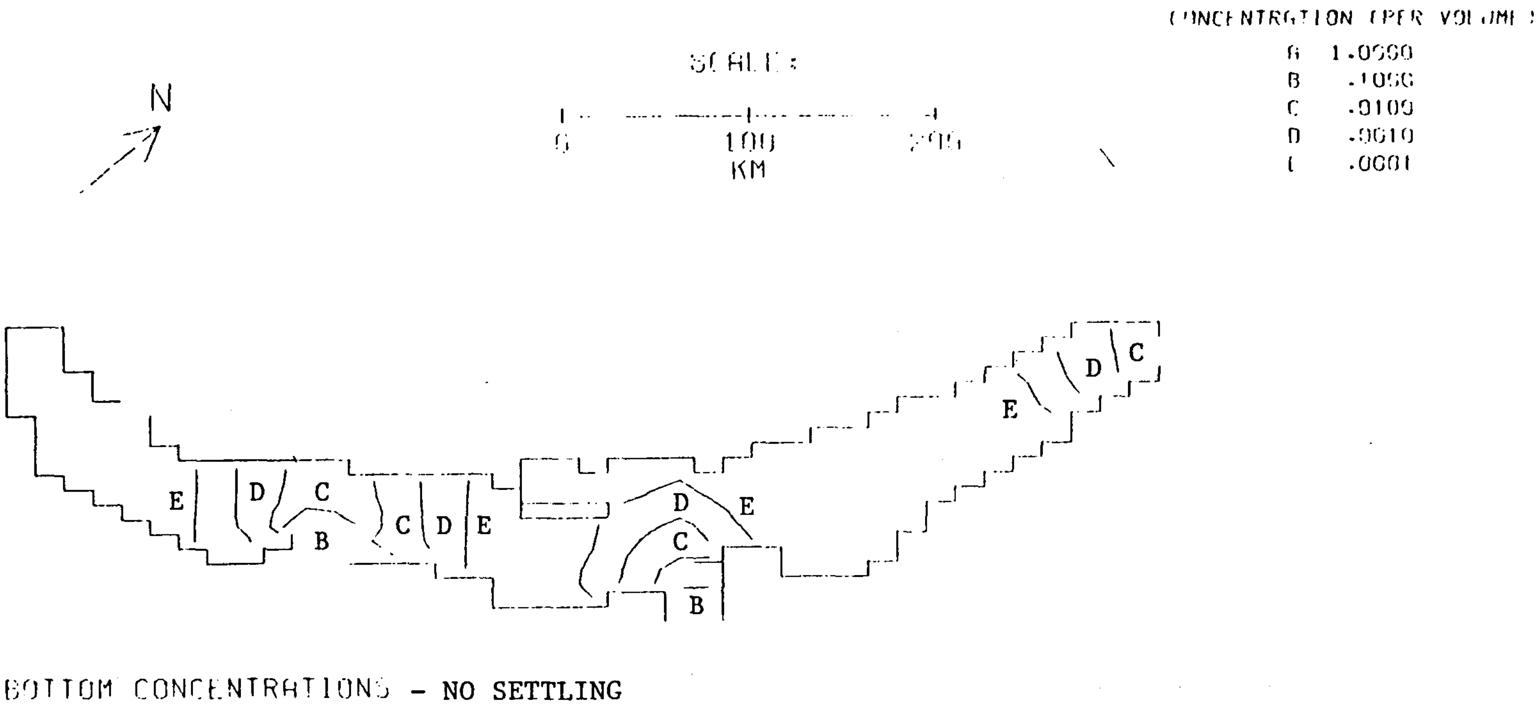


Figure C-6b. Dispersion model calculation for Lake Baikal after 28 days with steady southwest wind.

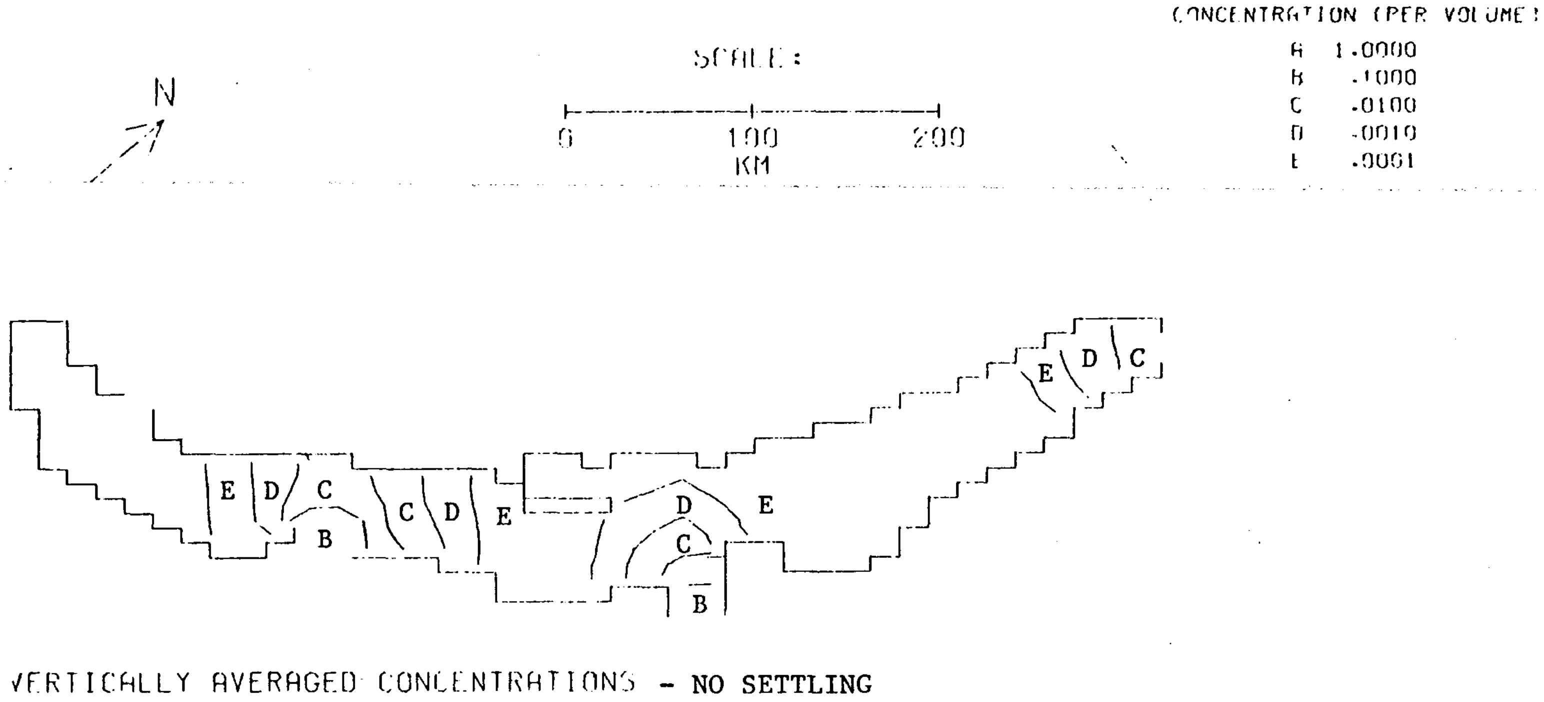


Figure C-6c. Dispersion model calculation for Lake Baikal after 28 days with steady southwest wind.

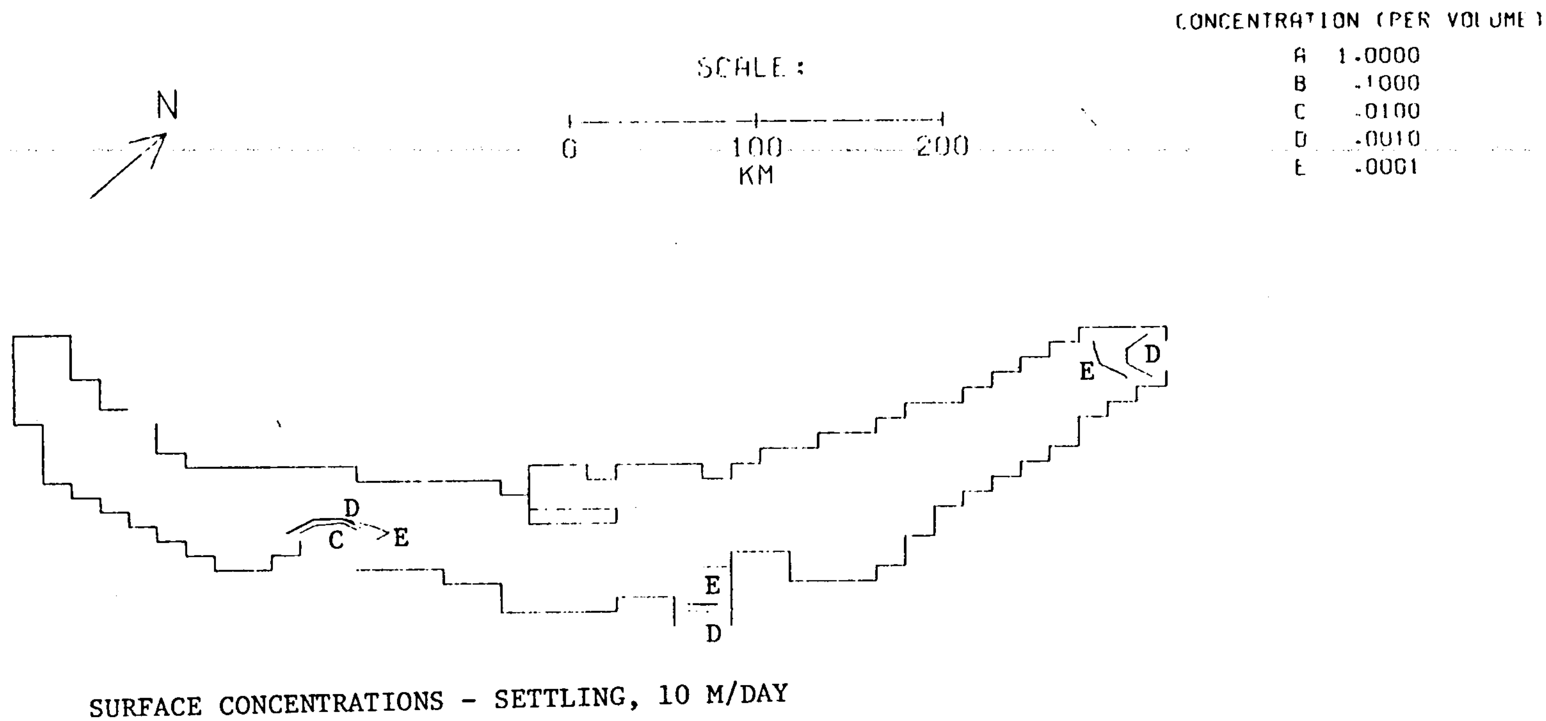
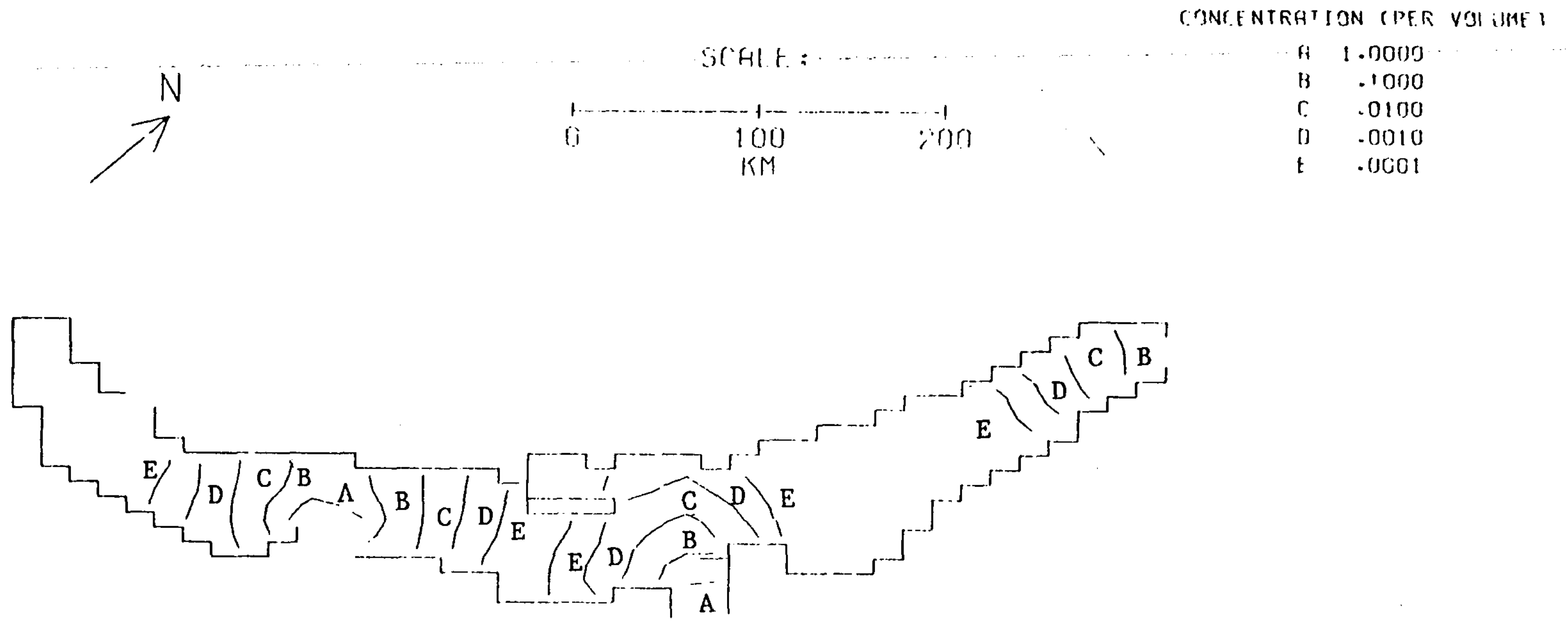
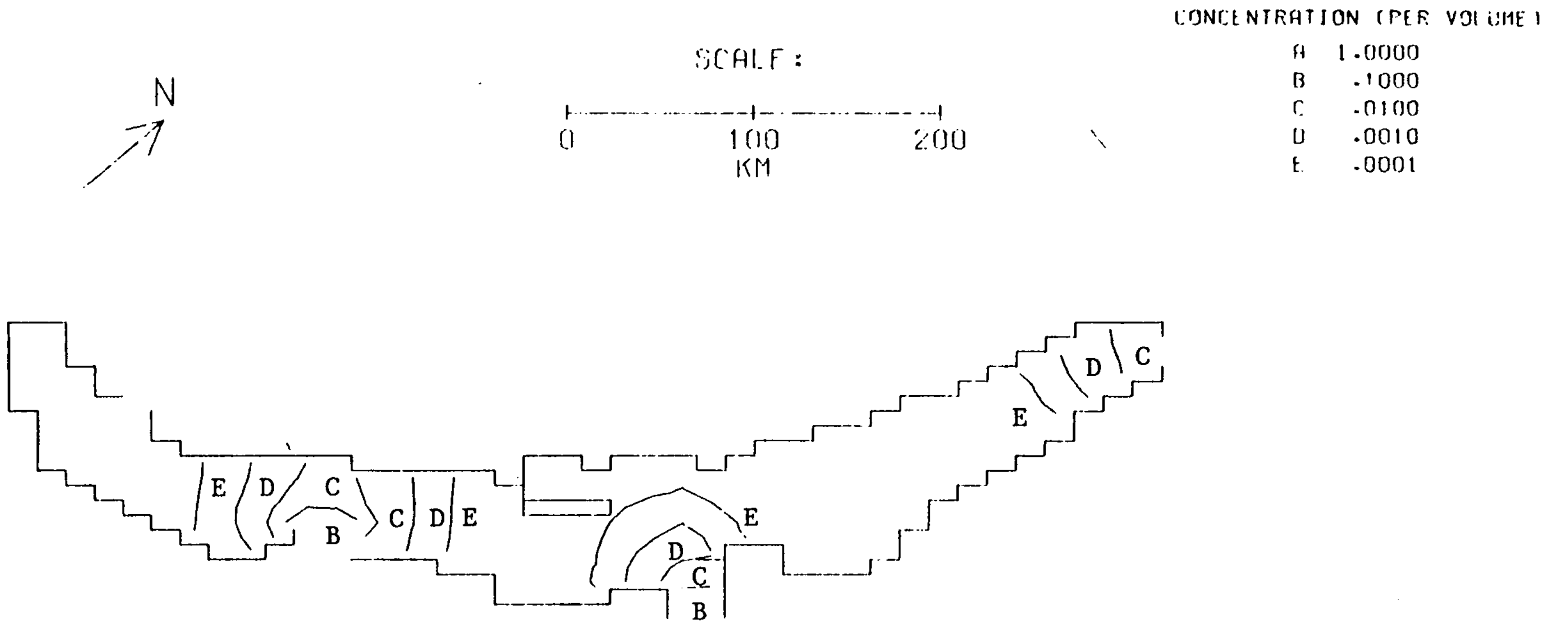


Figure C-6d. Dispersion model calculation for Lake Baikal after 28 days with steady southwest wind.



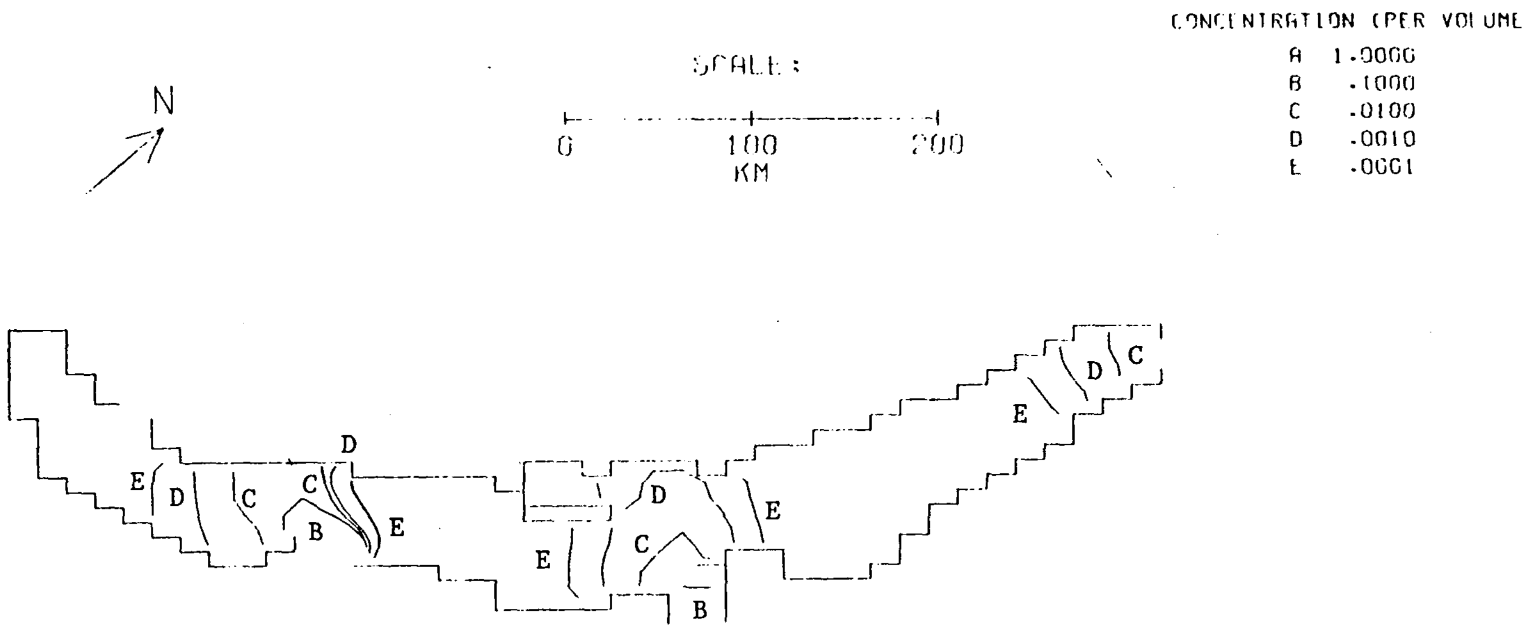
BOTTOM CONCENTRATIONS - SETTLING, 10 M/DAY

Figure C-6e. Dispersion model calculation for Lake Baikal after 28 days with steady southwest wind.



VERTICALLY AVERAGED CONCENTRATIONS - SETTLING, 10 M/DAY

Figure C-6f. Dispersion model calculation for Lake Baikal after 28 days with steady southwest wind.



SURFACE CONCENTRATIONS - NO SETTLING

Figure C-7a. Dispersion model calculation for Lake Baikal ater 28 days of steady northeast wind.

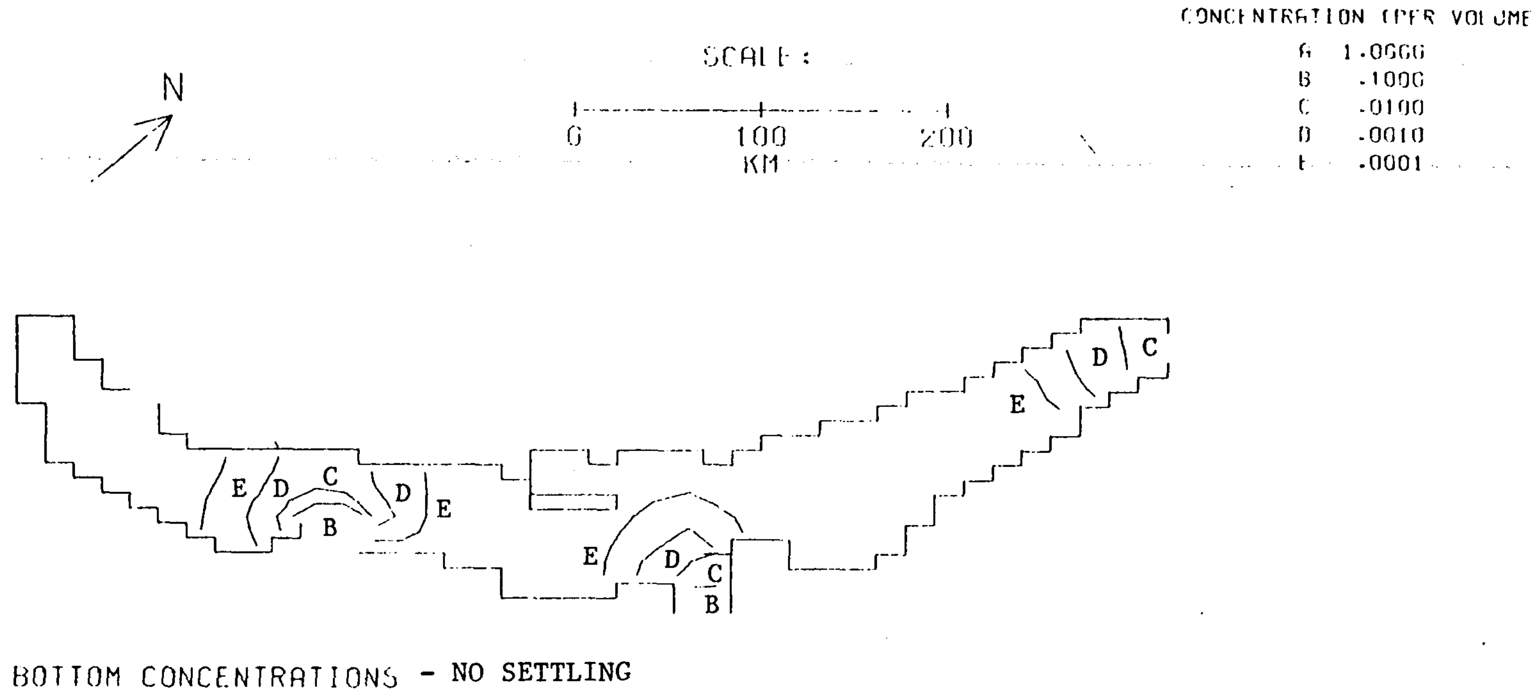


Figure C-7b. Dispersion model calculation for Lake Baikal after 28 days of steady northeast wind.

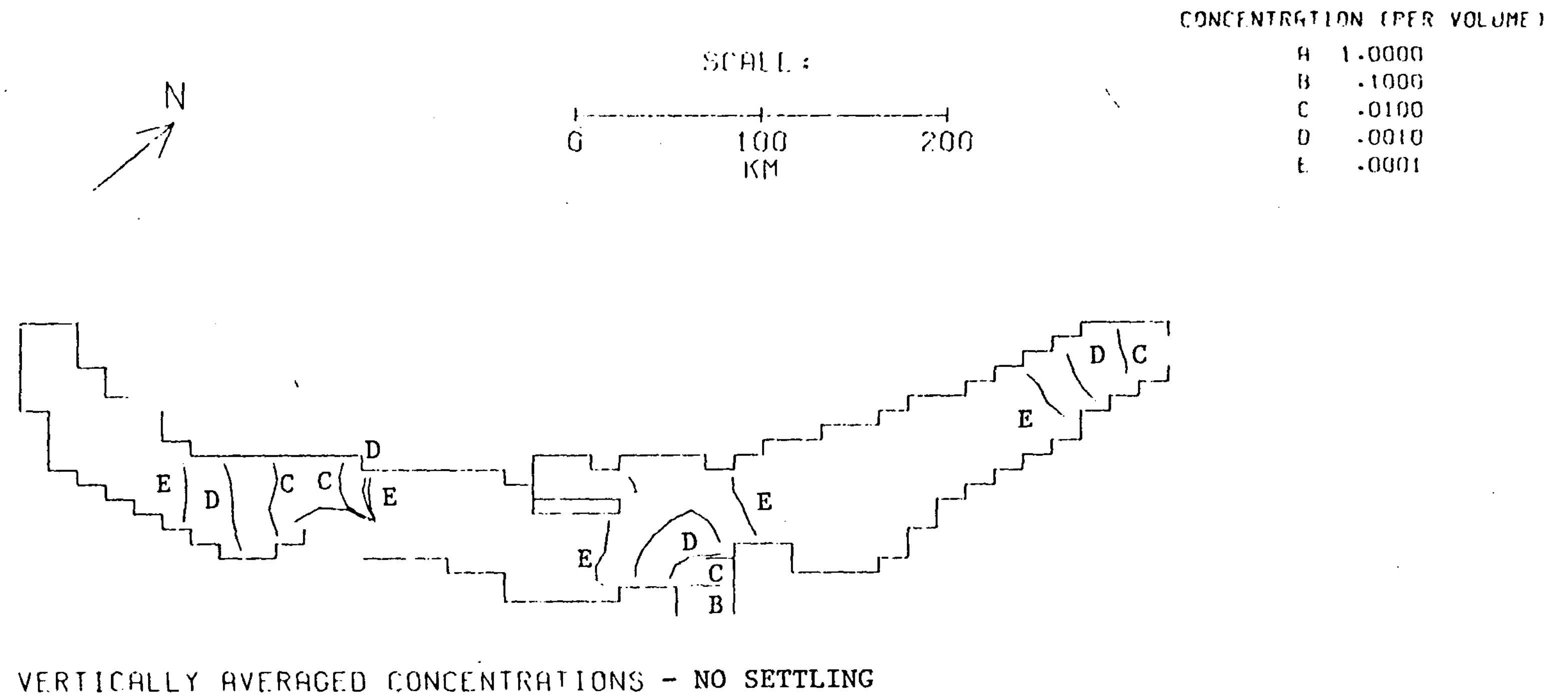


Figure C-7c. Dispersion model calculation for Lake Baikal after 28 days of steady northeast wind.

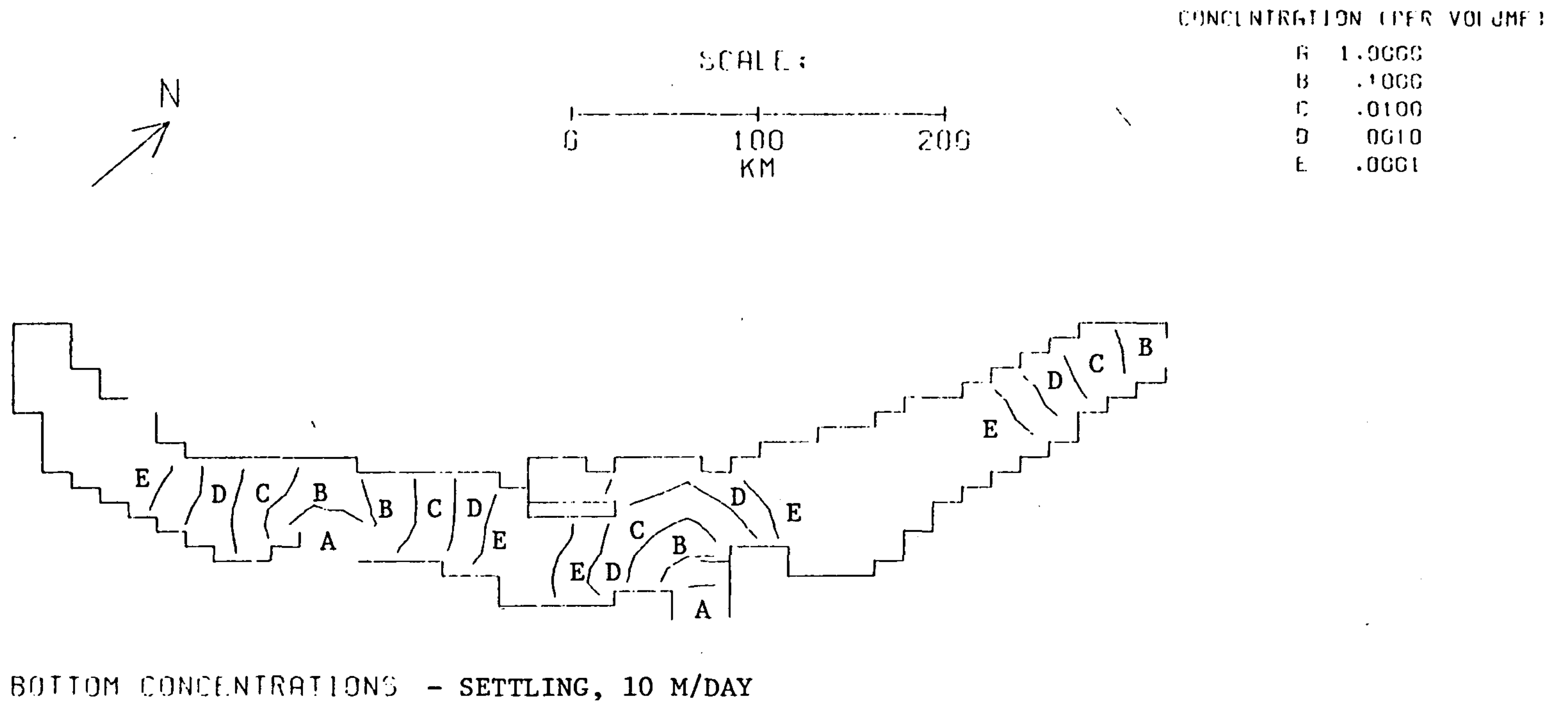
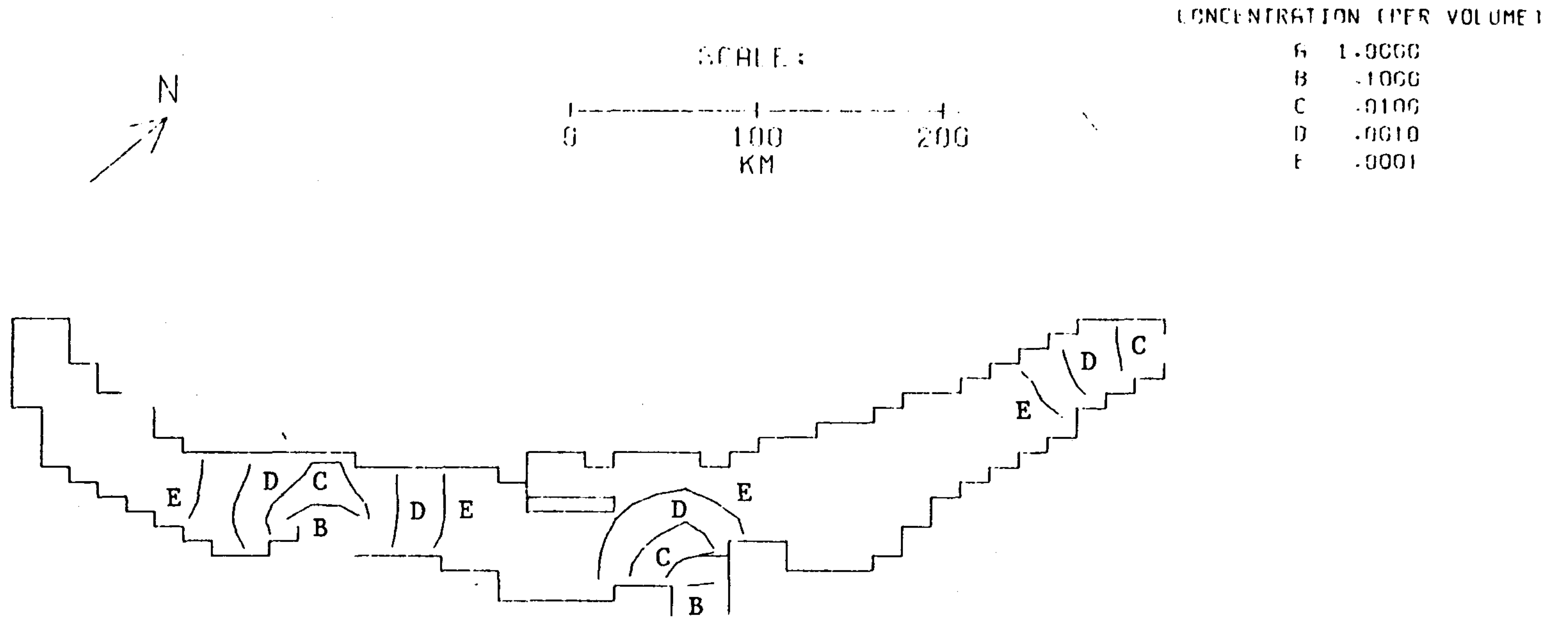
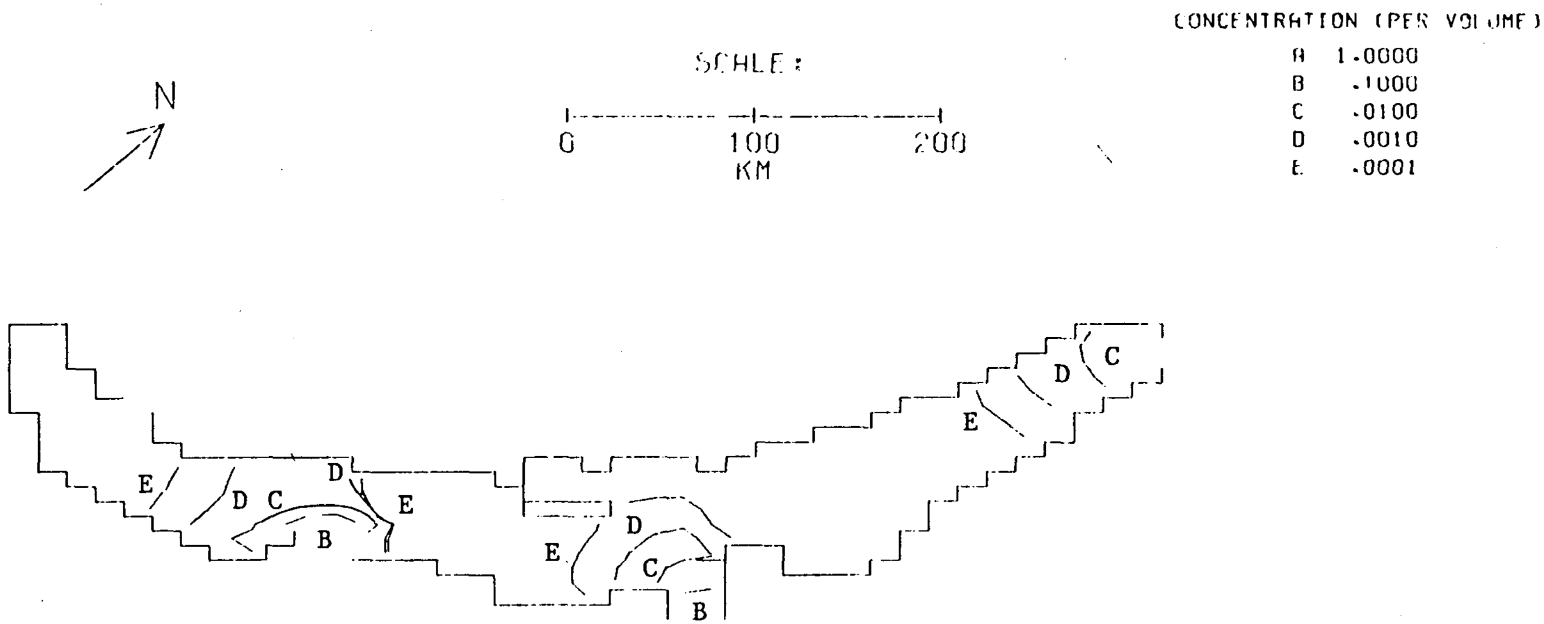


Figure C-7e. Dispersion model calculation for Lake Baikal after 28 days of steady northeast wind.



VERTICALLY AVERAGED CONCENTRATIONS - SETTLING, 10 M/DAY

Figure C-7f. Dispersion model calculation for Lake Baikal after 28 days of steady northeast wind.



SURFACE CONCENTRATIONS - NO SETTLING

Figure C-8a. Dispersion model calculation for Lake Baikal after 28 days with steady northwest wind.

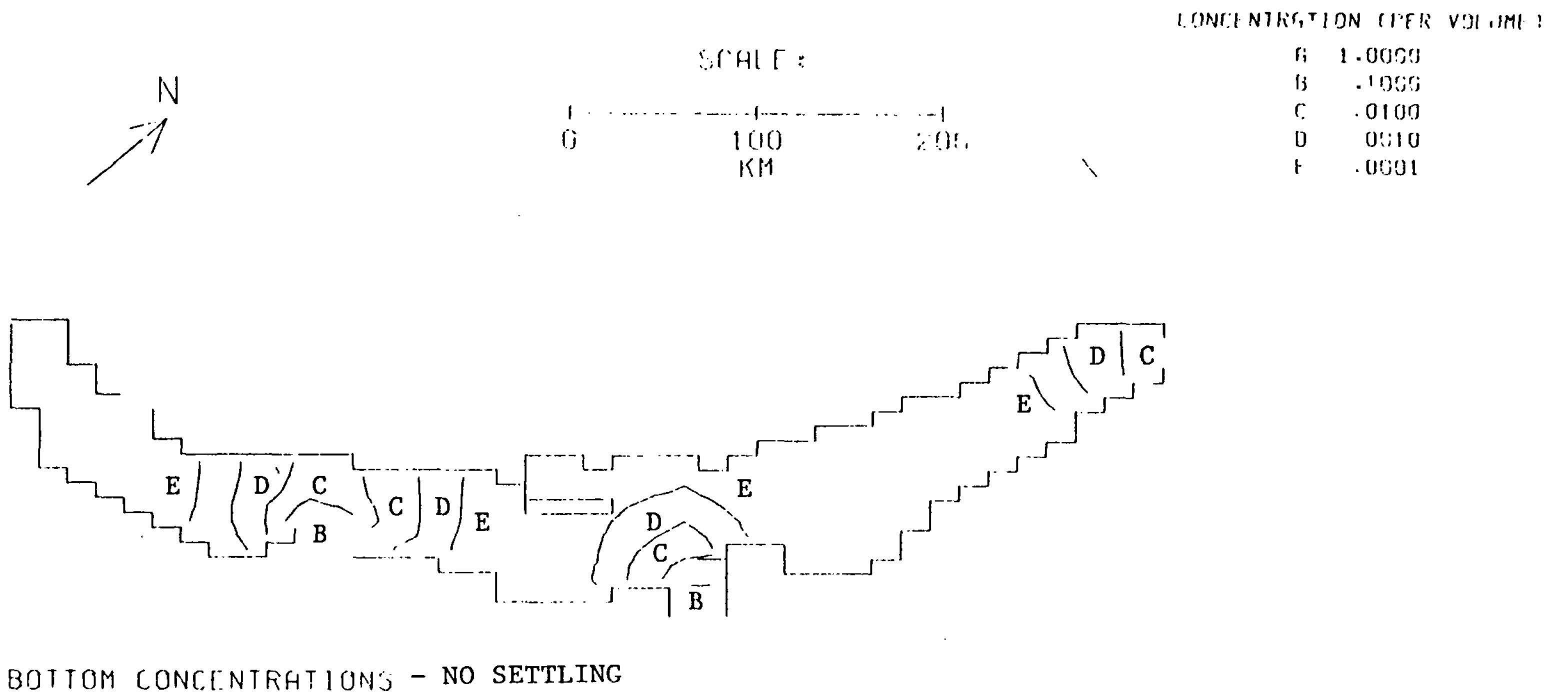


Figure C-8b. Dispersion model calculation for Lake Baikal after 28 days with steady northwest wind.

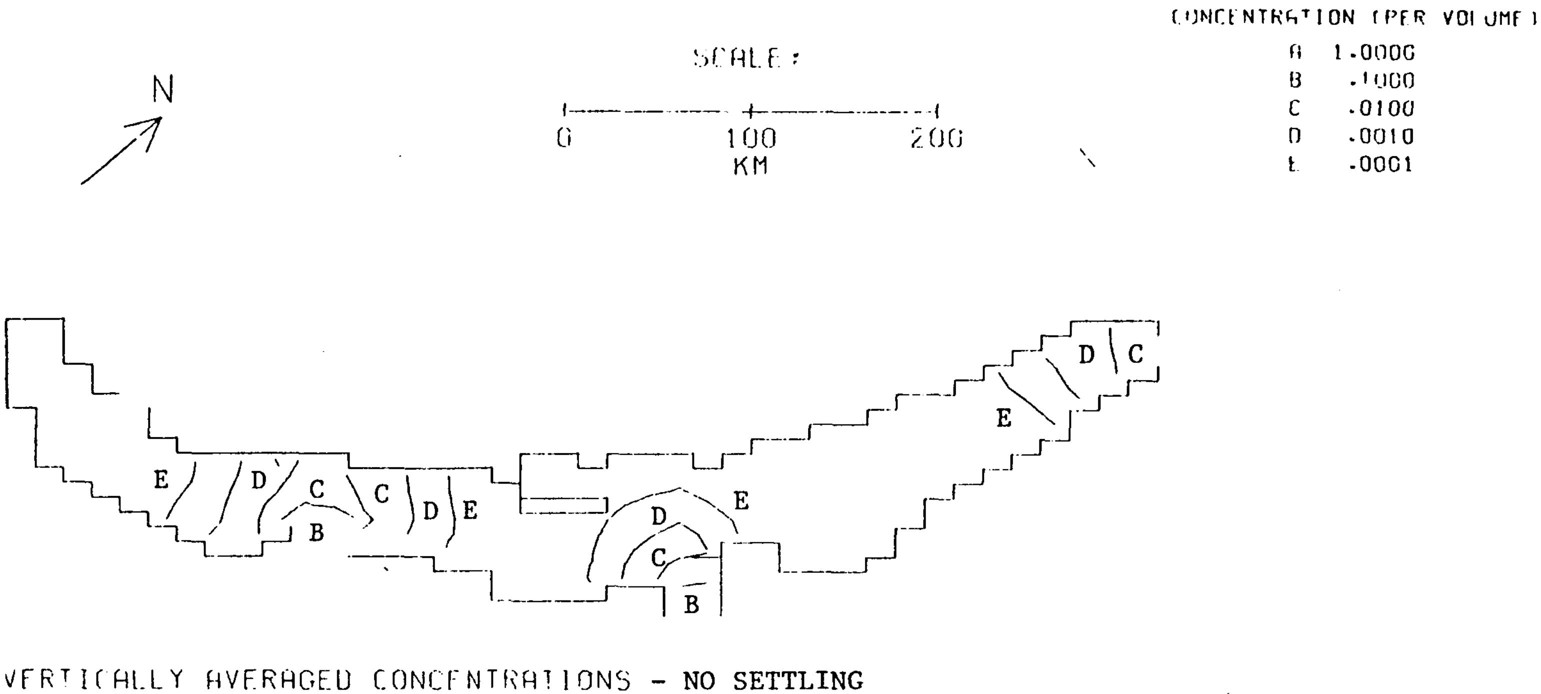
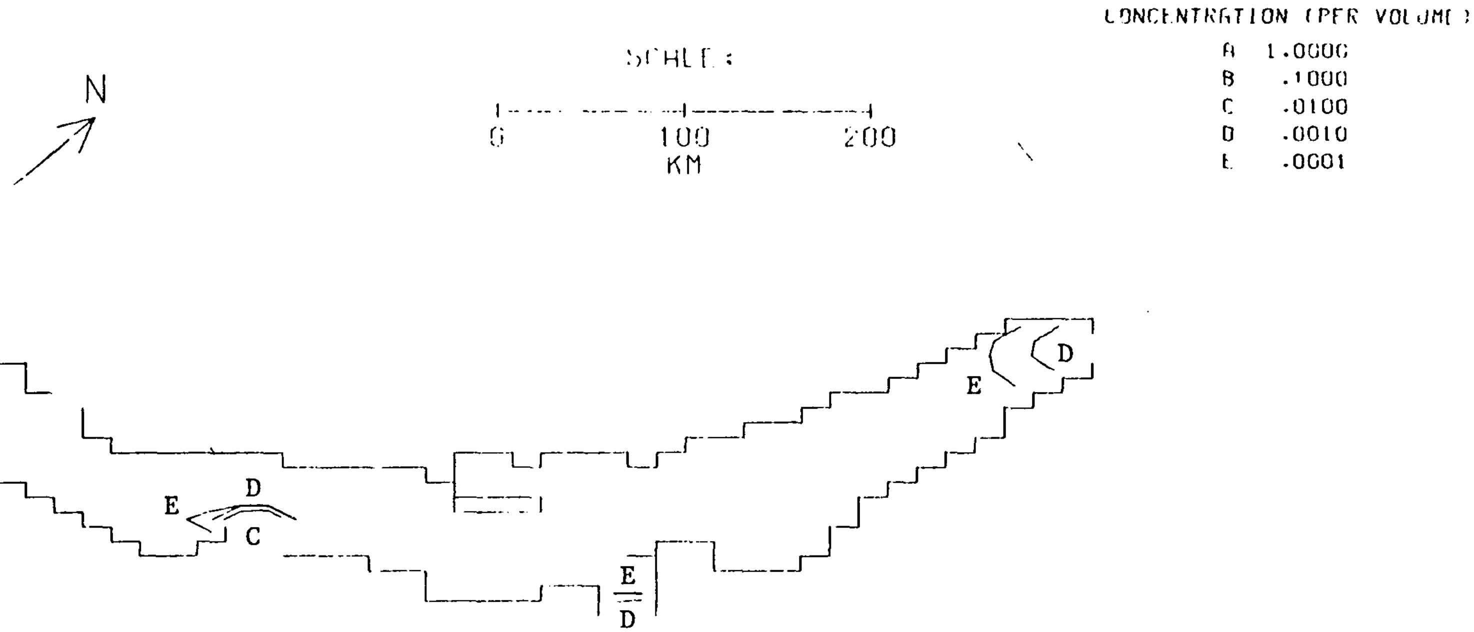
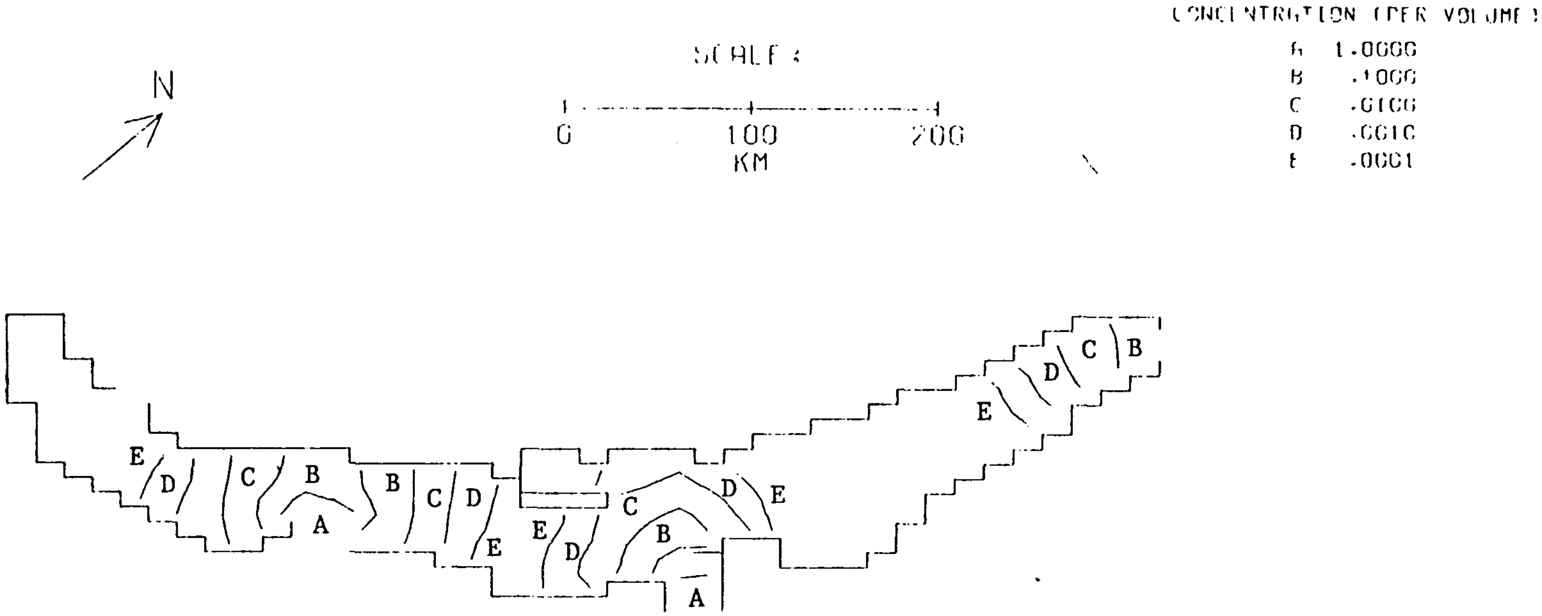


Figure C-8c. Dispersion model calculation for Lake Baikal ater 28 days with steady northwest wind.



SURFACE CONCENTRATIONS - SETTLING, 10 M/DAY

Figure C-8d. Dispersion model calculation for Lake Baikal after 28 days with steady northwest wind.



BOTTOM CONCENTRATIONS - SETTLING, 10 M/DAY

Figure C-8e. Dispersion model calculation for Lake Baikal after 28 days with steady northwest wind.

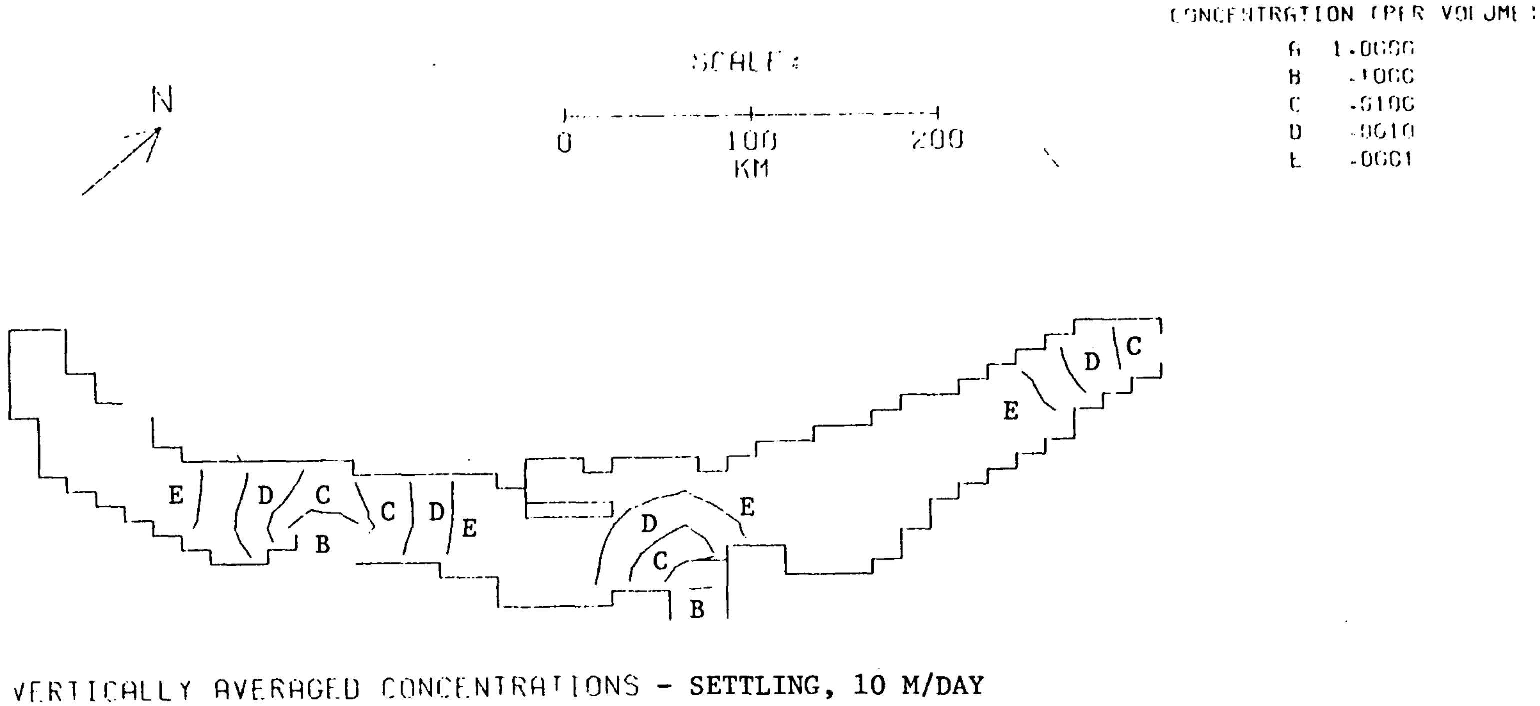
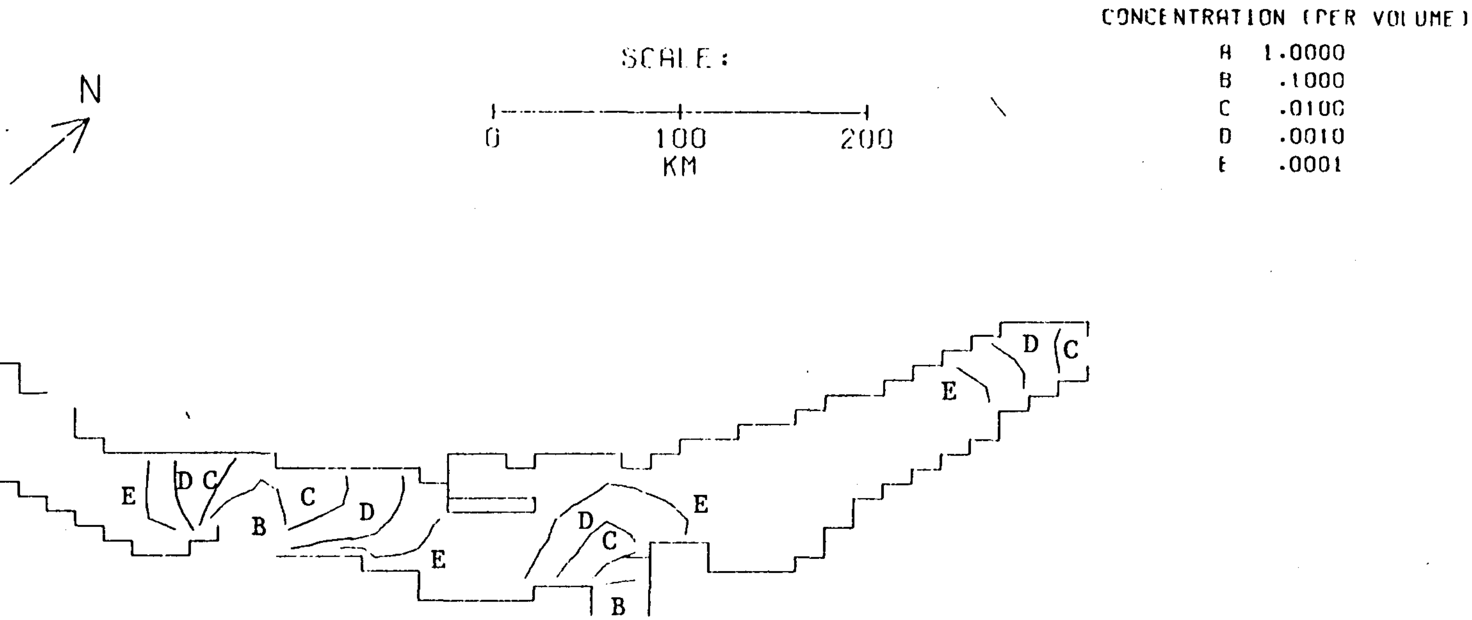
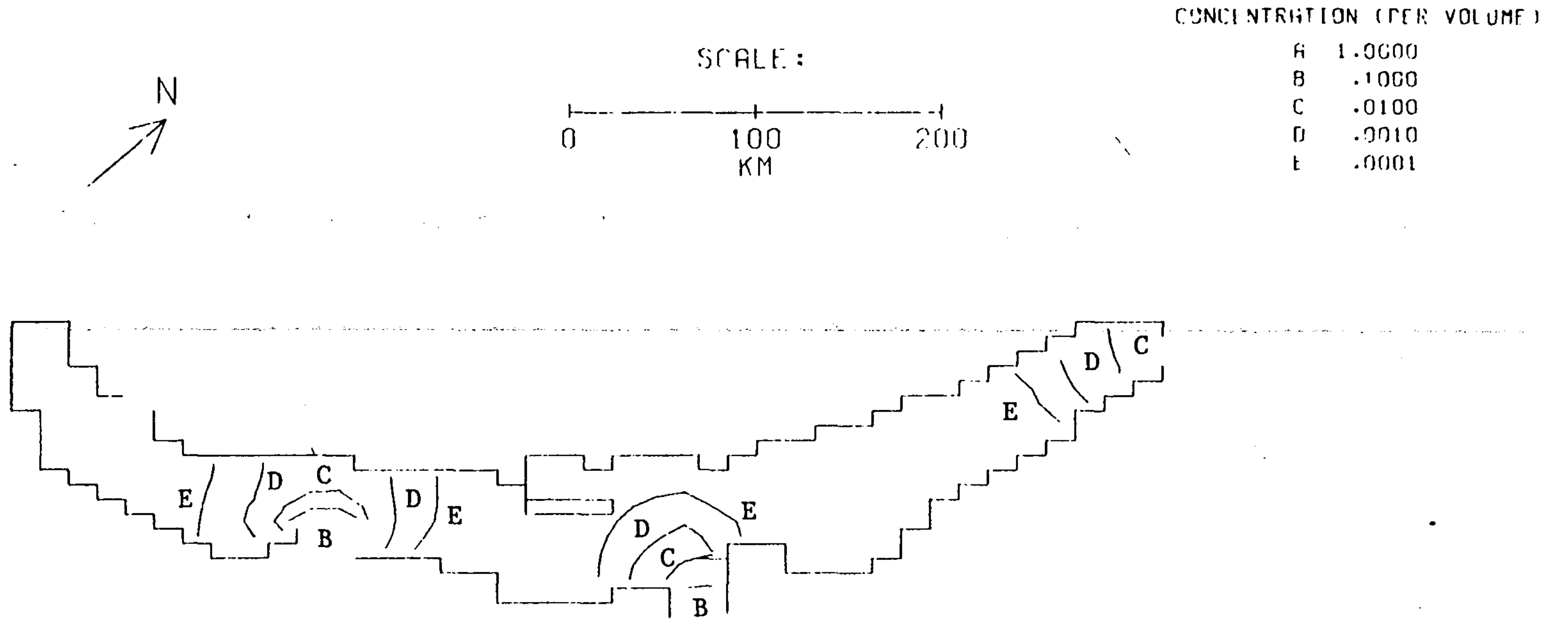


Figure C-8f. Dispersion model calculation for Lake Baikal after 28 days with steady northwest wind.



SURFACE CONCENTRATIONS - NO SETTLING

Figure C-9a. Dispersion model calculation for Lake Baikal after 28 days with steady southeast wind.



BOTTOM CONCENTRATIONS - NO SETTLING

Figure C-9b. Dispersion model calculation for Lake Baikal after 28 days with steady southeast wind.

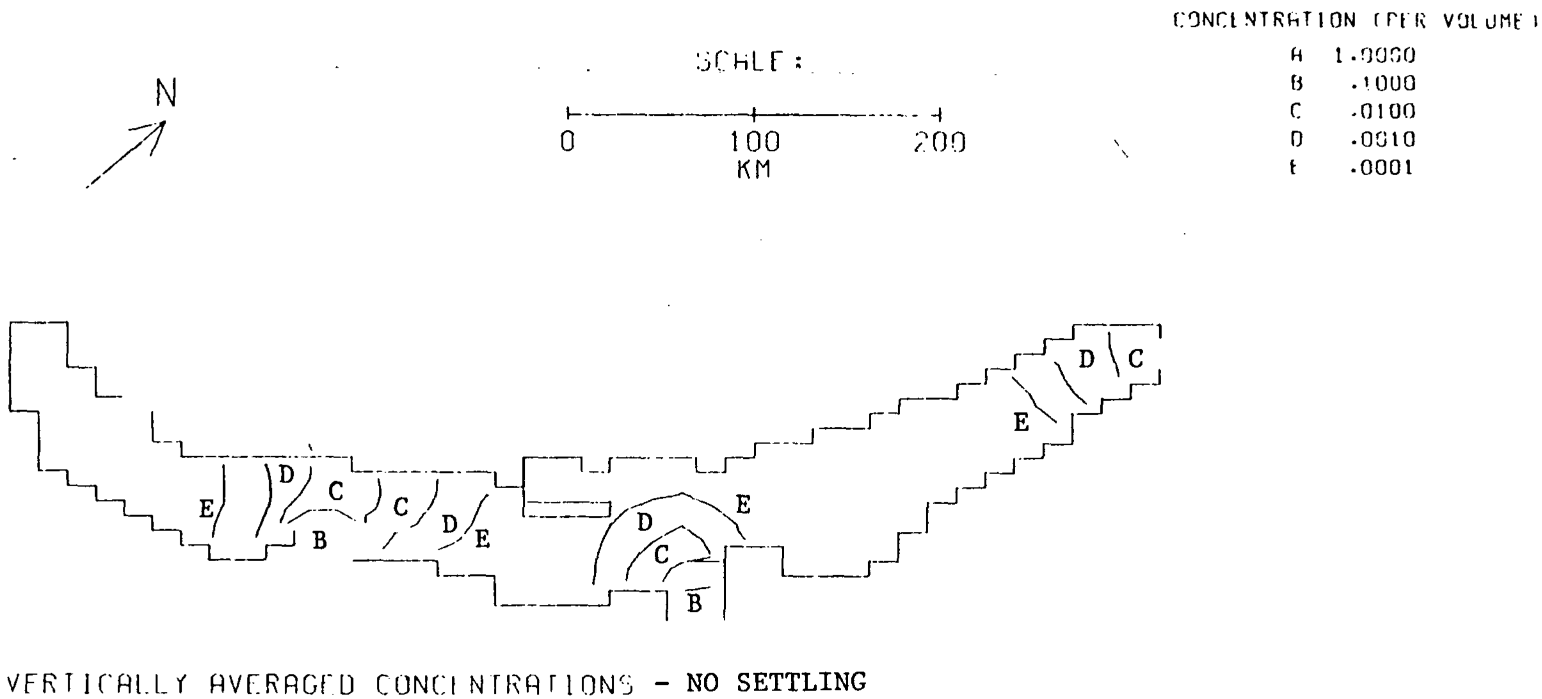
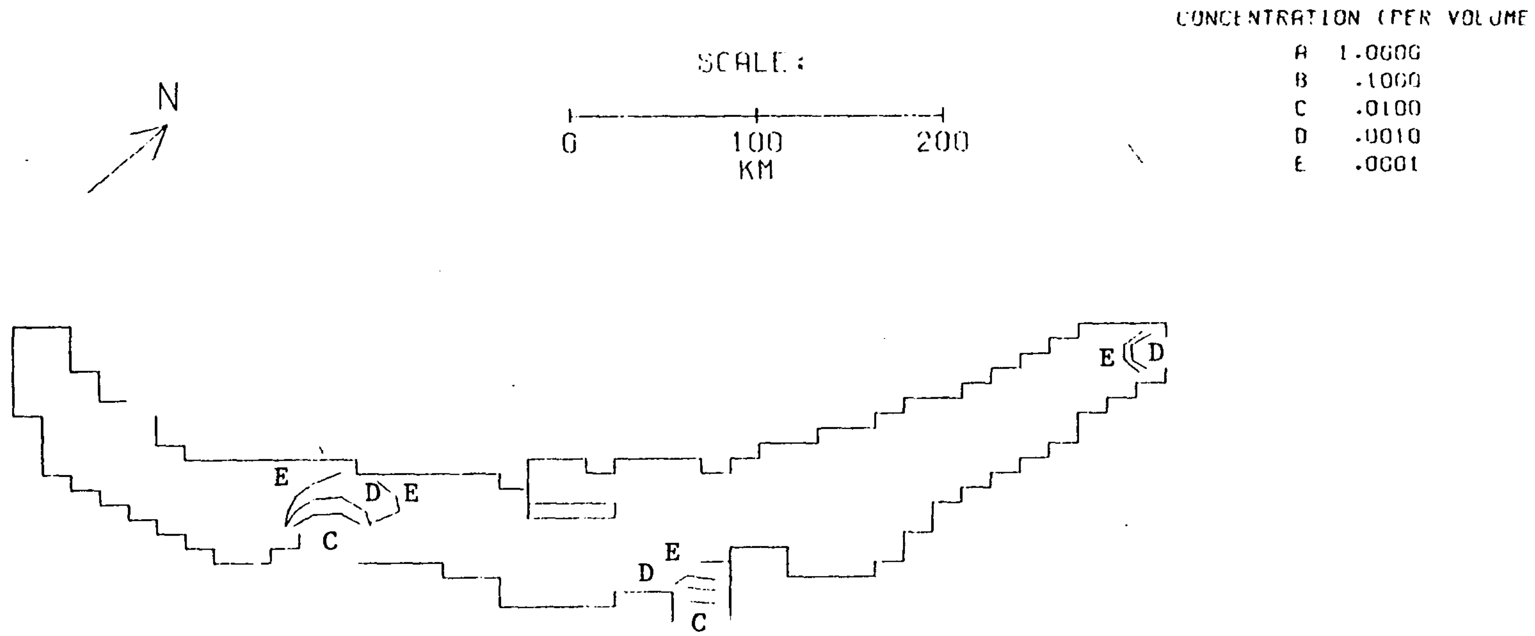
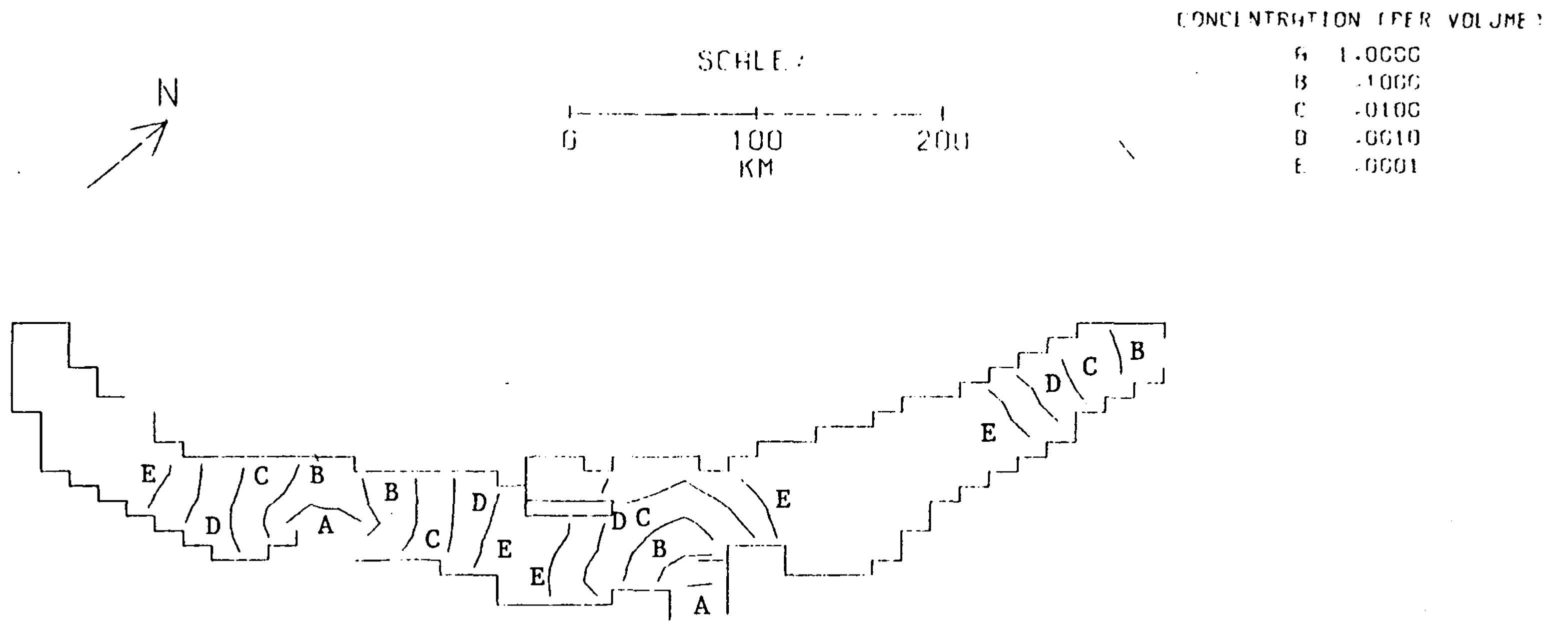


Figure C-9c. Dispersion model calculation for Lake Baikal after 28 days with steady southeast wind.



SURFACE CONCENTRATIONS - SETTLING, 10 M/DAY

Figure C-9d. Dispersion model calculation for Lake Baikal after 28 days with steady southeast wind.



BOTTOM CONCENTRATIONS - SETTLING, 10 M/DAY

Figure C-9e. Dispersion model calculation for Lake Baikal after 28 days with steady southeast wind.

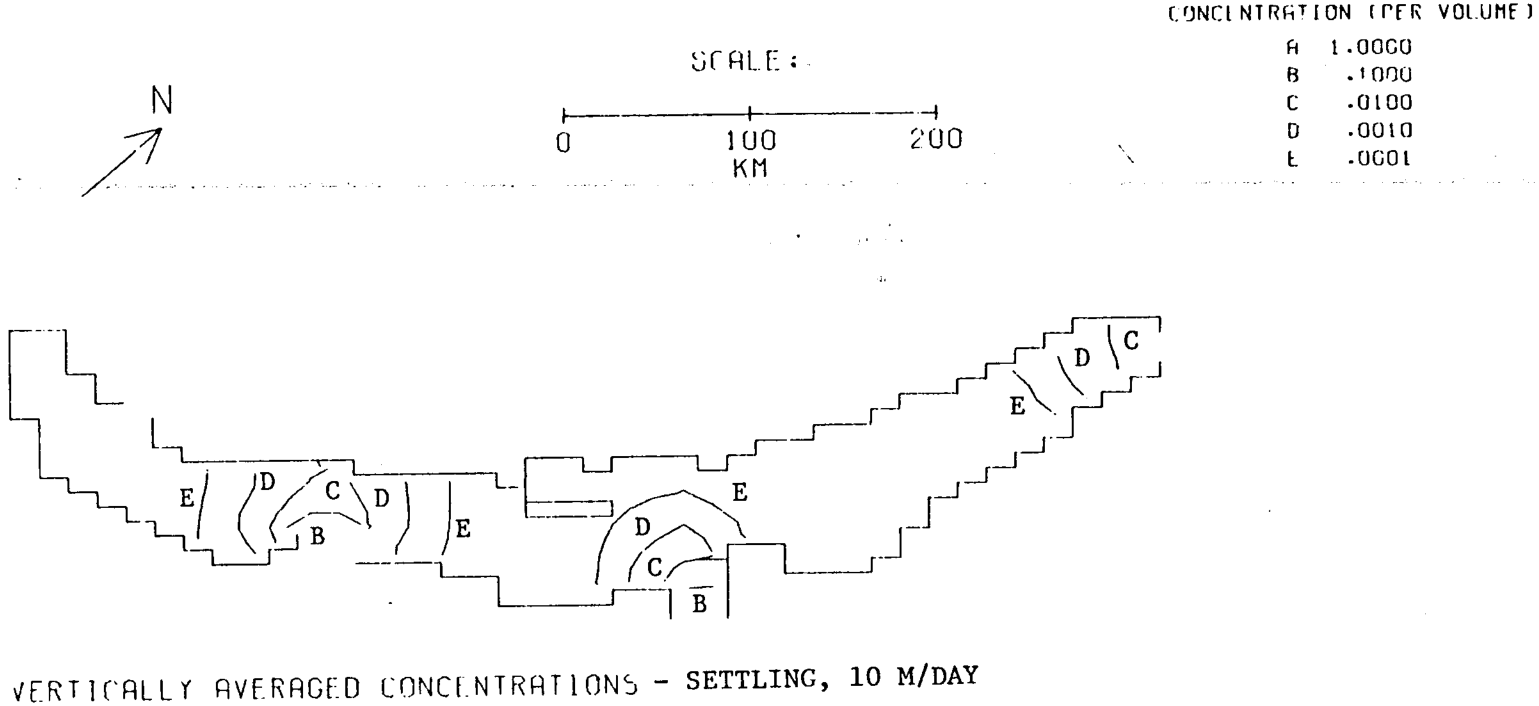


Figure C-9f. Dispersion model calculation for Lake Baikal after 28 days with steady southeast wind.

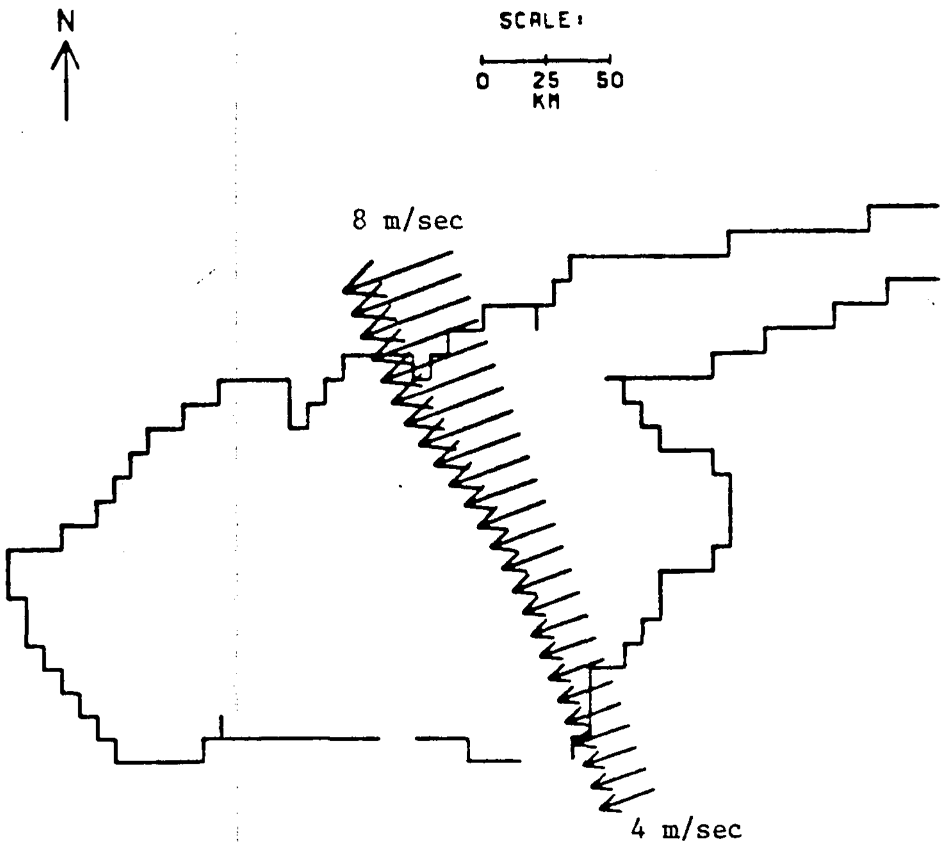


Figure C-10. Case 1 winds used in hydrodynamic model calculation for Sea of Azov.

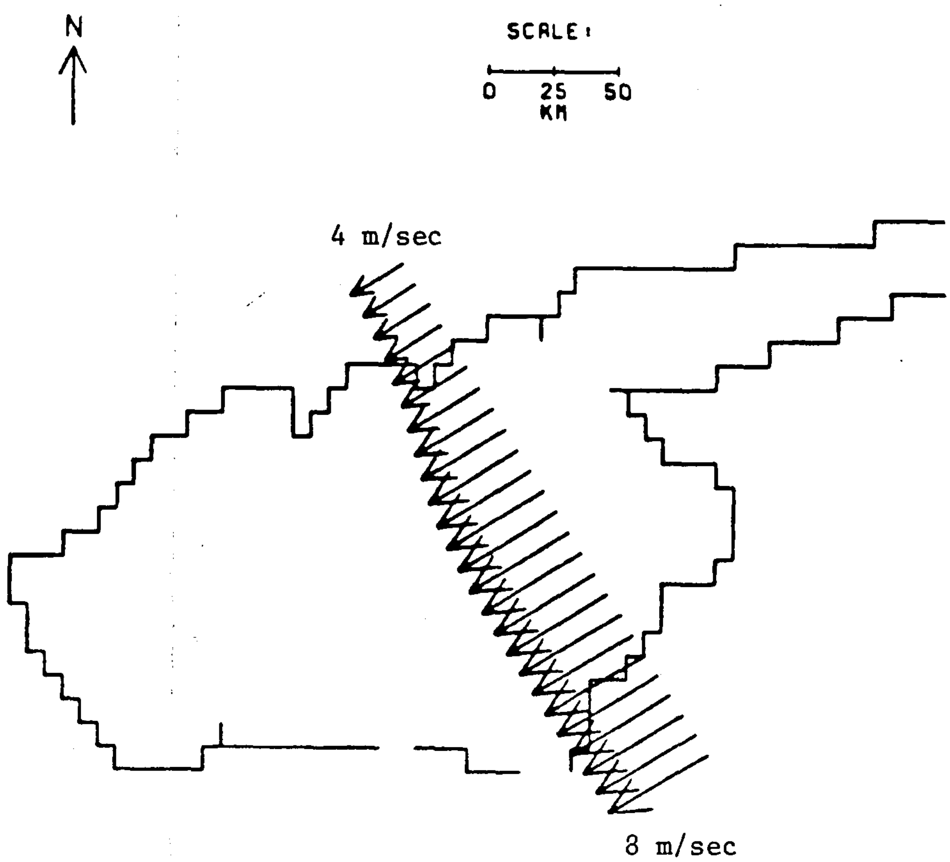


Figure C-11. Case 2 winds used in hydrodynamic model calculation for Sea of Azov.

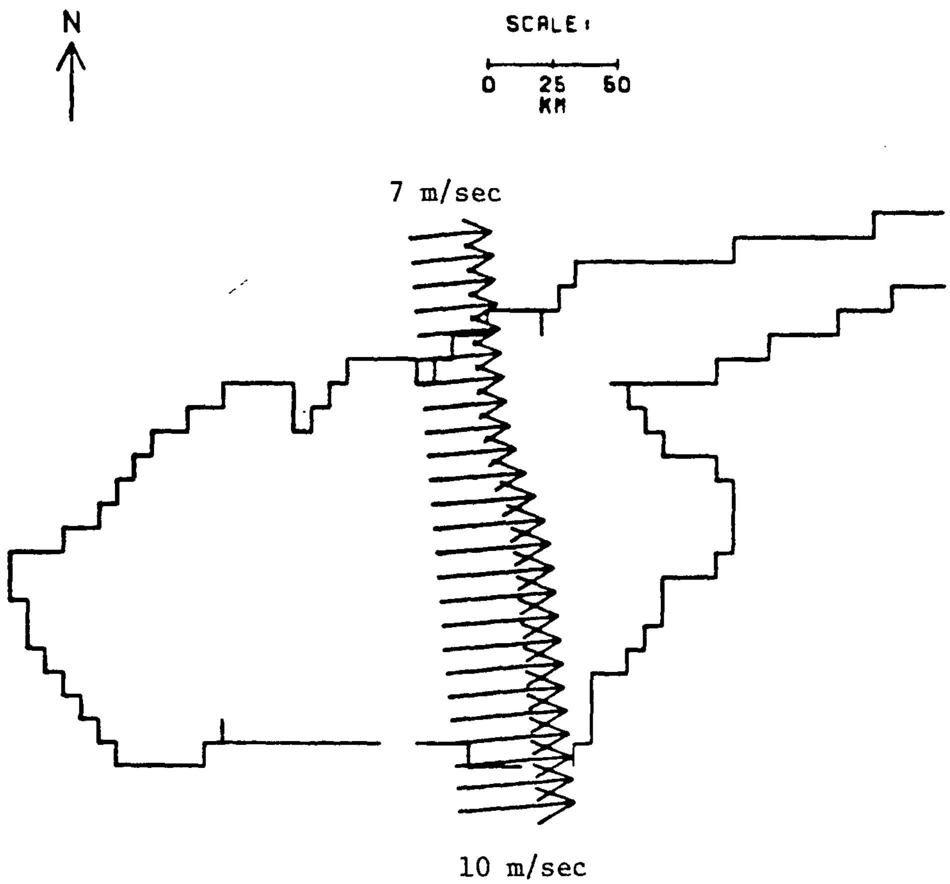


Figure C-12. Case 3 winds used in hydrodynamic model calculation for Sea of Azov.

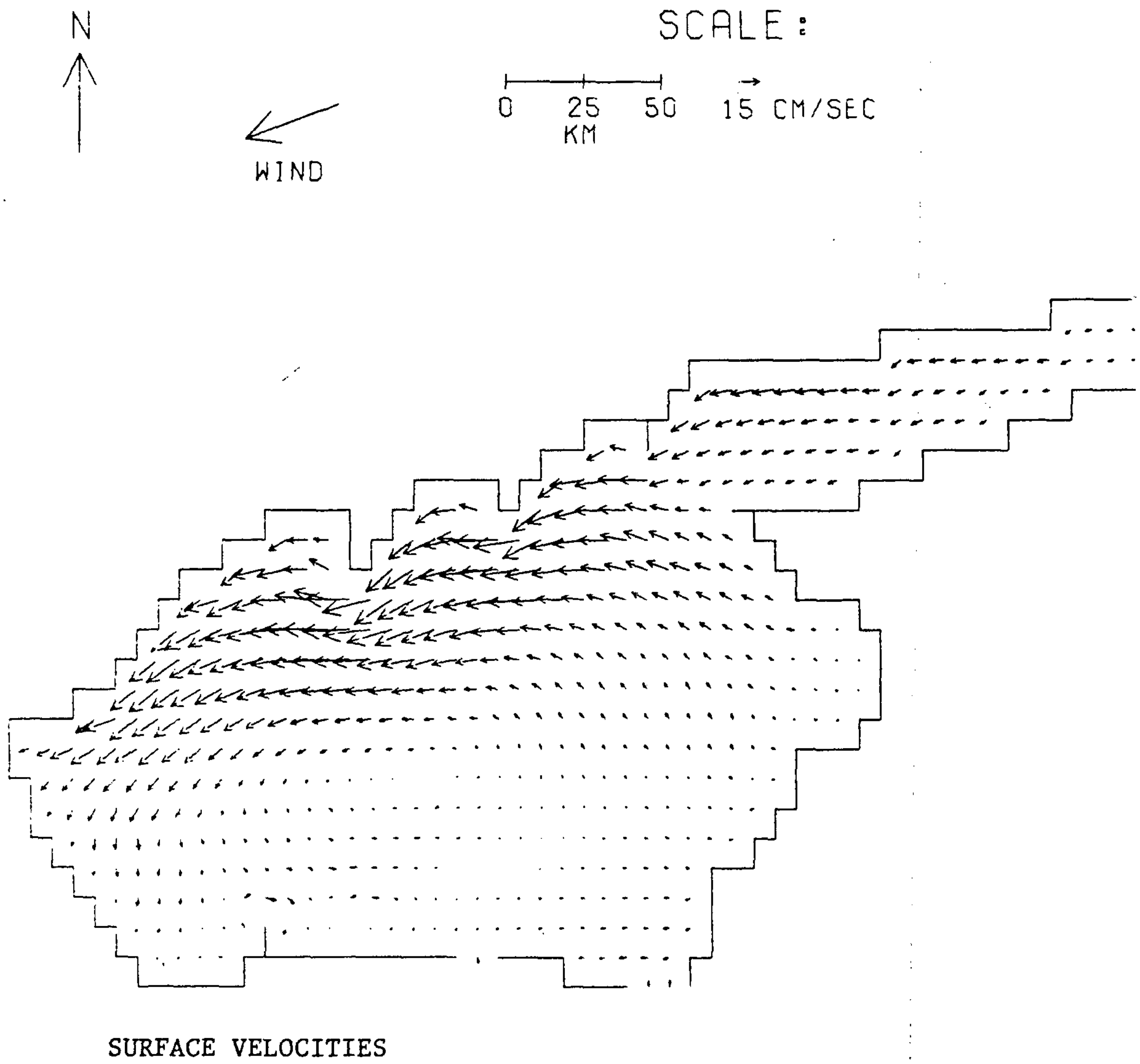


Figure C-13a. Case 1 hydrodynamic model calculation for Sea of Azov after 2 days.

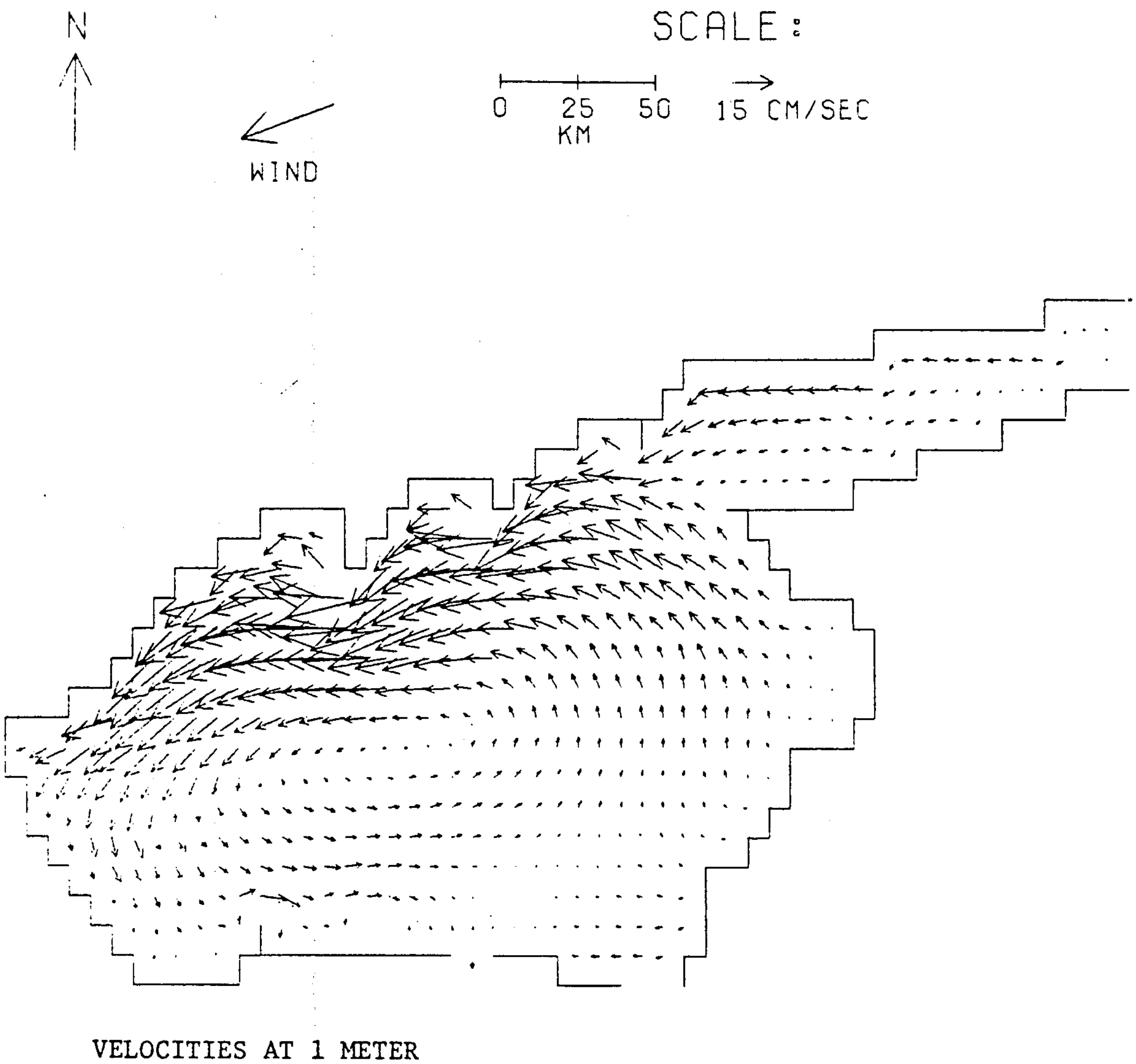


Figure C-13b. Case 1 hydrodynamic model calculation for Sea of Azov after 2 days.

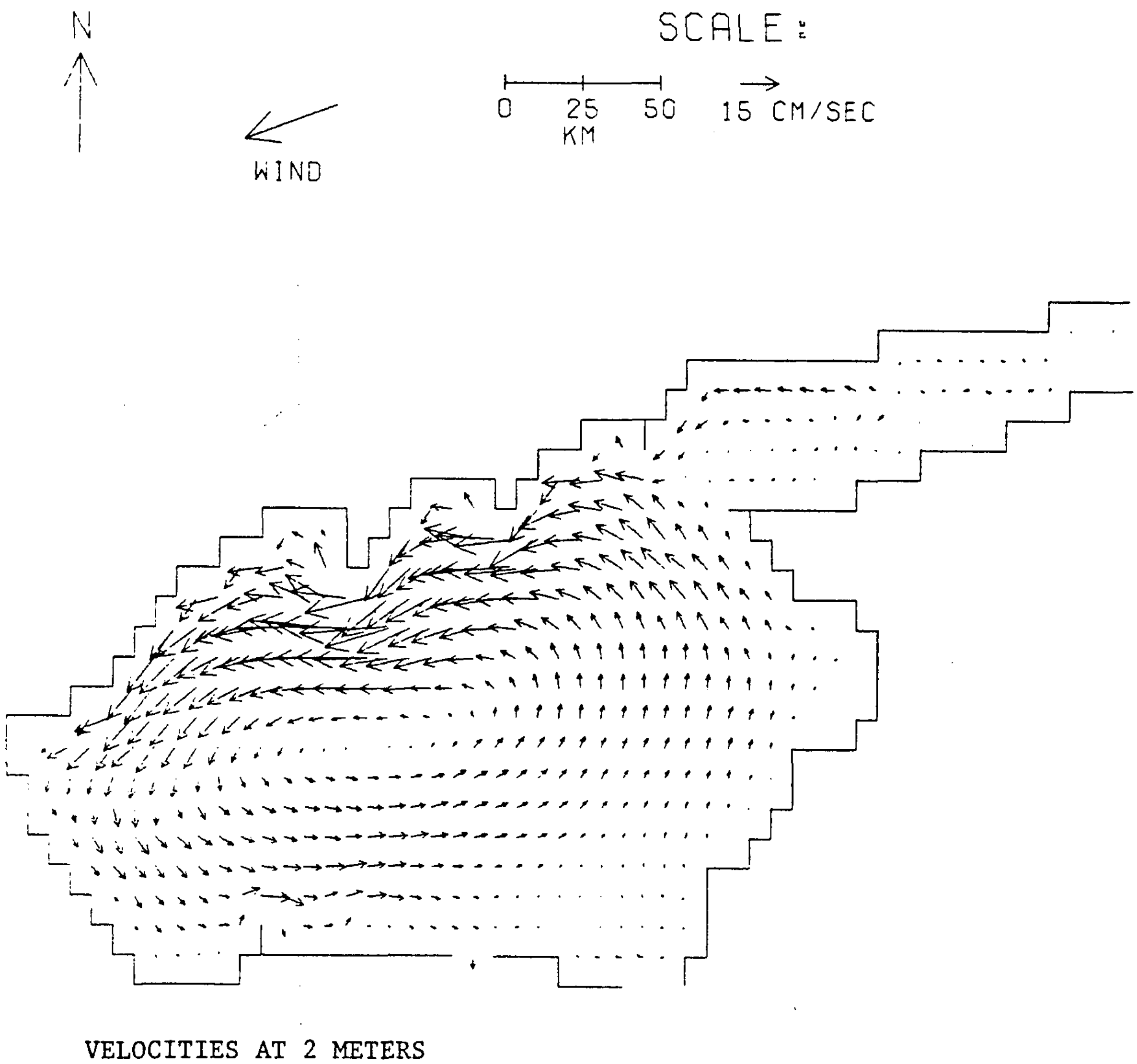
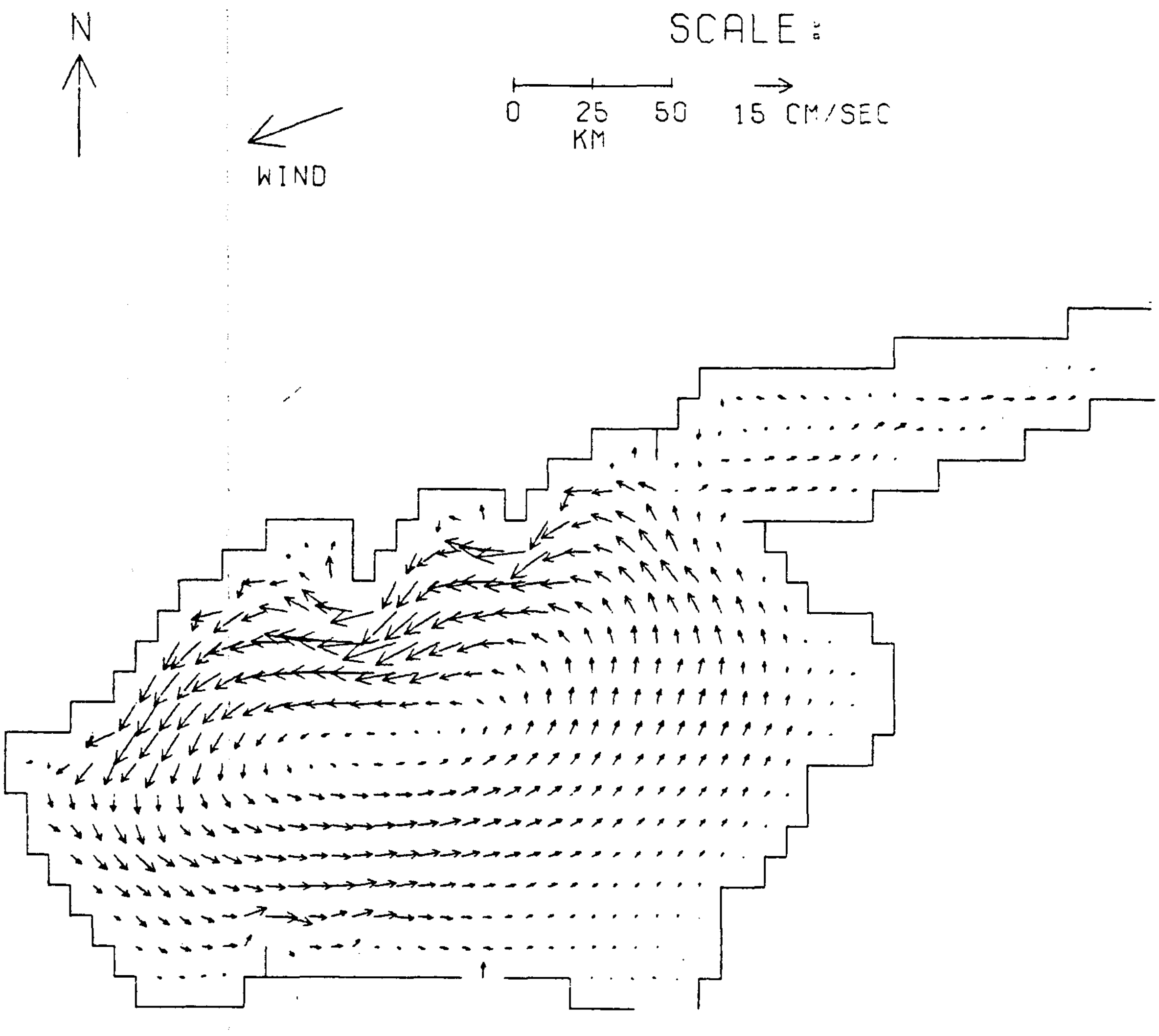
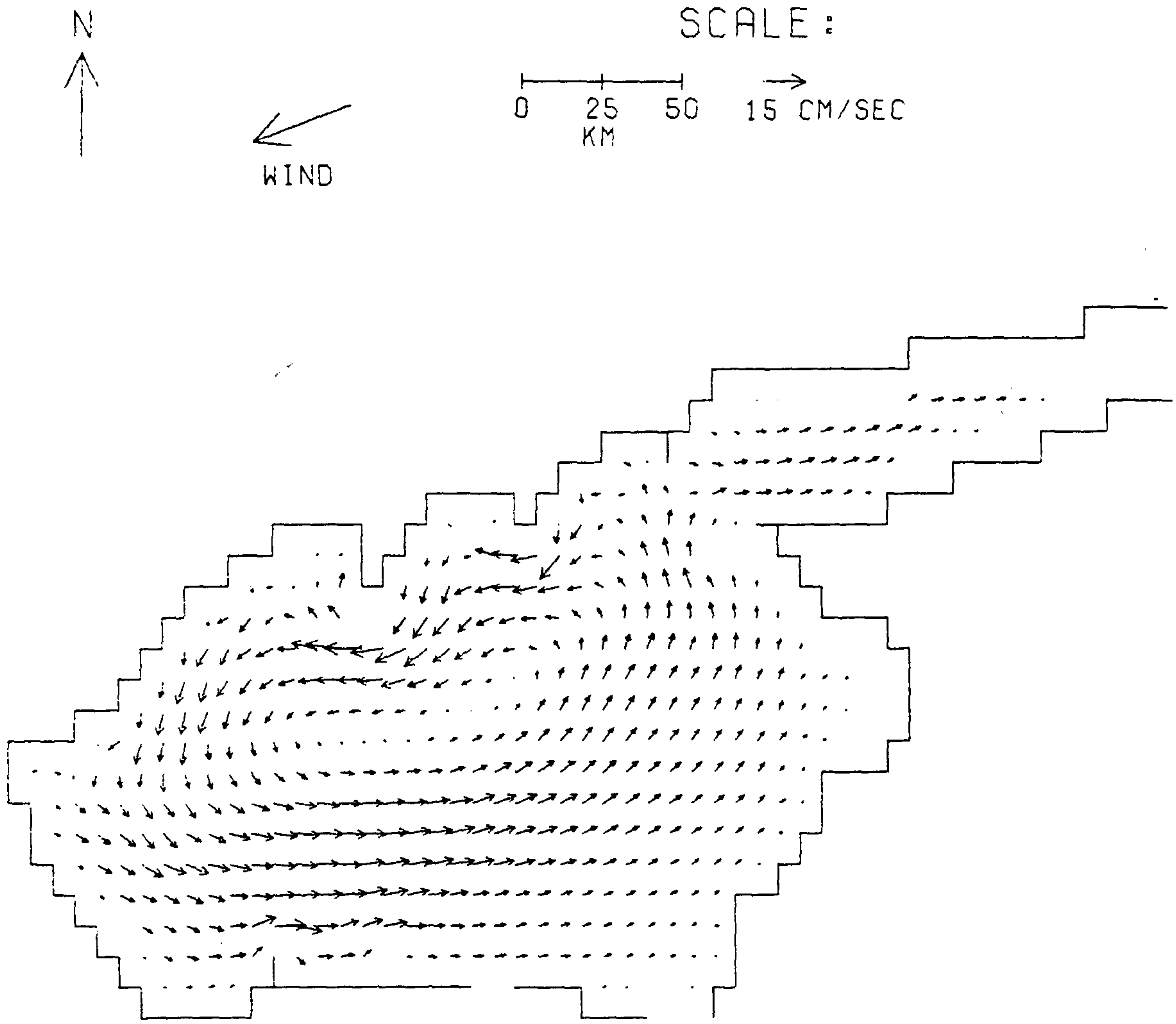


Figure C-13c. Case 1 hydrodynamic model calculation for Sea of Azov after 2 days.



VELOCITIES AT 3 METERS

Figure C-13d. Case 1 hydrodynamic model calculation for Sea of Azov after 2 days.



VELOCITIES AT 5 METERS

Figure C-13e. Case 1 hydrodynamic model calculation for Sea of Azov after 2 days.

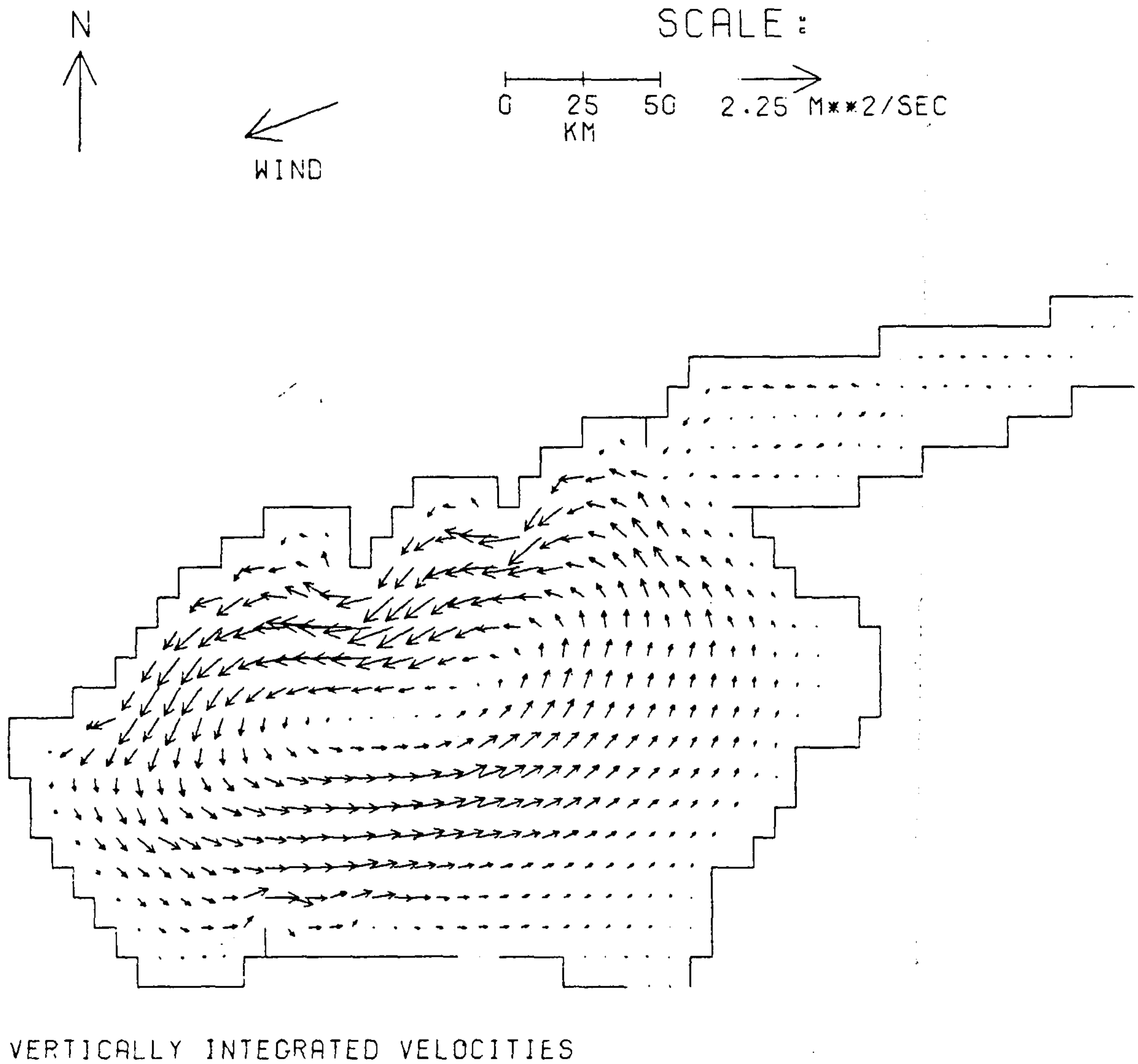


Figure C-13f. Case 1 hydrodynamic model calculation for Sea of Azov after 2 days.

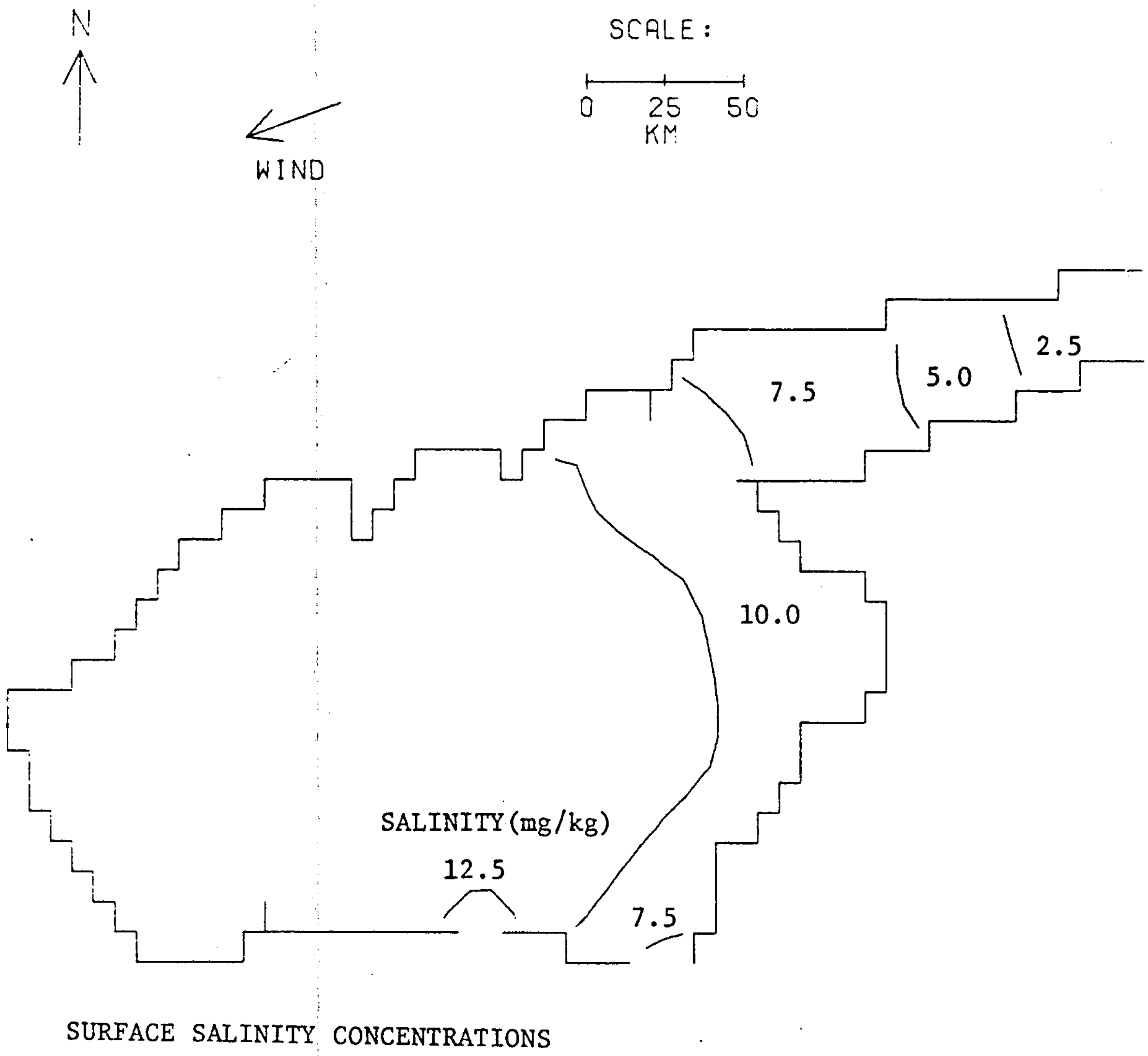


Figure C-13g. Case 1 hydrodynamic model calculation for Sea of Azov after 2 days.

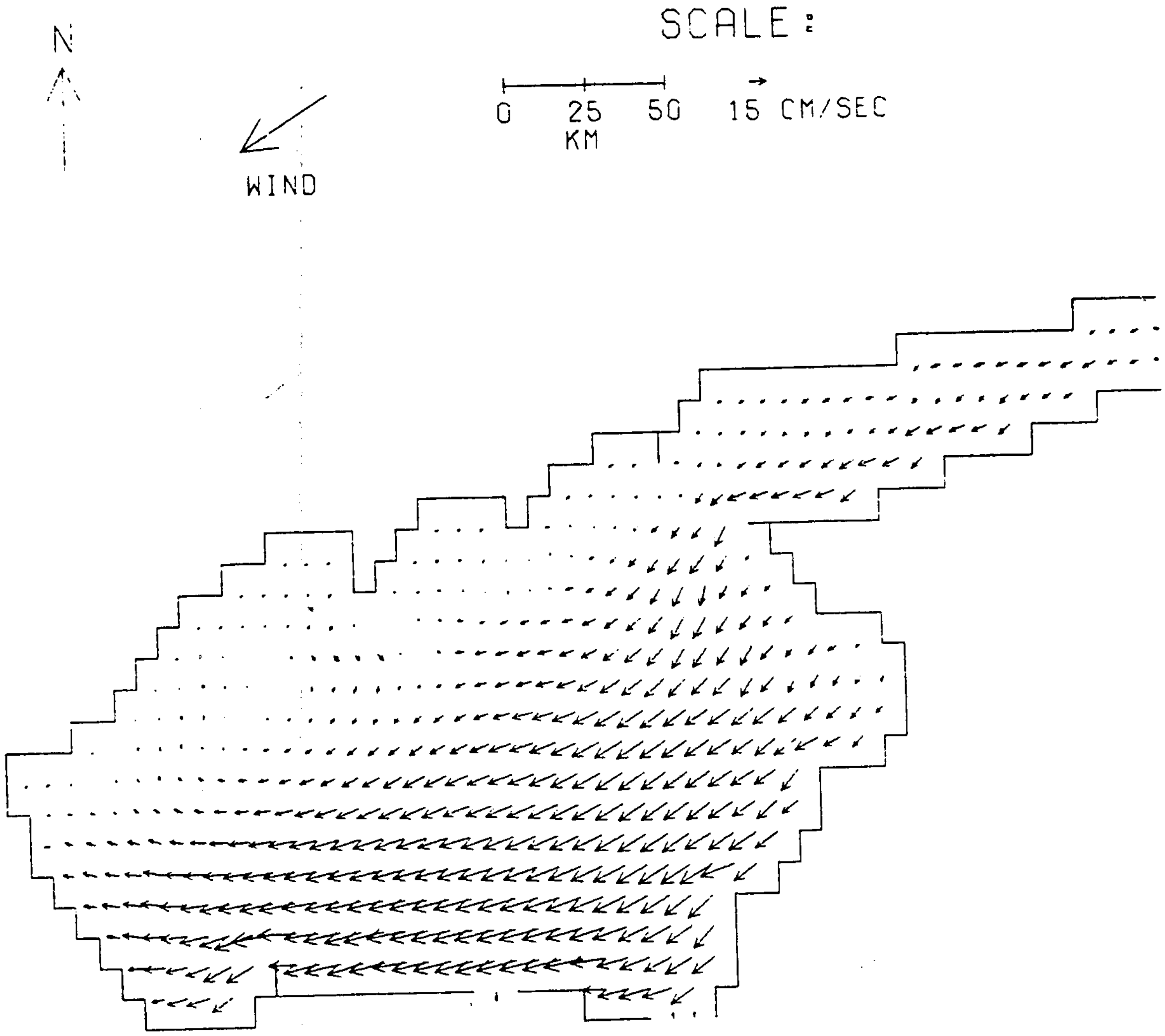


Figure C-14a. Case 2 hydrodynamic model calculation for Sea of Azov after 2 days.

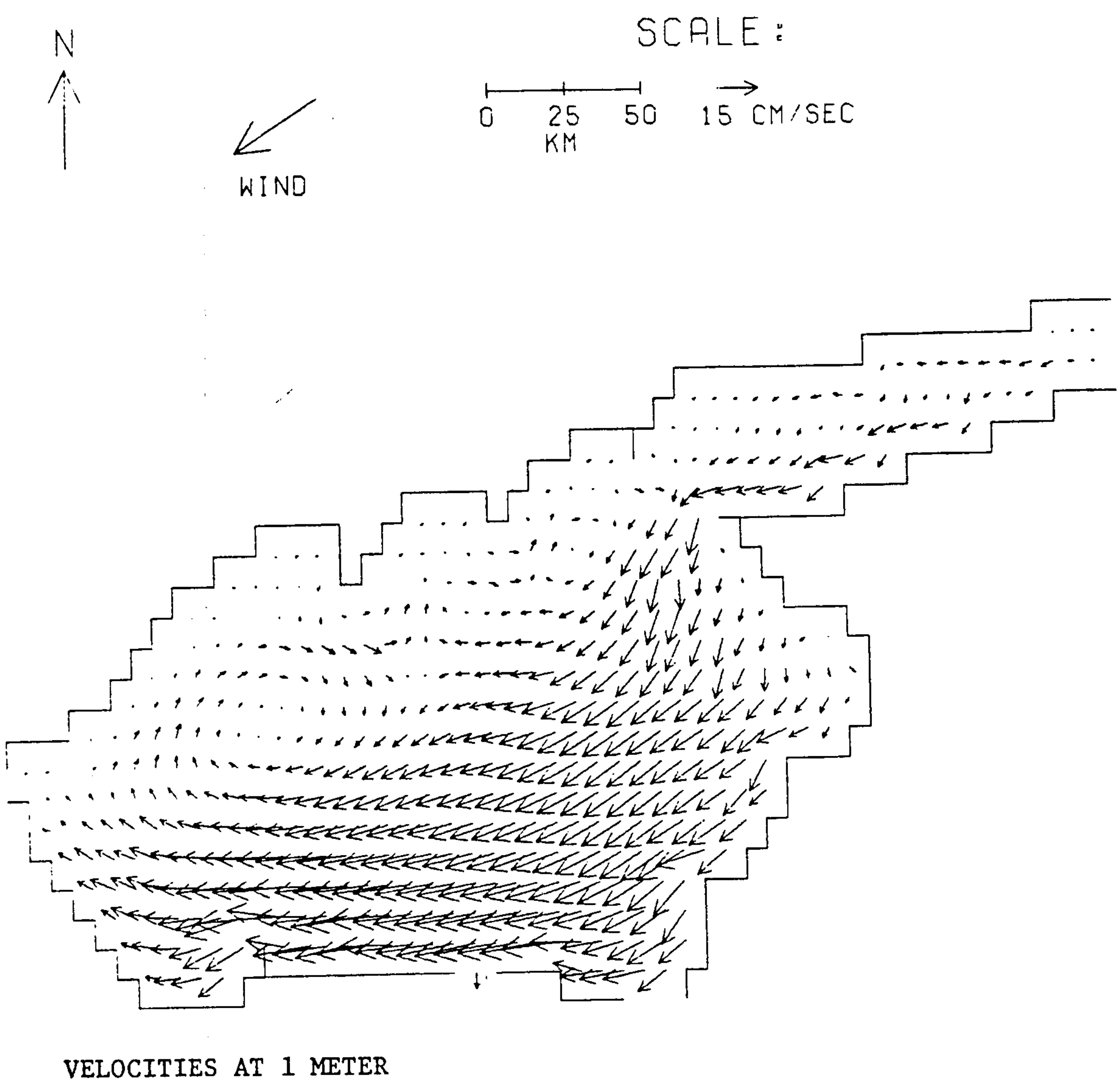
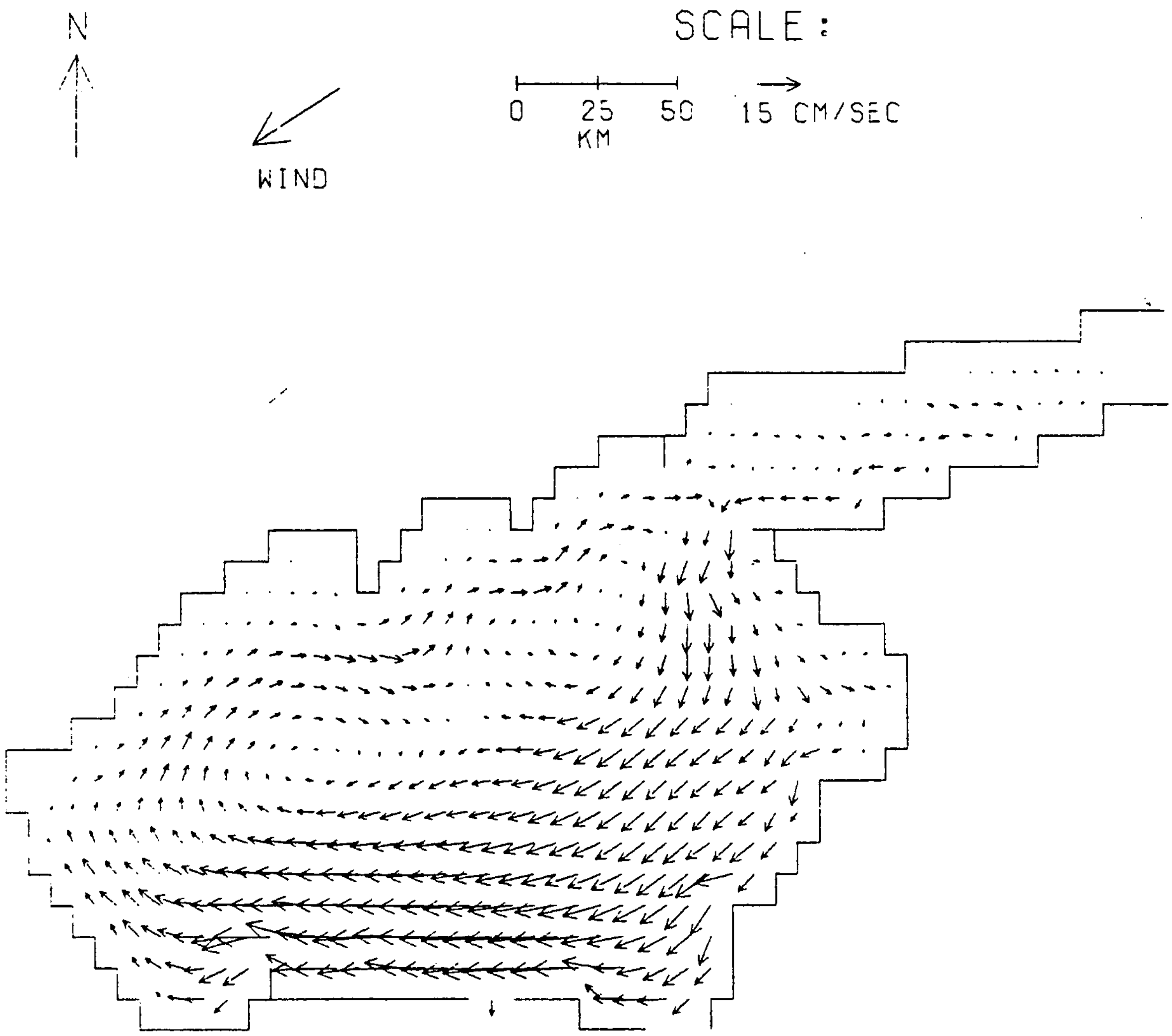


Figure C-14b. Case 2 hydrodynamic model calculation for Sea of Azov after 2 days.



VELOCITIES AT 2 METERS

Figure C-14c. Case 2 hydrodynamic model calculation for Sea of Azov after 2 days.

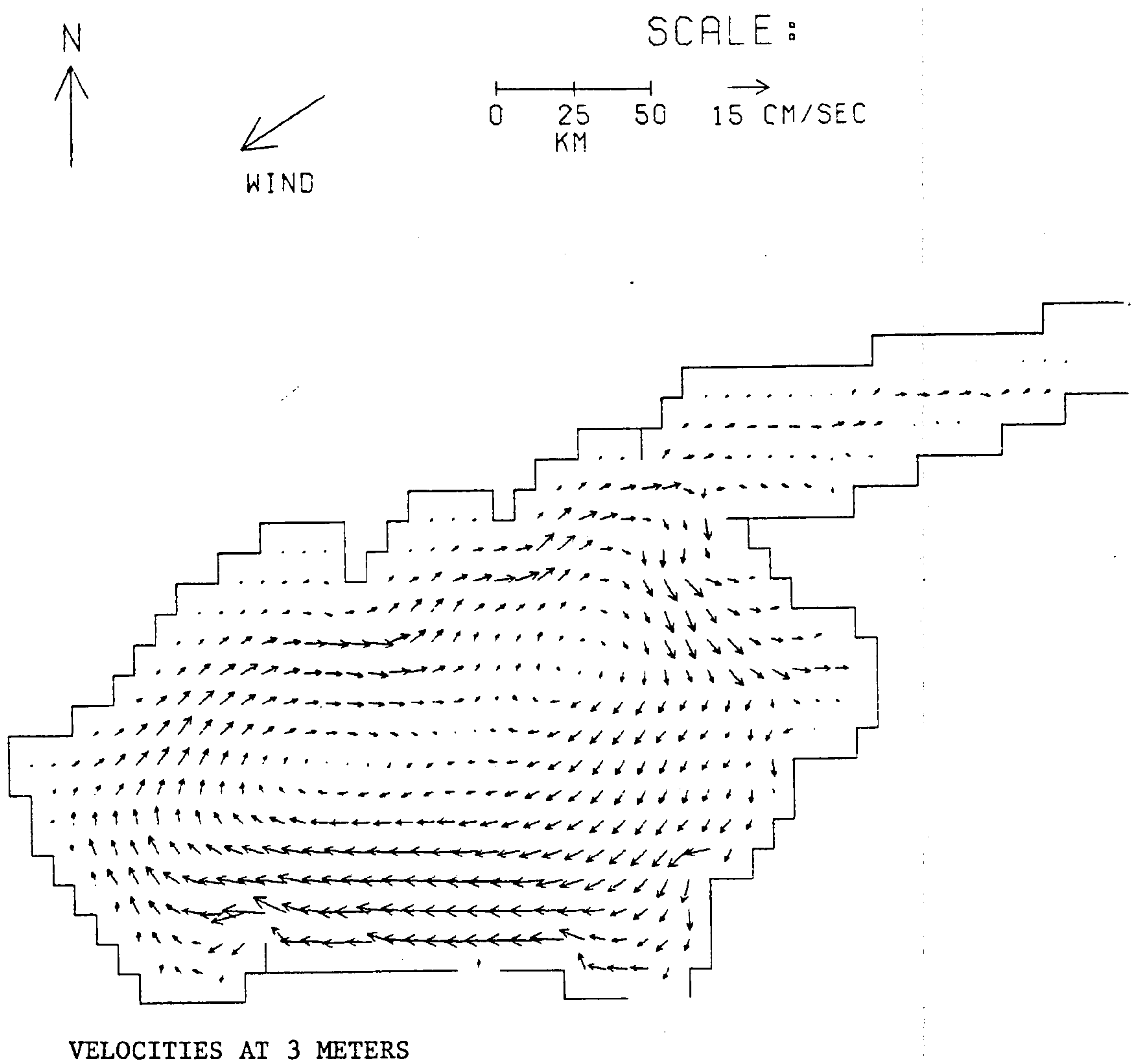
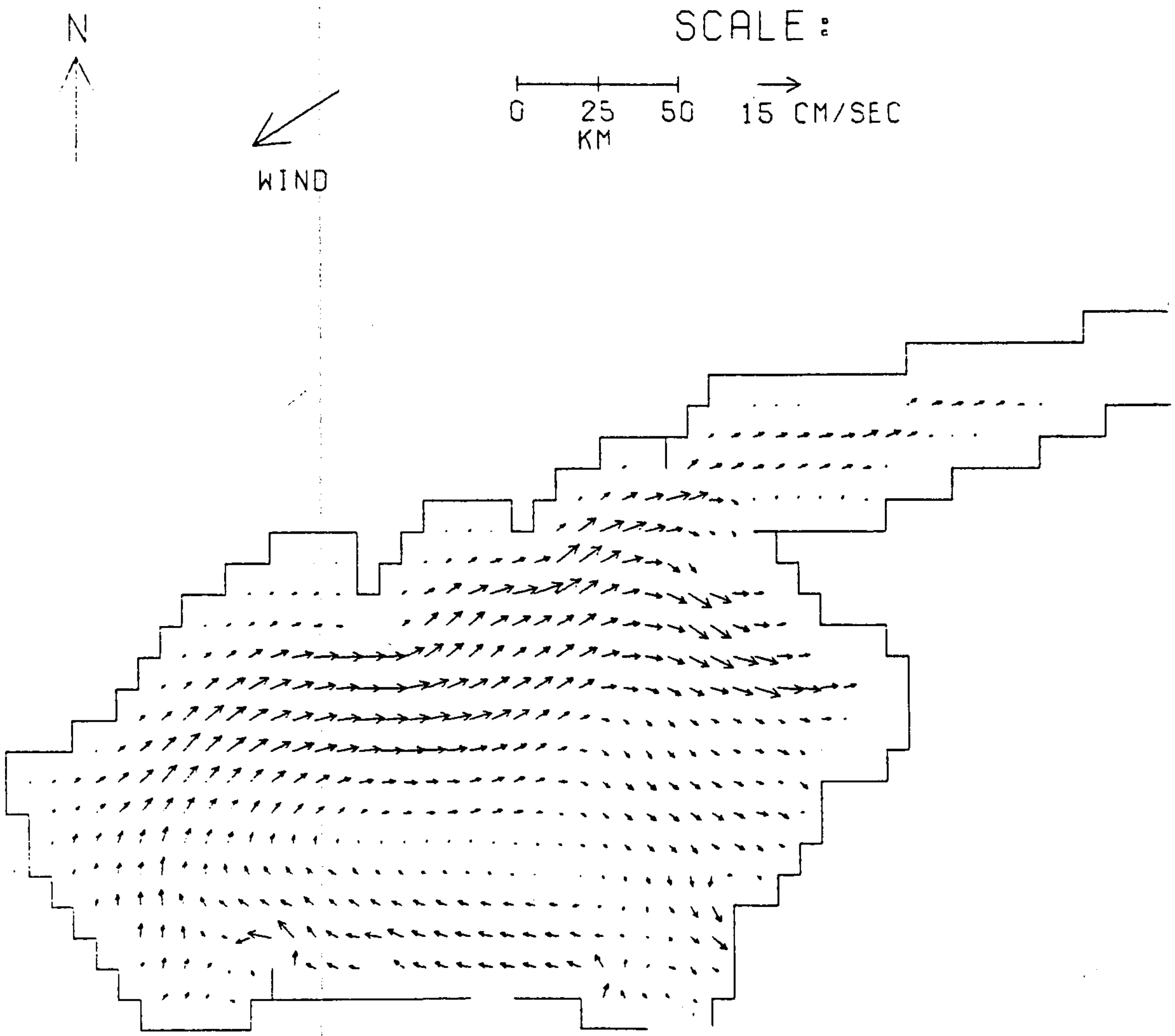


Figure C-14d. Case 2 hydrodynamic model calculation for Sea of Azov after 2 days.



VELOCITIES AT 5 METERS

Figure C-14e. Case 2 hydrodynamic model calculation for Sea of Azov after 2 days.

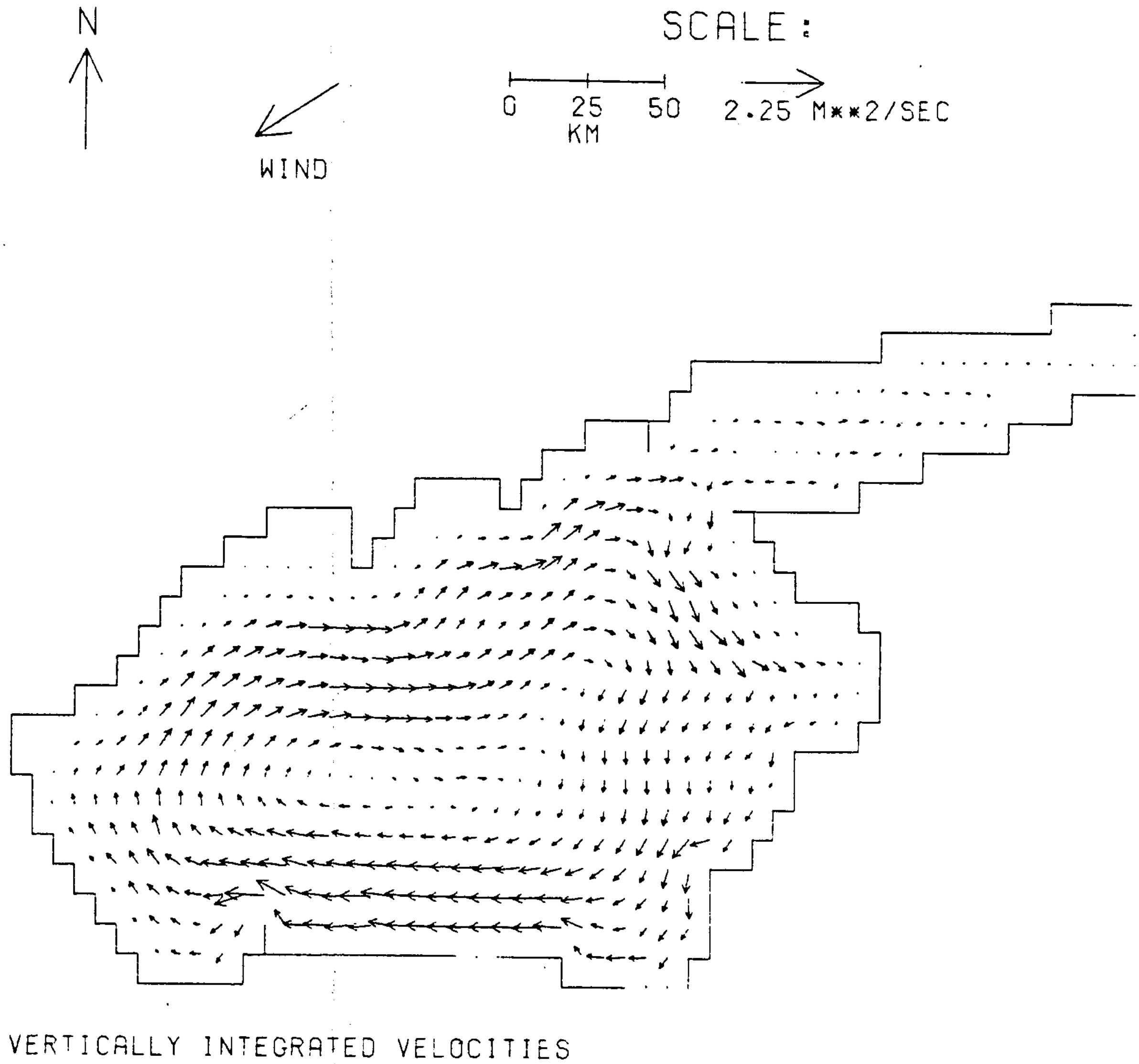


Figure C-14f. Case 2 hydrodynamic model calculation for Sea of Azov after 2 days.

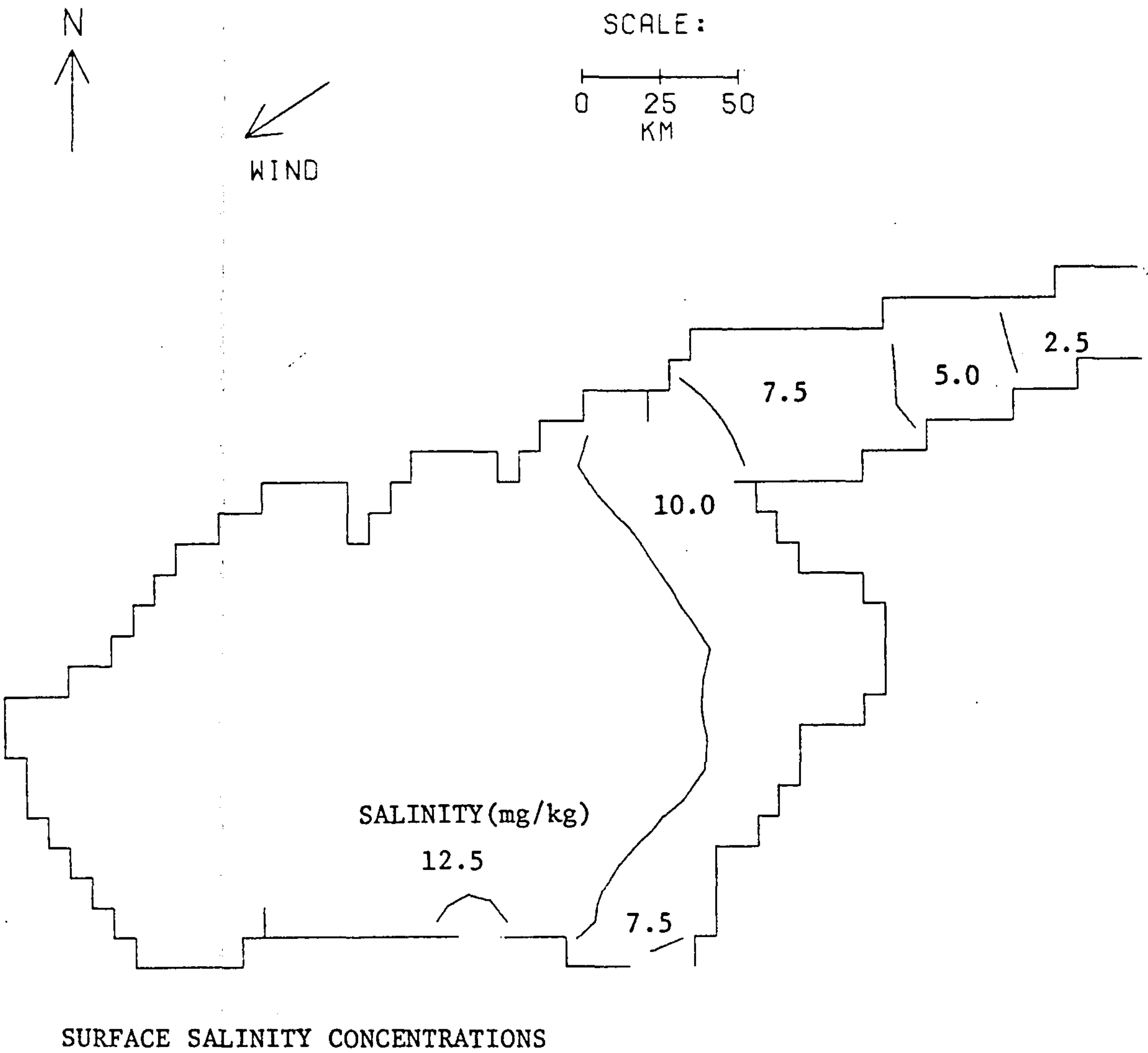
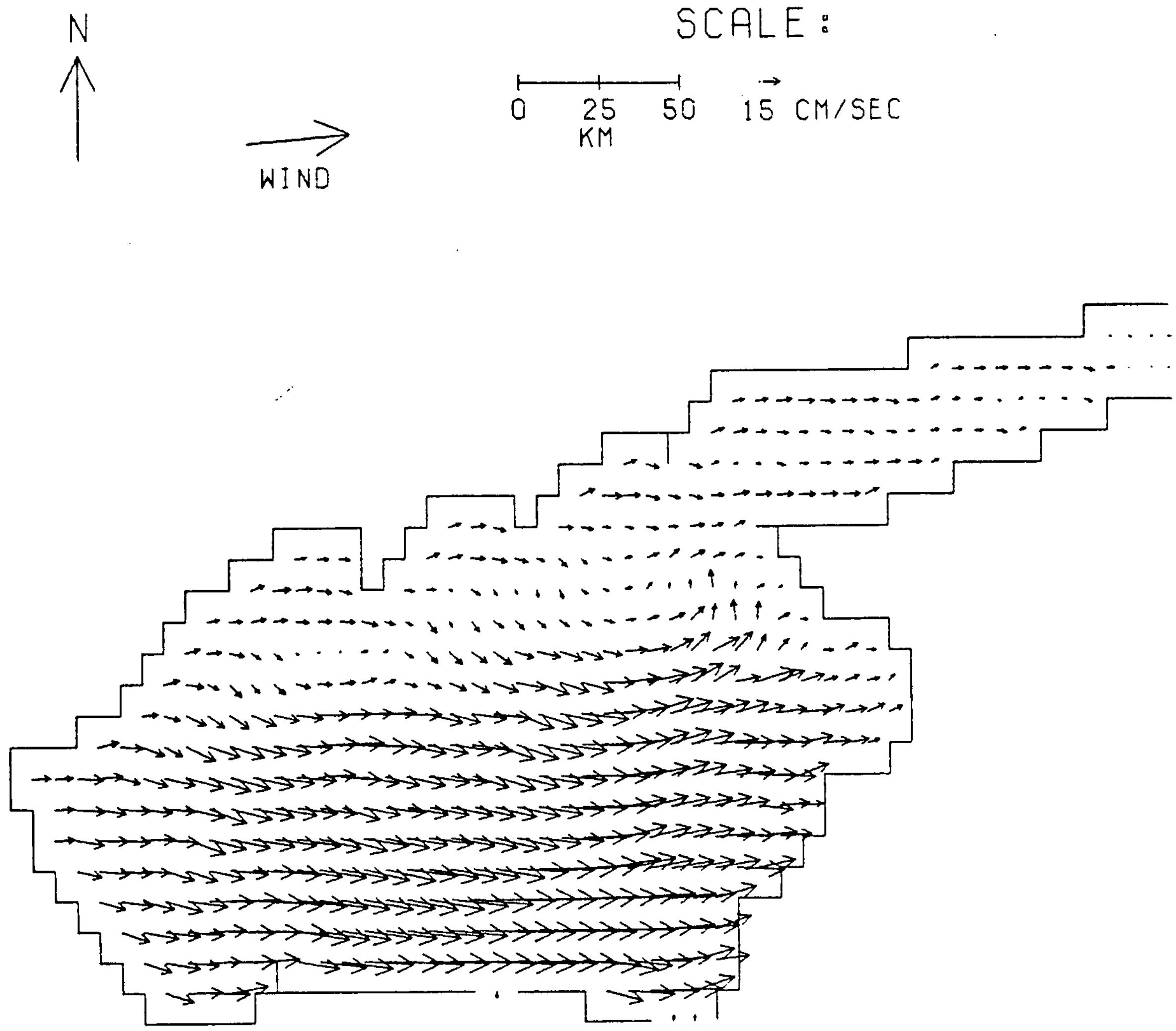
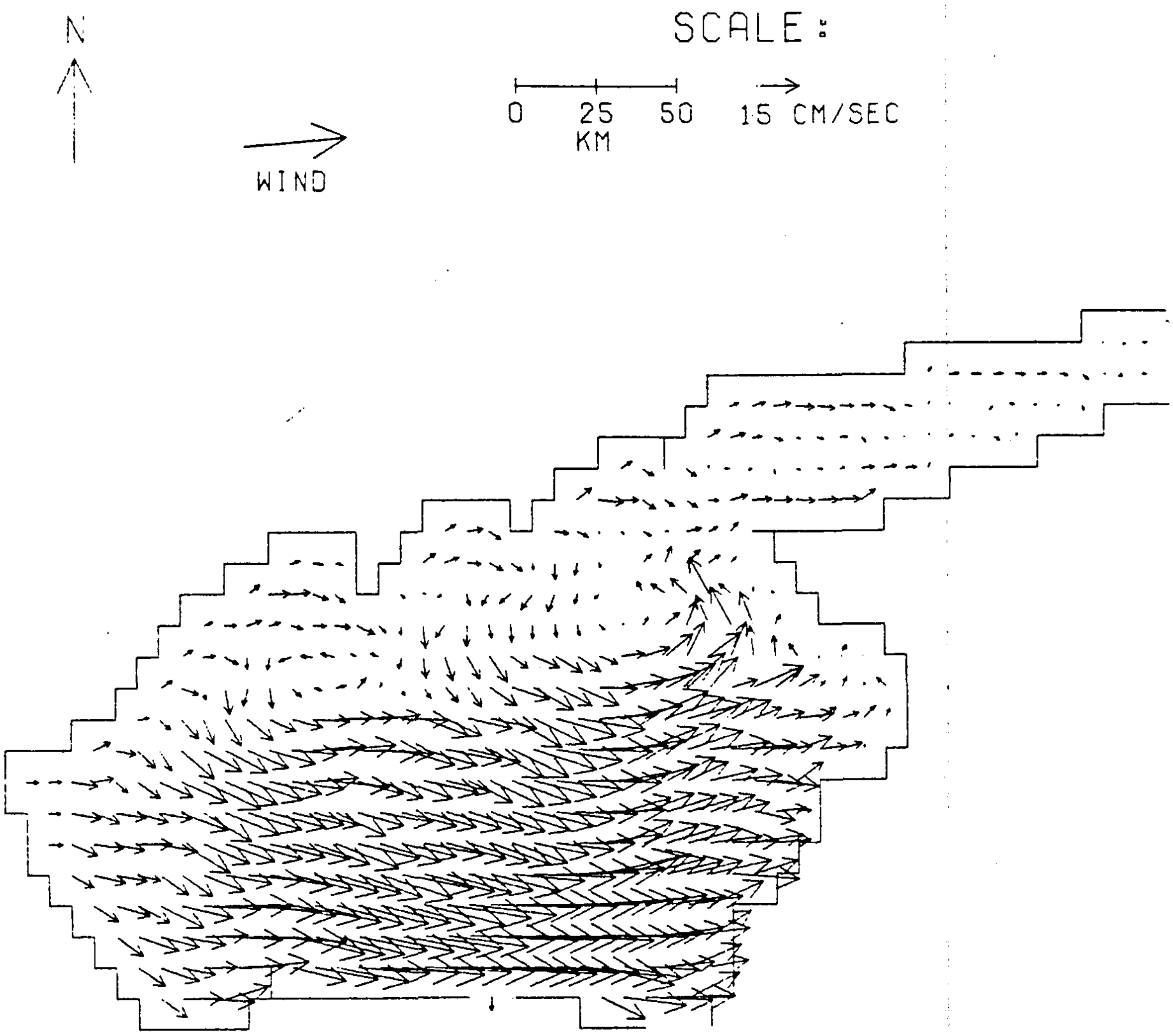


Figure C-14g. Case 2 hydrodynamic model calculation for Sea of Azov after 2 days.



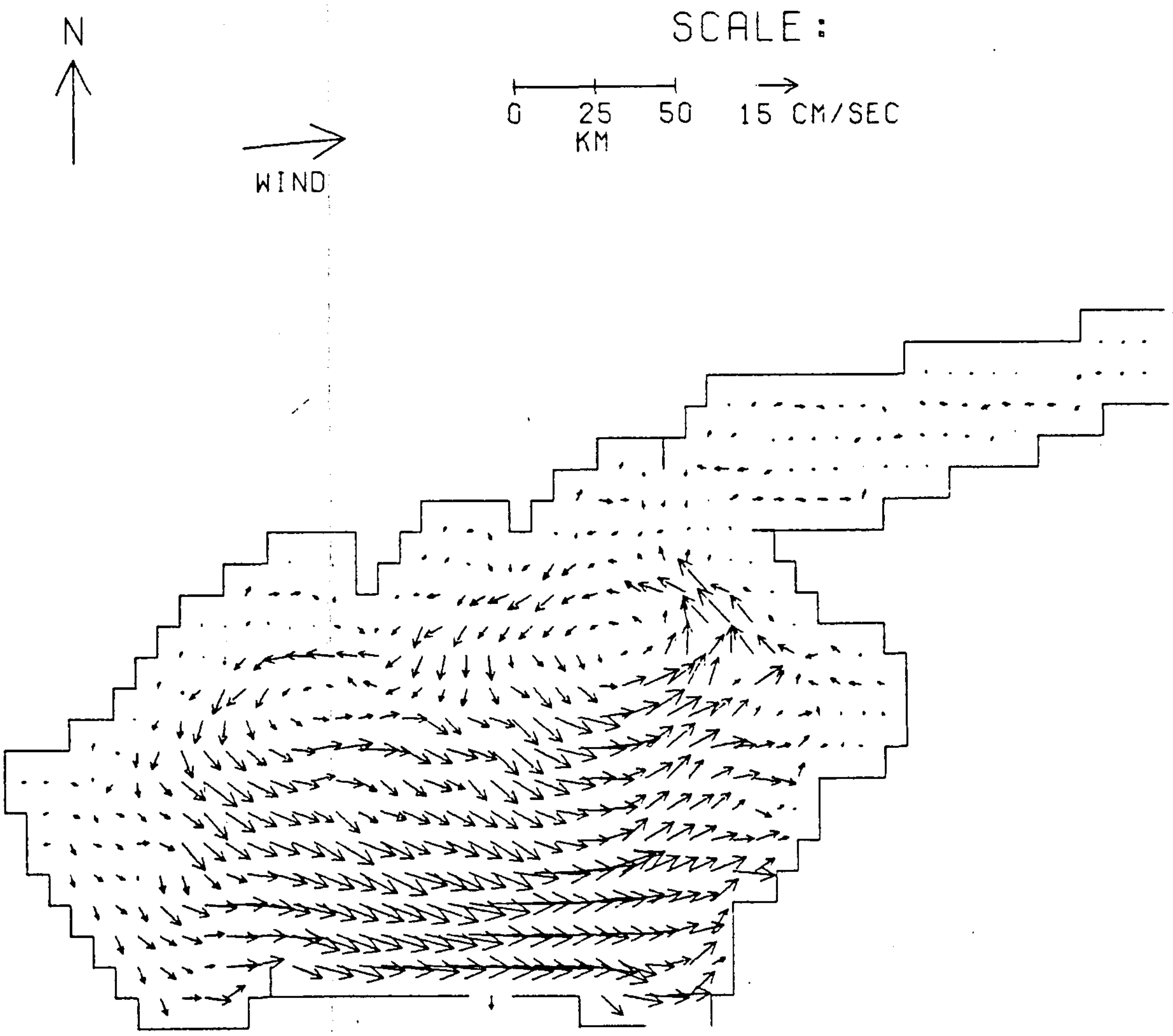
SURFACE VELOCITIES

Figure C-15a. Case 3 (variable wind) hydrodynamic model calculations for Sea of Azov after 2 days.



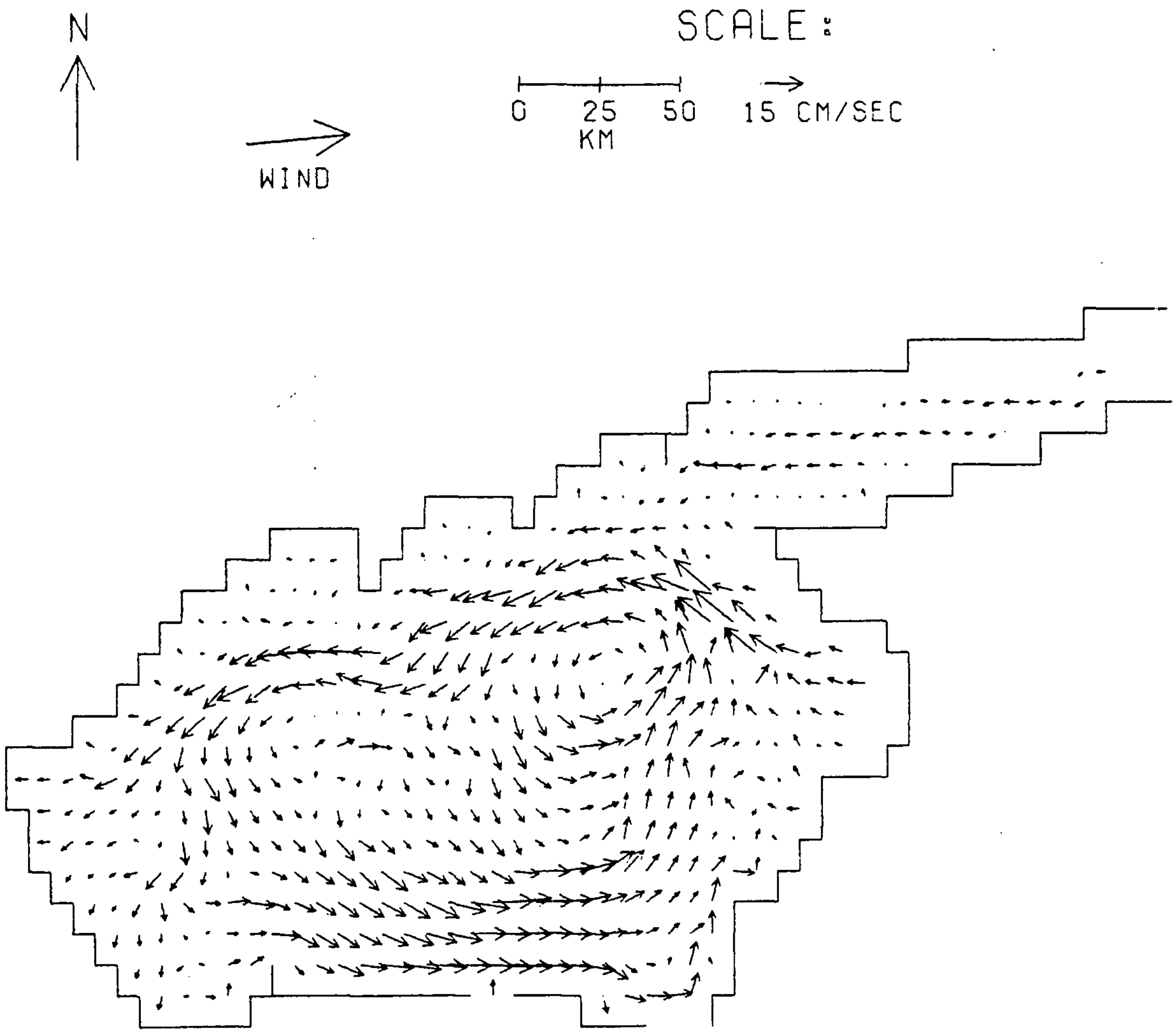
VELOCITIES AT 1 METER

Figure C-15b. Case 3 (variable wind) hydrodynamic model calculations for Sea of Azov after 2 days.



VELOCITIES AT 2 METERS

Figure C-15c. Case 3 (variable wind) hydrodynamic model calculation for Sea of Azov after 2 days.



VELOCITIES AT 3 METERS

Figure C-15d. Case 3 (variable wind) hydrodynamic model calculations for Sea of Azov after 2 days.

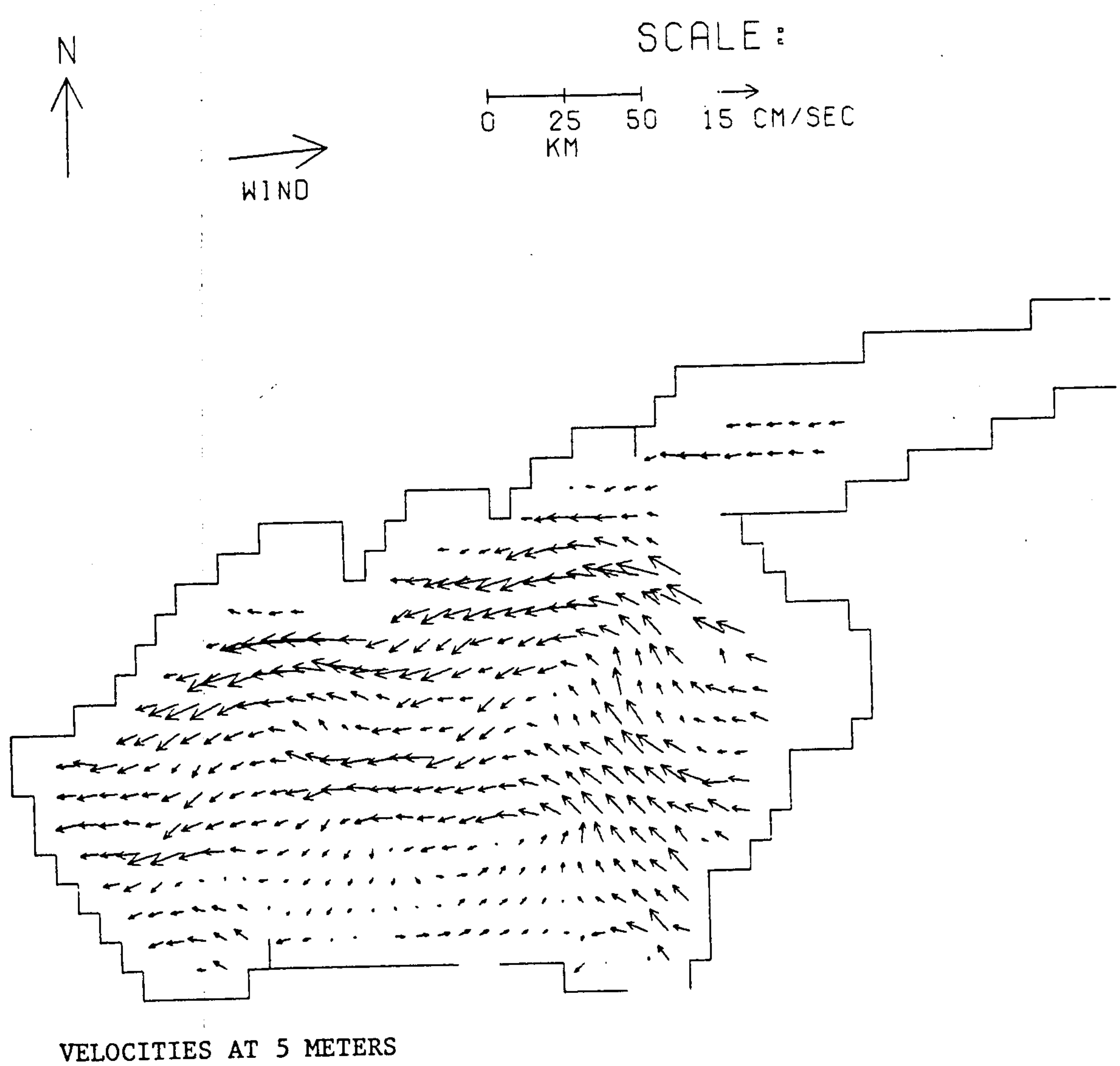


Figure C-15e. Case 3 (variable wind) hydrodynamic model calculation for Sea of Azov after 2 days.

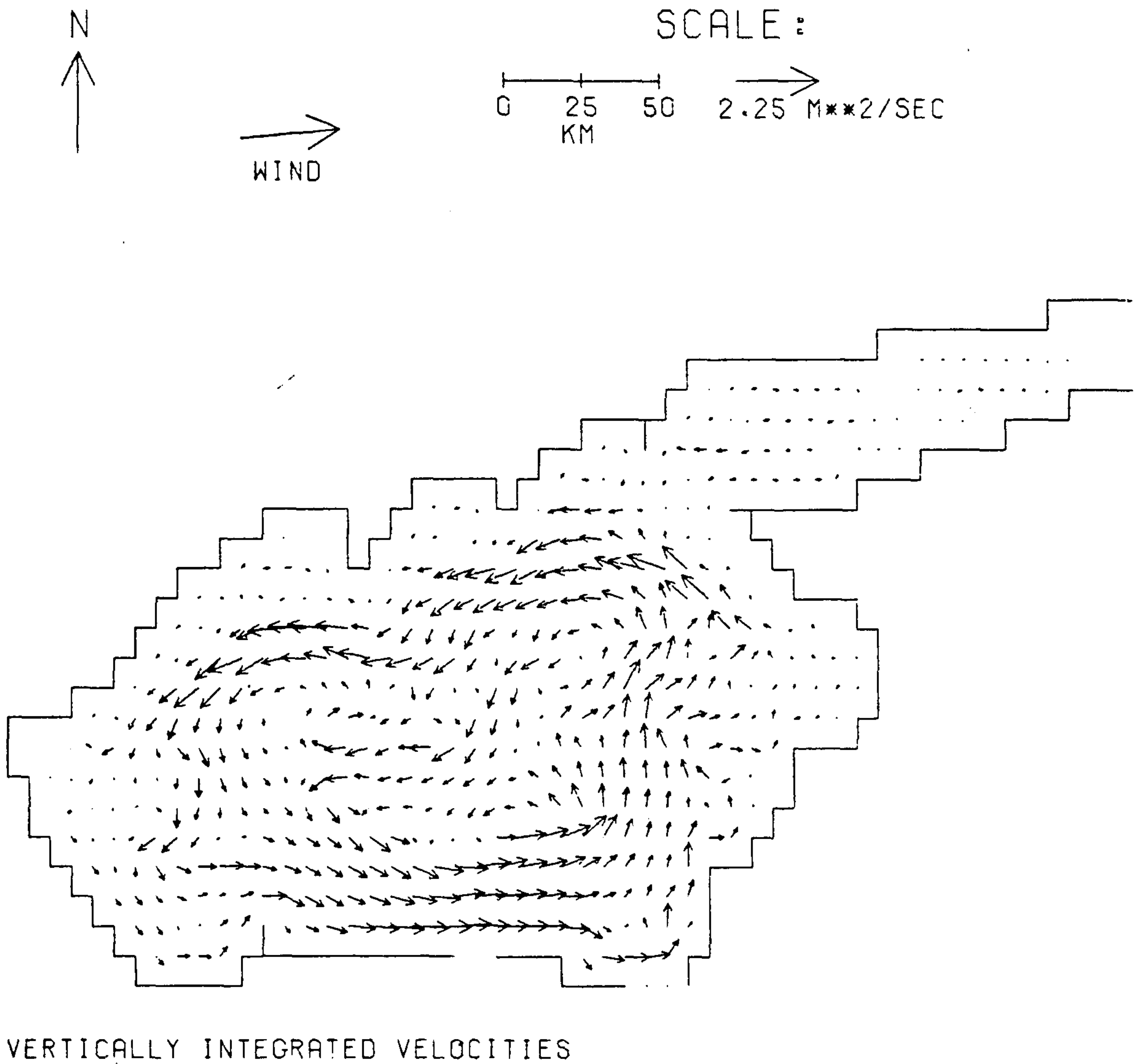


Figure C-15f. Case 3 (variable wind) hydrodynamic model calculation for Sea of Azov after 2 days.

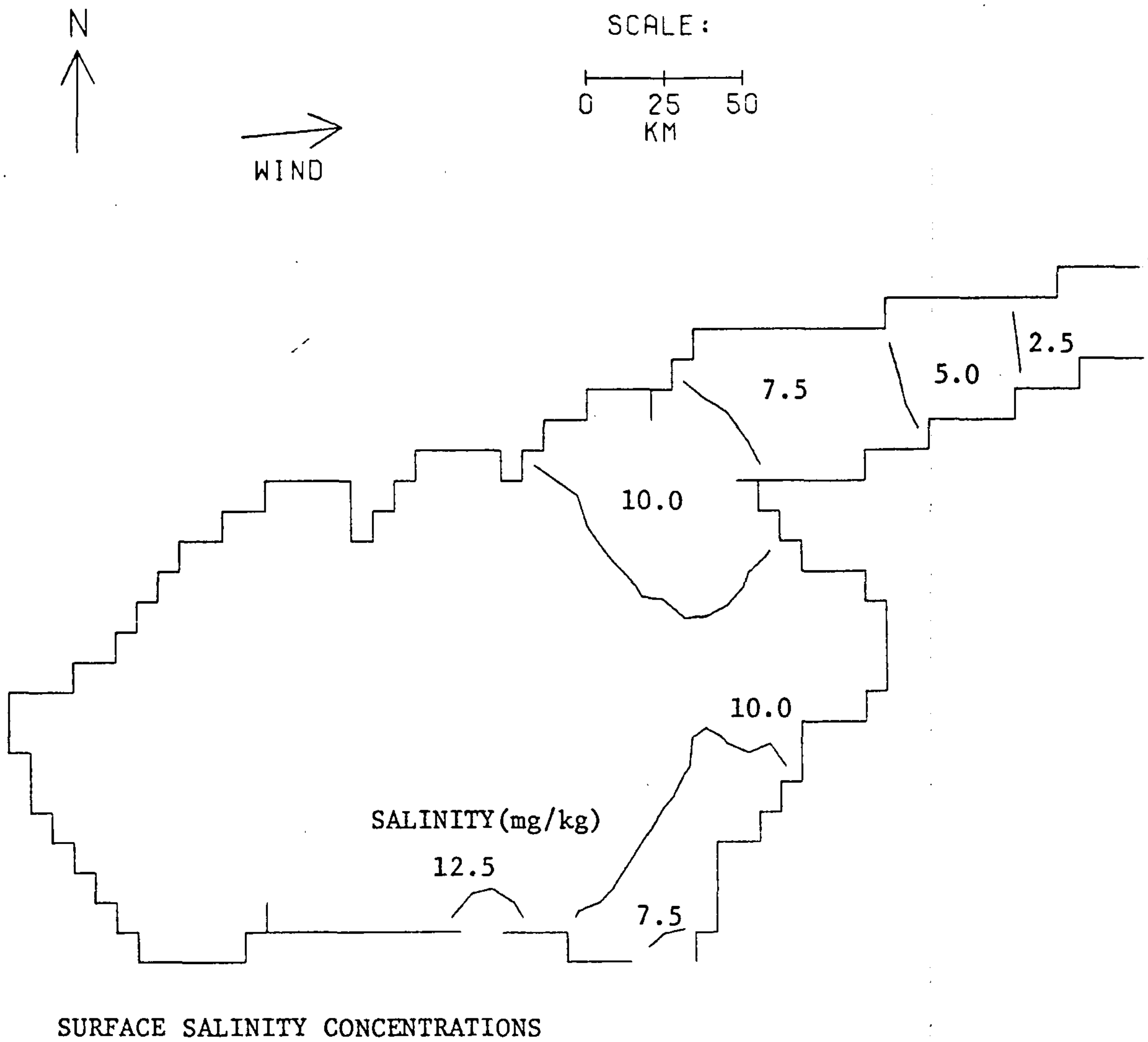
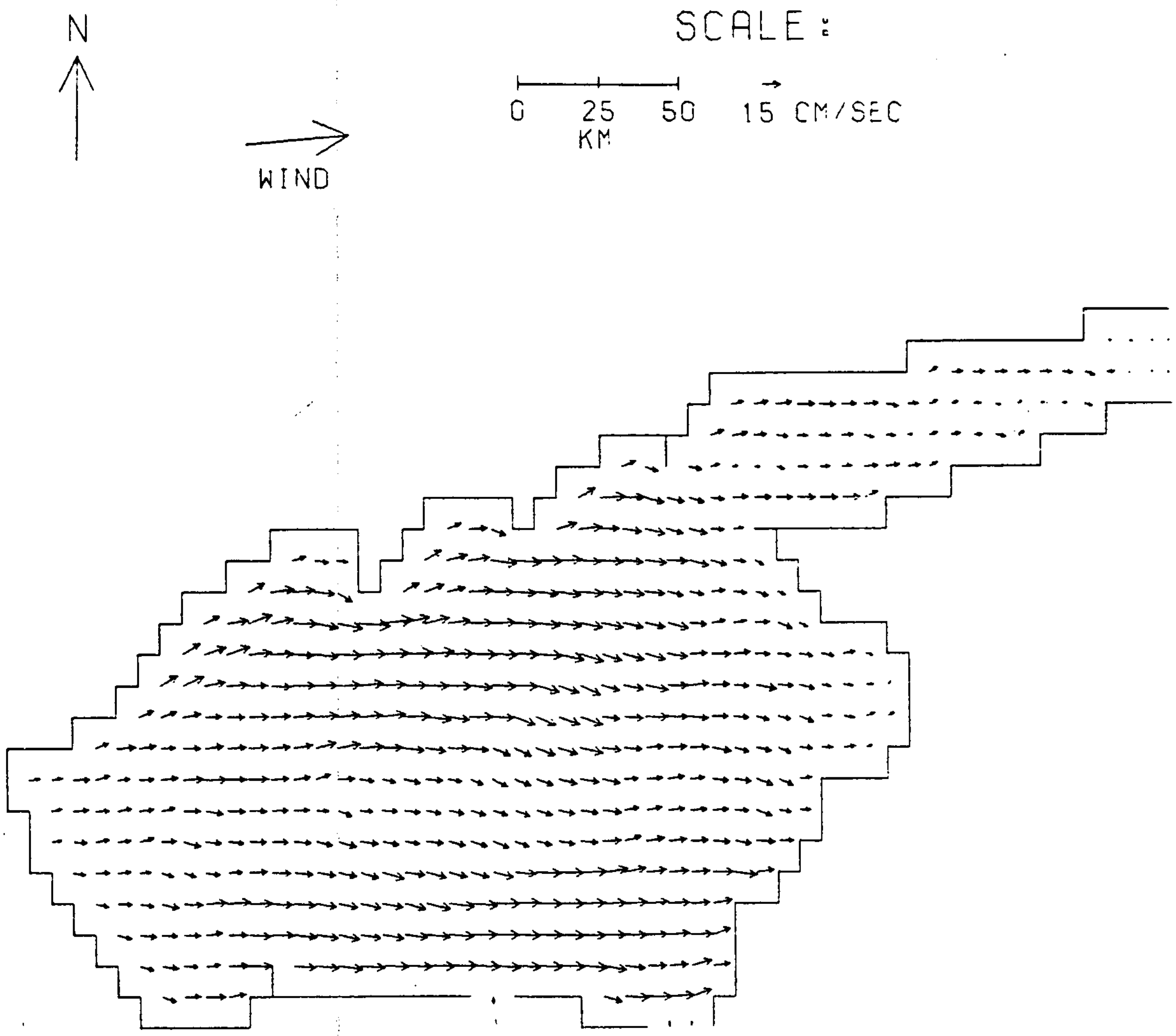
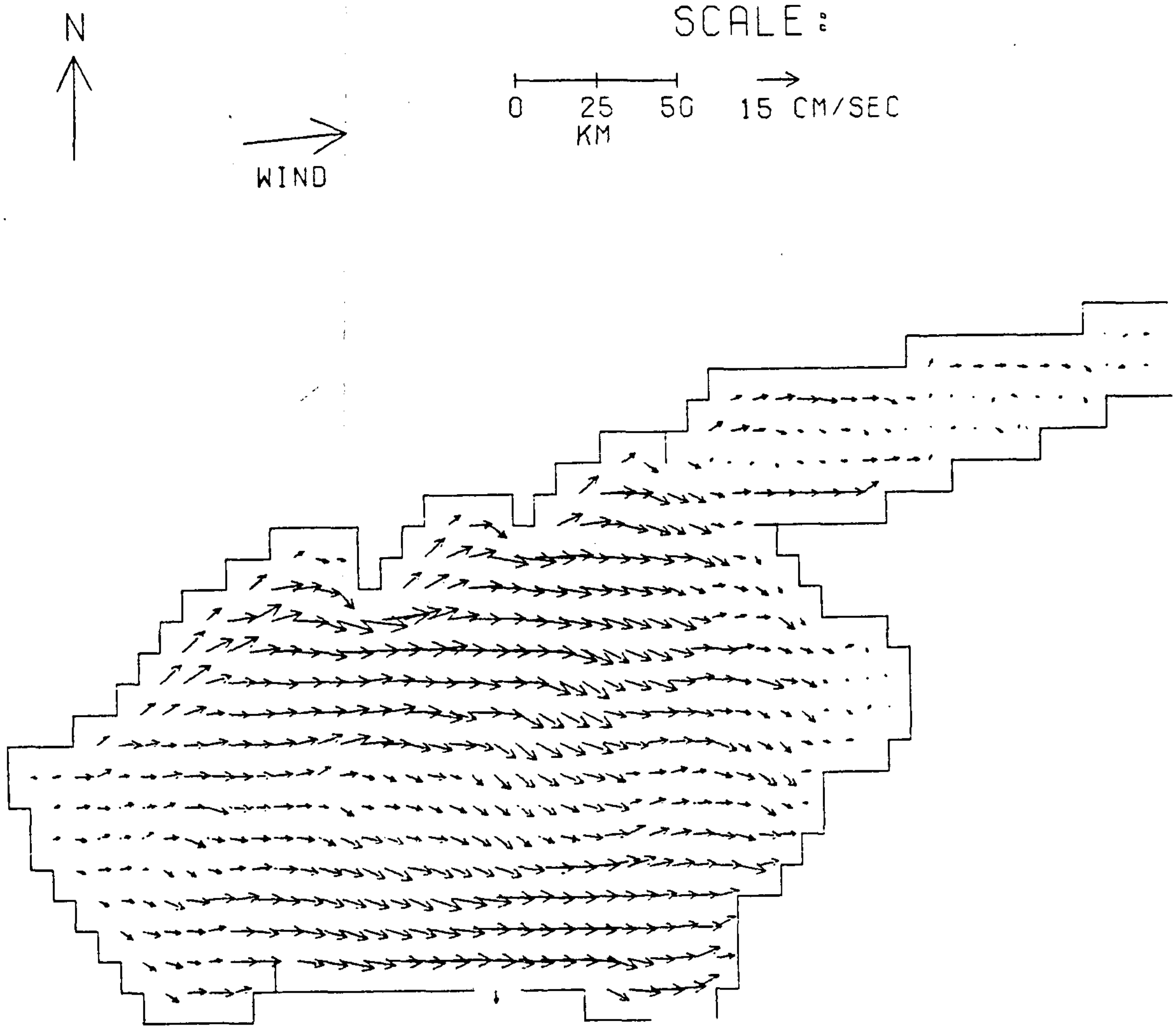


Figure C-15g. Case 2 (variable wind) hydrodynamic model calculation for Sea of Azov after 2 days.



SURFACE VELOCITIES

Figure C-16a. Case 3 (constant wind) hydrodynamic model calculation for Sea of Azov after 2 days.



VELOCITIES AT 1 METER

Figure C-16b. Case 3 (constant wind) hydrodynamic model calculation for Sea of Azov after 2 days.

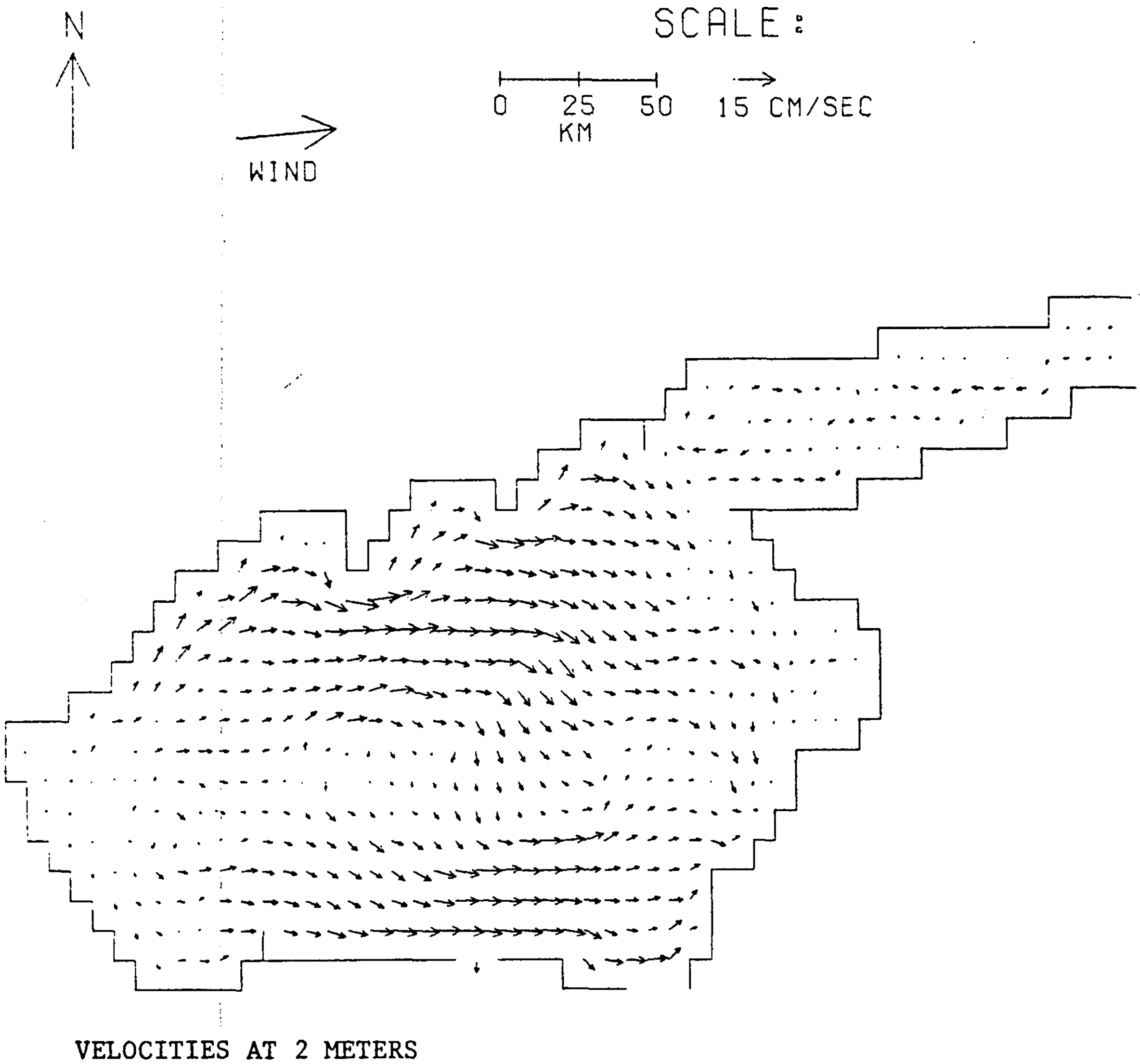


Figure C-16c. Case 3 (constant wind) hydrodynamic model calculation for Sea of Azov after 2 days.

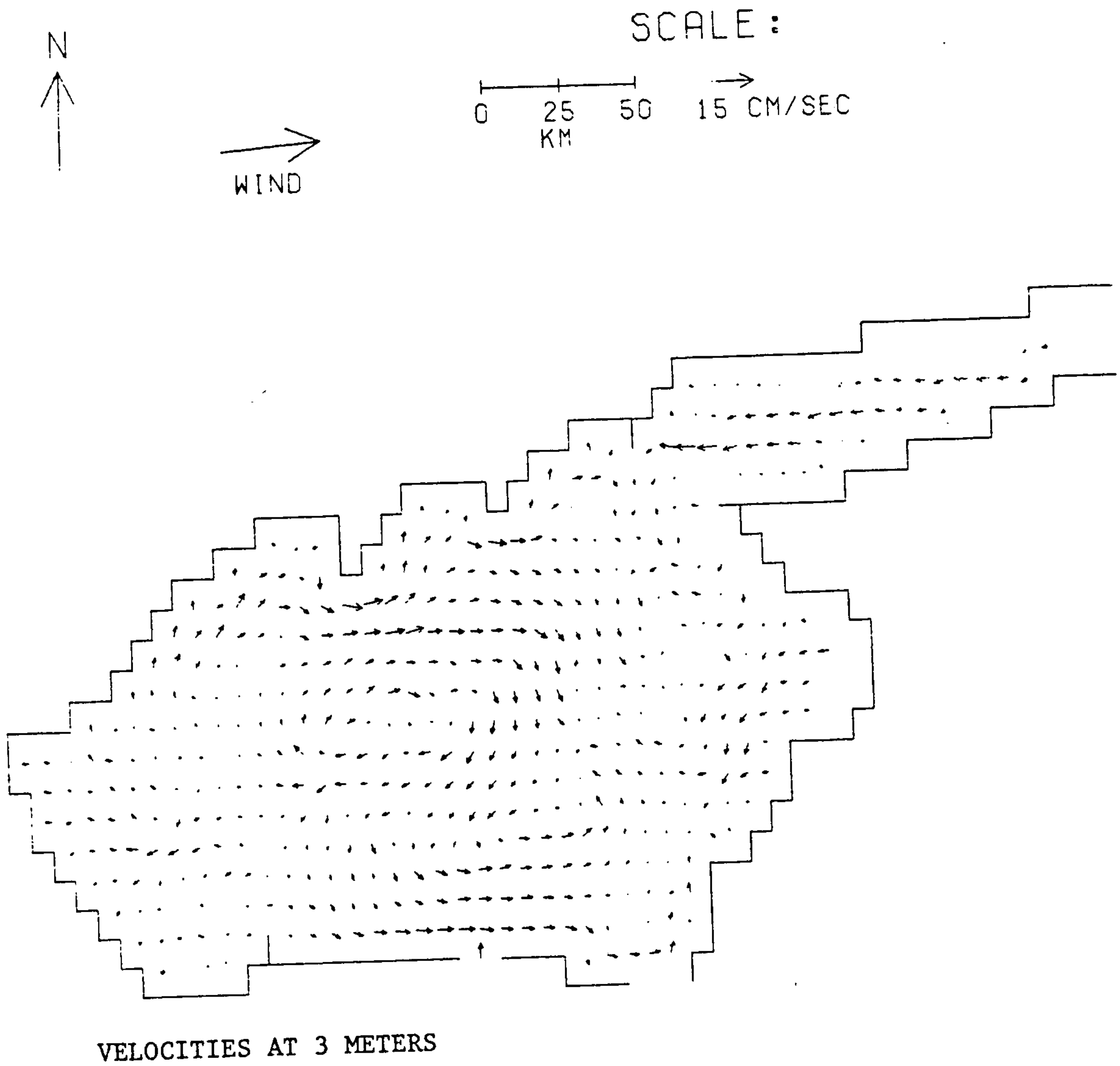


Figure C-16d. Case 3 (constant wind) hydrodynamic model calculation for Sea of Azov after 2 days.

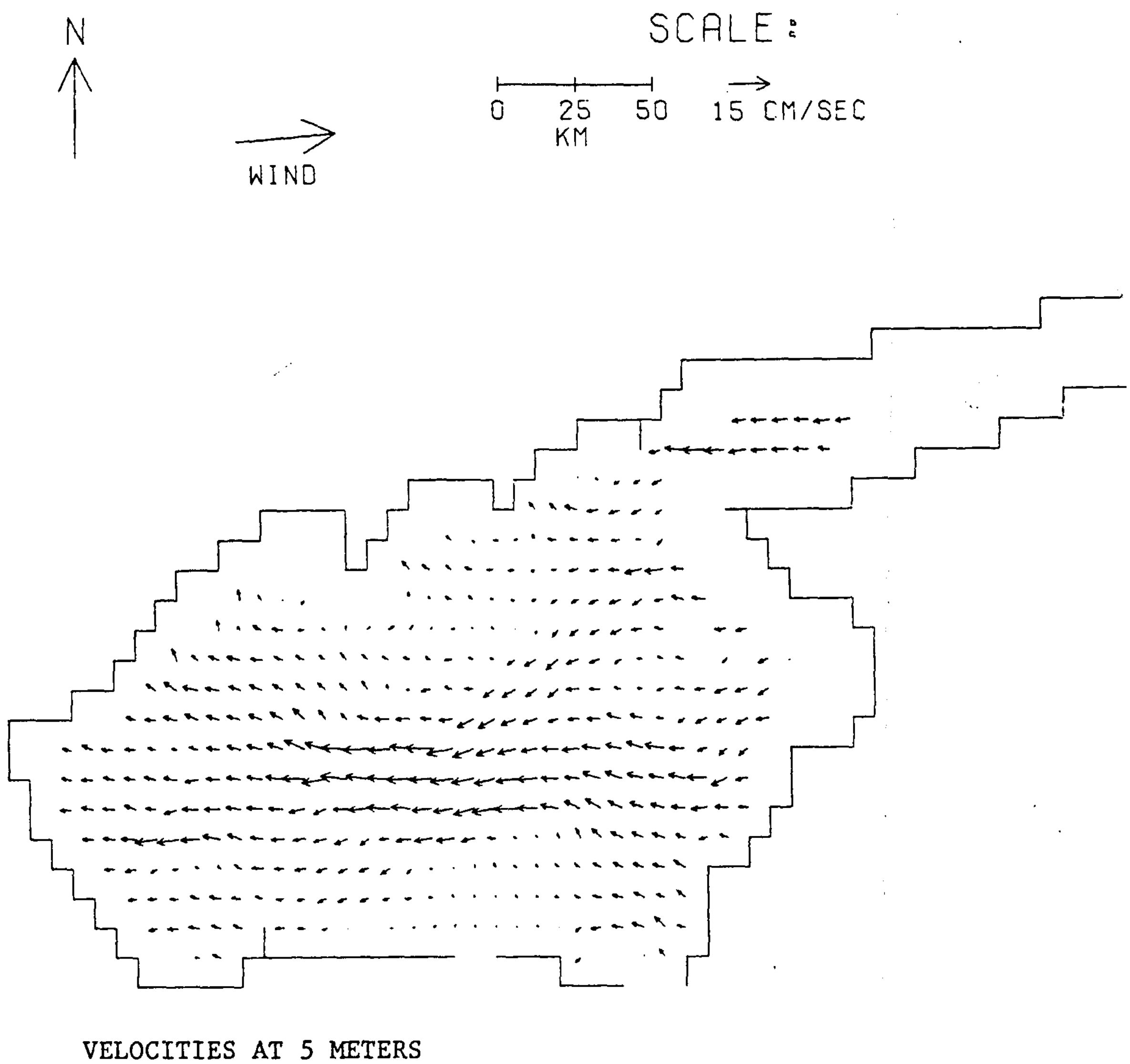


Figure C-16e. Case 3 (constant wind) hydrodynamic model calculation for Sea of Azov after 2 days.

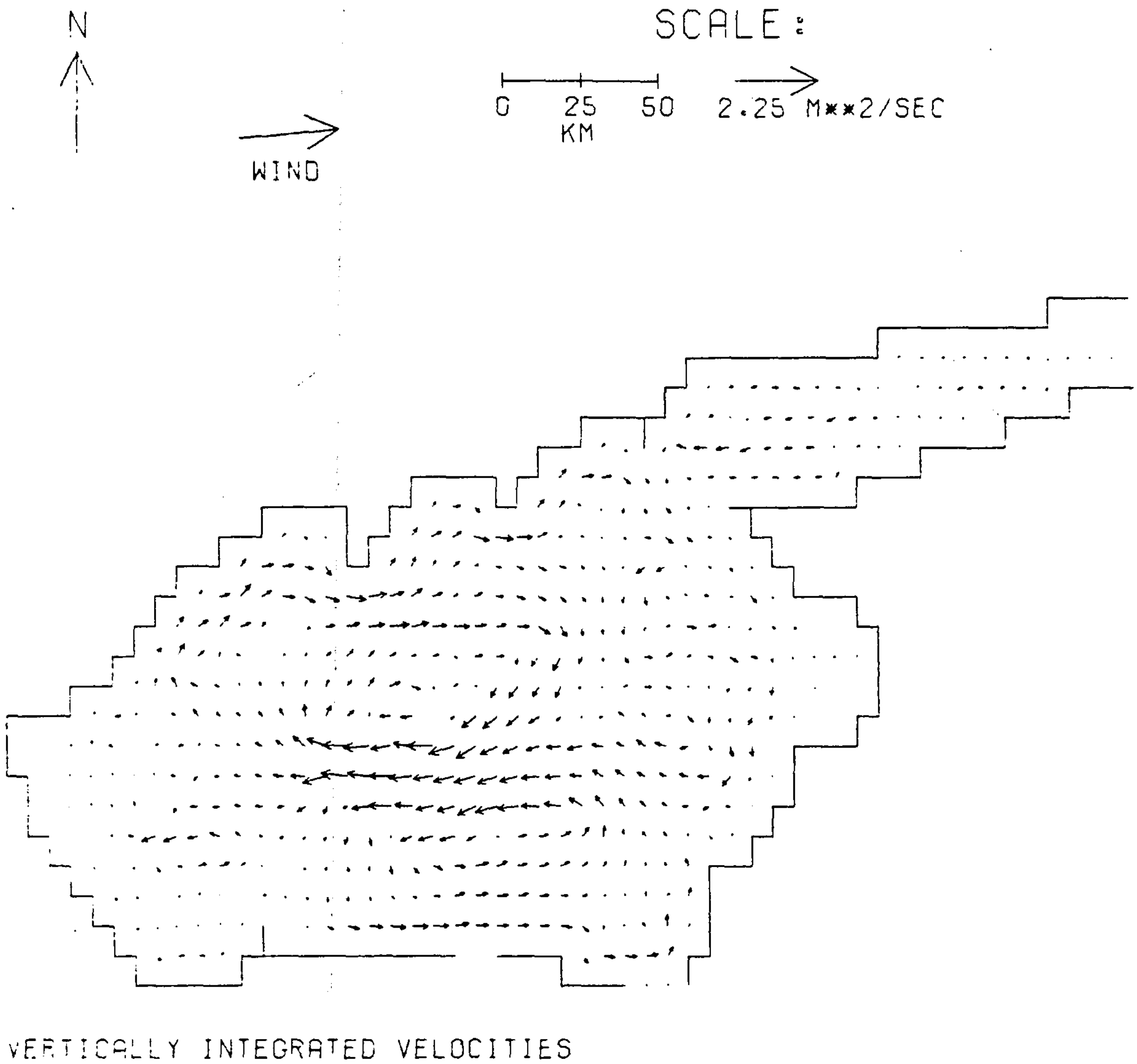


Figure C-16f. Case 3 (constant wind) hydrodynamic model calculation for Sea of Azov after 2 days.

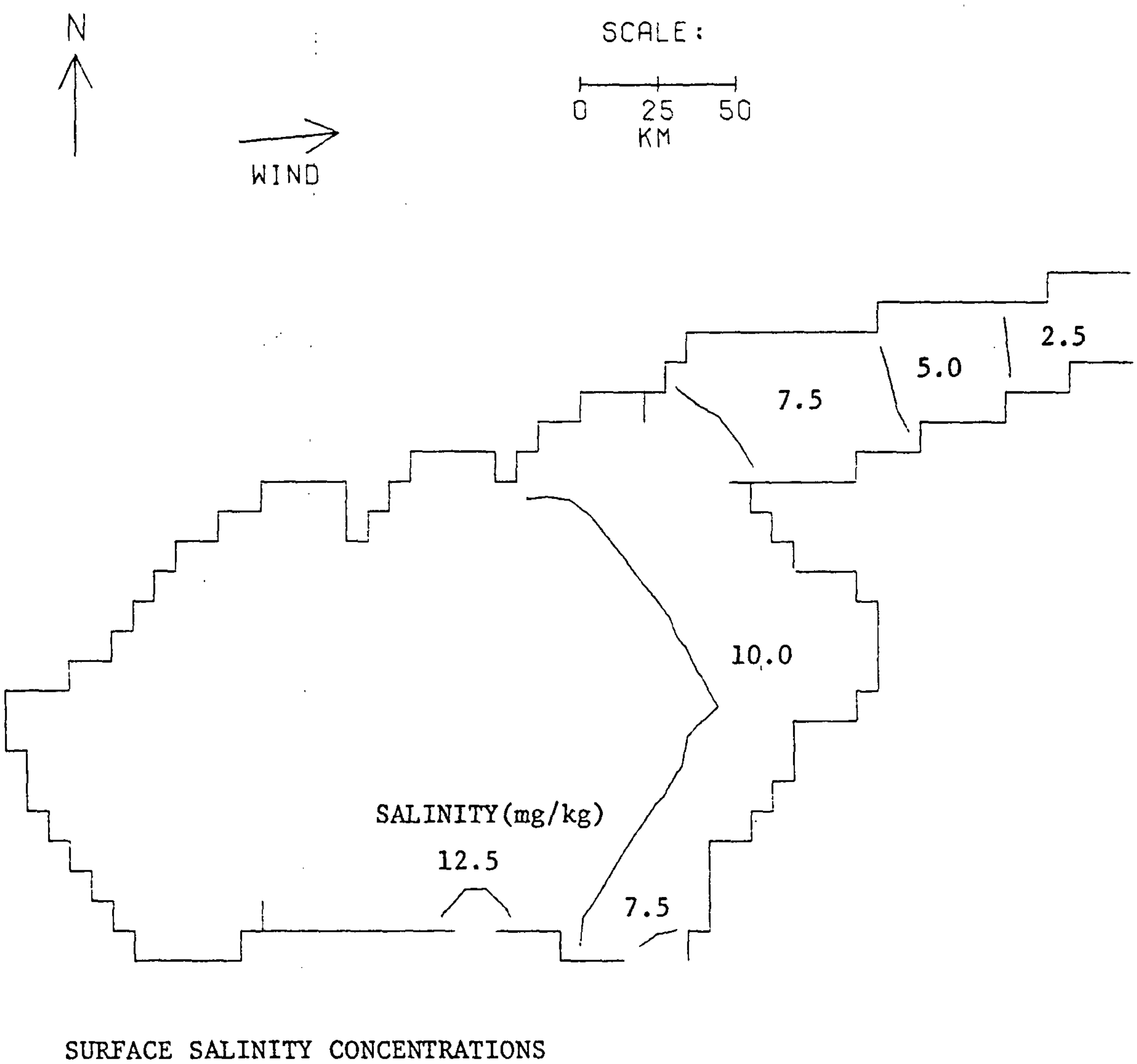
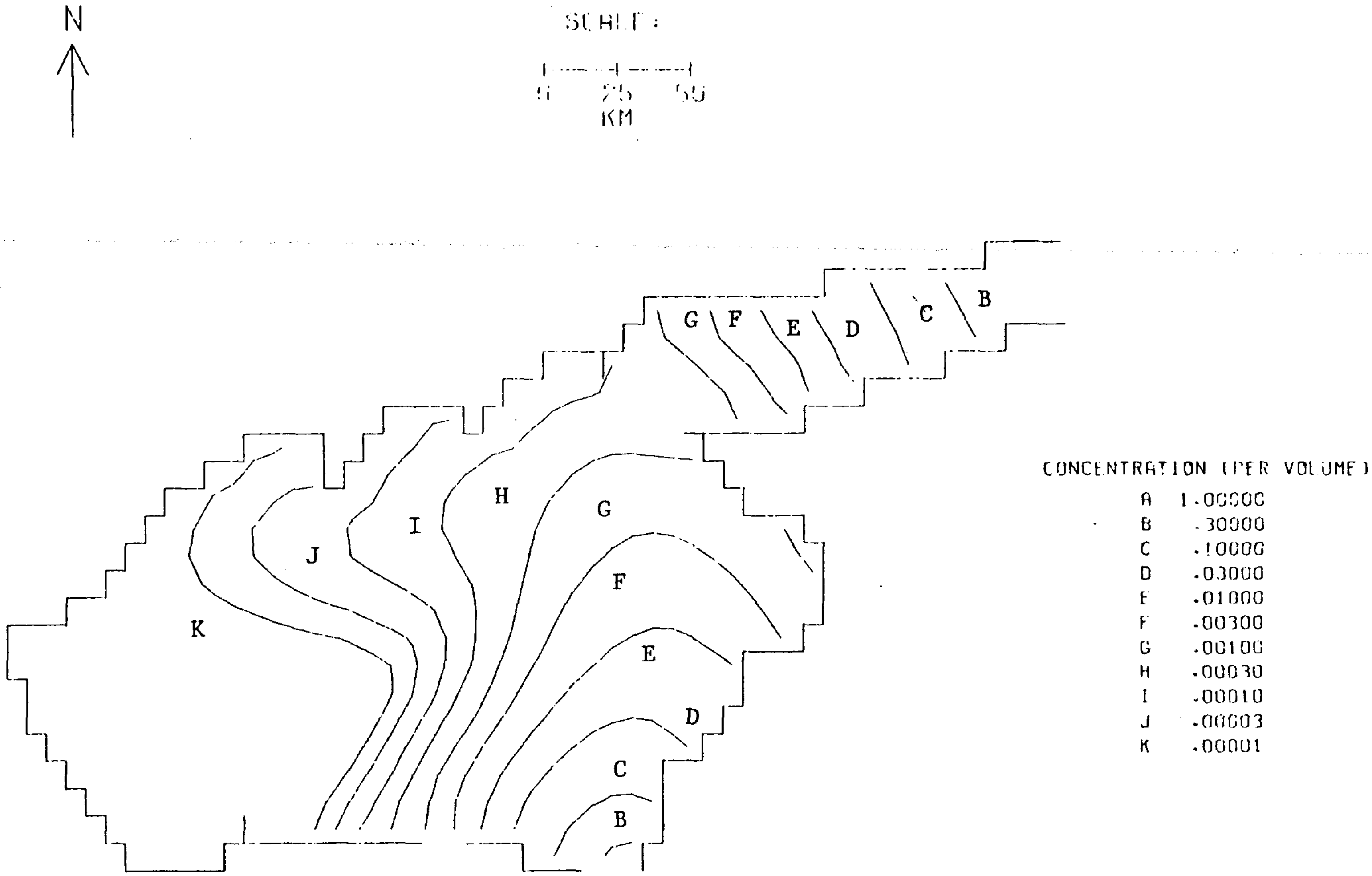


Figure C-16g. Case 3 (constant wind) hydrodynamic model calculation for Sea of Azov after 2 days.



SURFACE CONCENTRATIONS - NO SETTLING

Figure C-17a. Case 1 dispersion model calculation for Sea of Azov after 28 days.

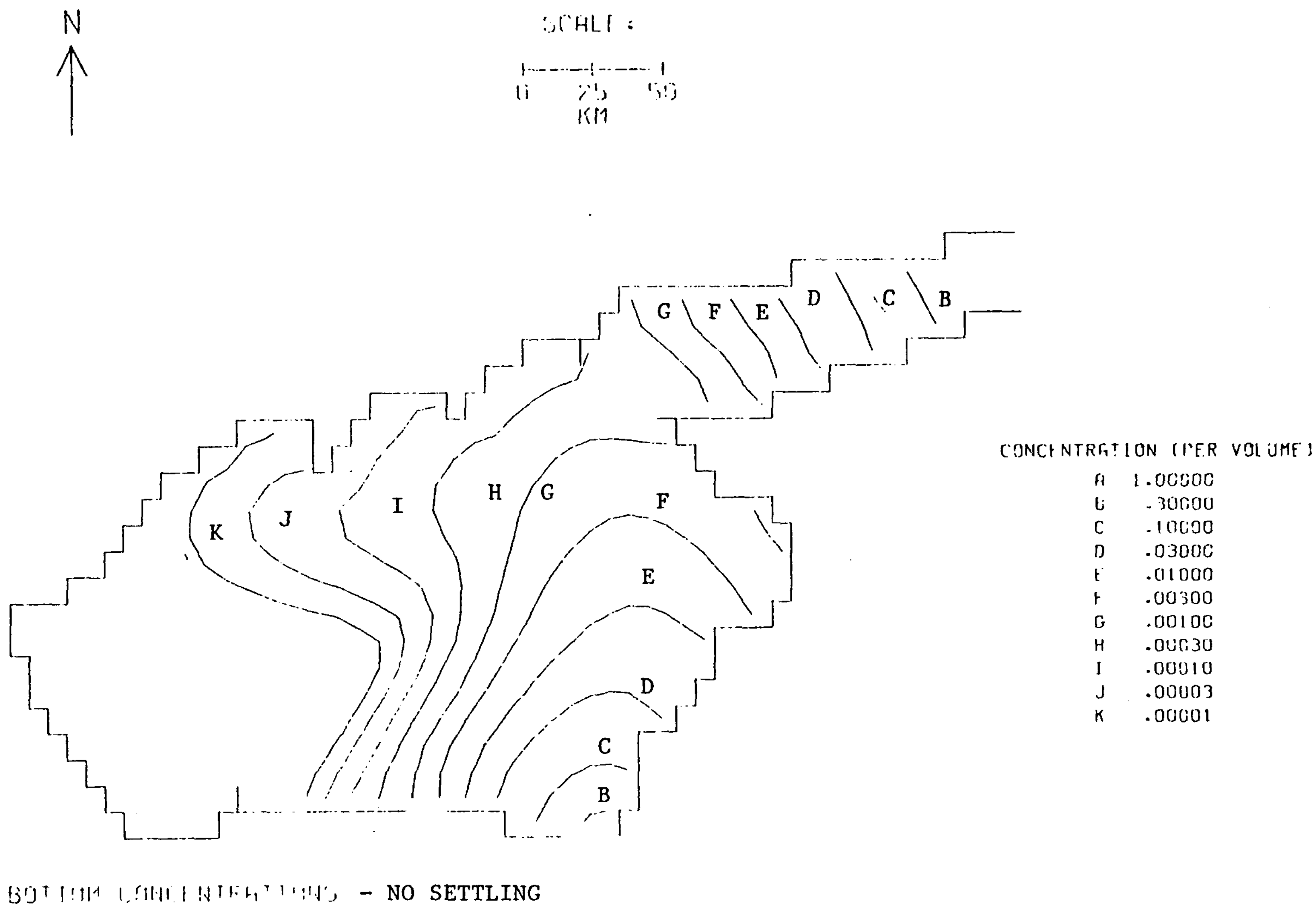


Figure C-17b. Case 1 dispersion model calculation for Sea of Azov after 28 days.

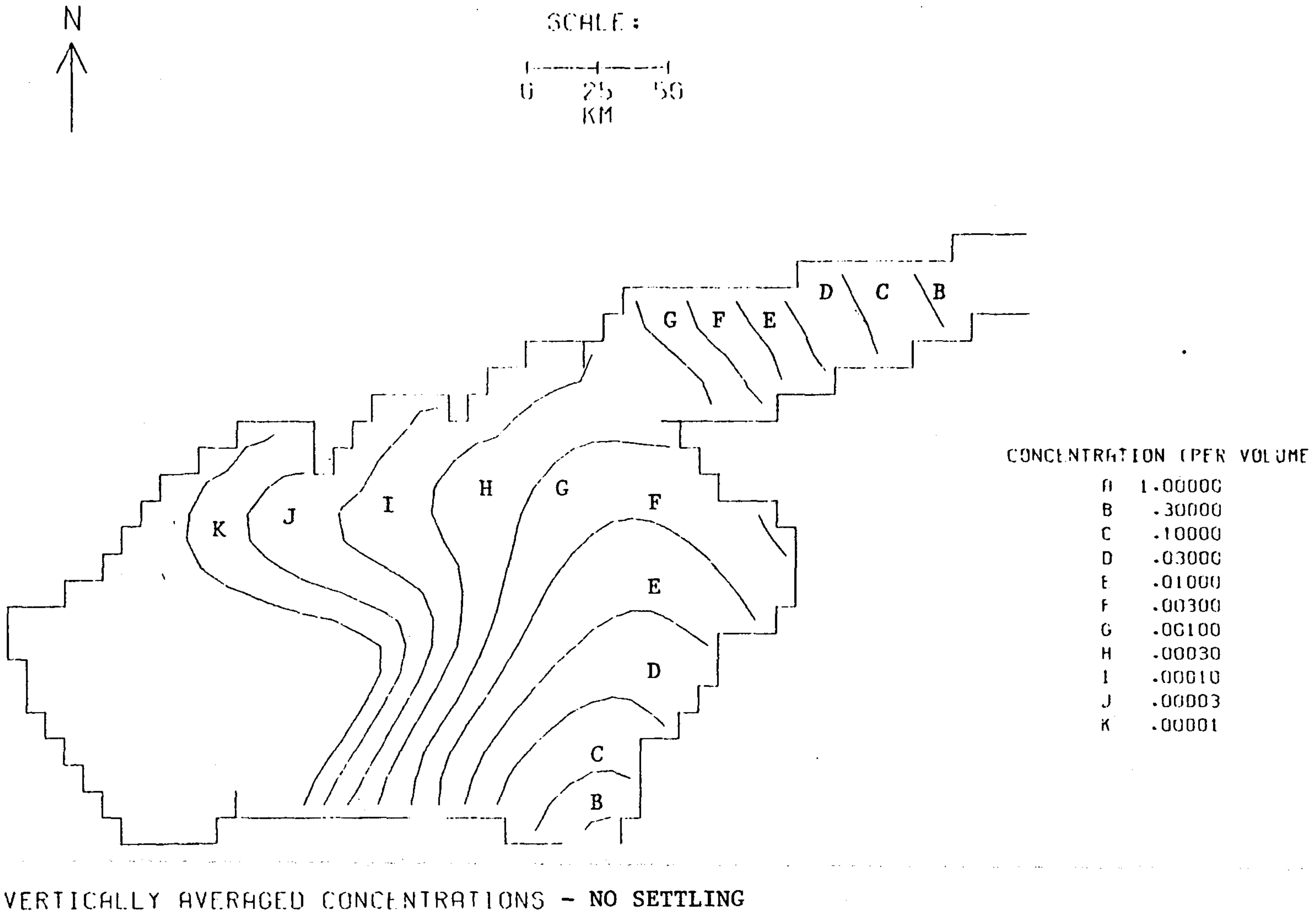
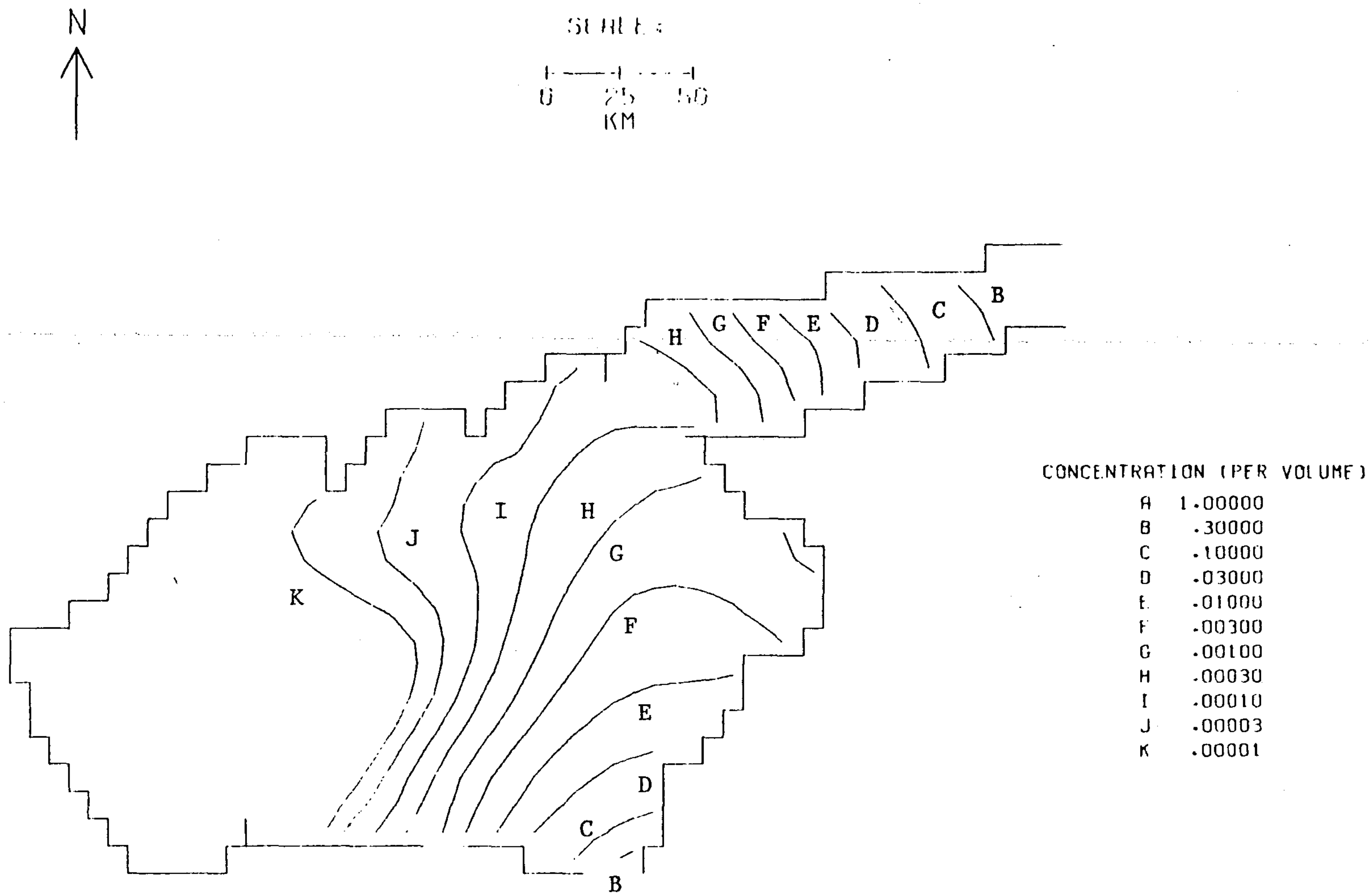


Figure C-17c. Case 1 dispersion model calculation for Sea of Azov after 28 days.



SURFACE CONCENTRATIONS - SETTLING, 10 M/DAY

Figure C-17d. Case 1 dispersion model calculation for Sea of Azov after 28 days.

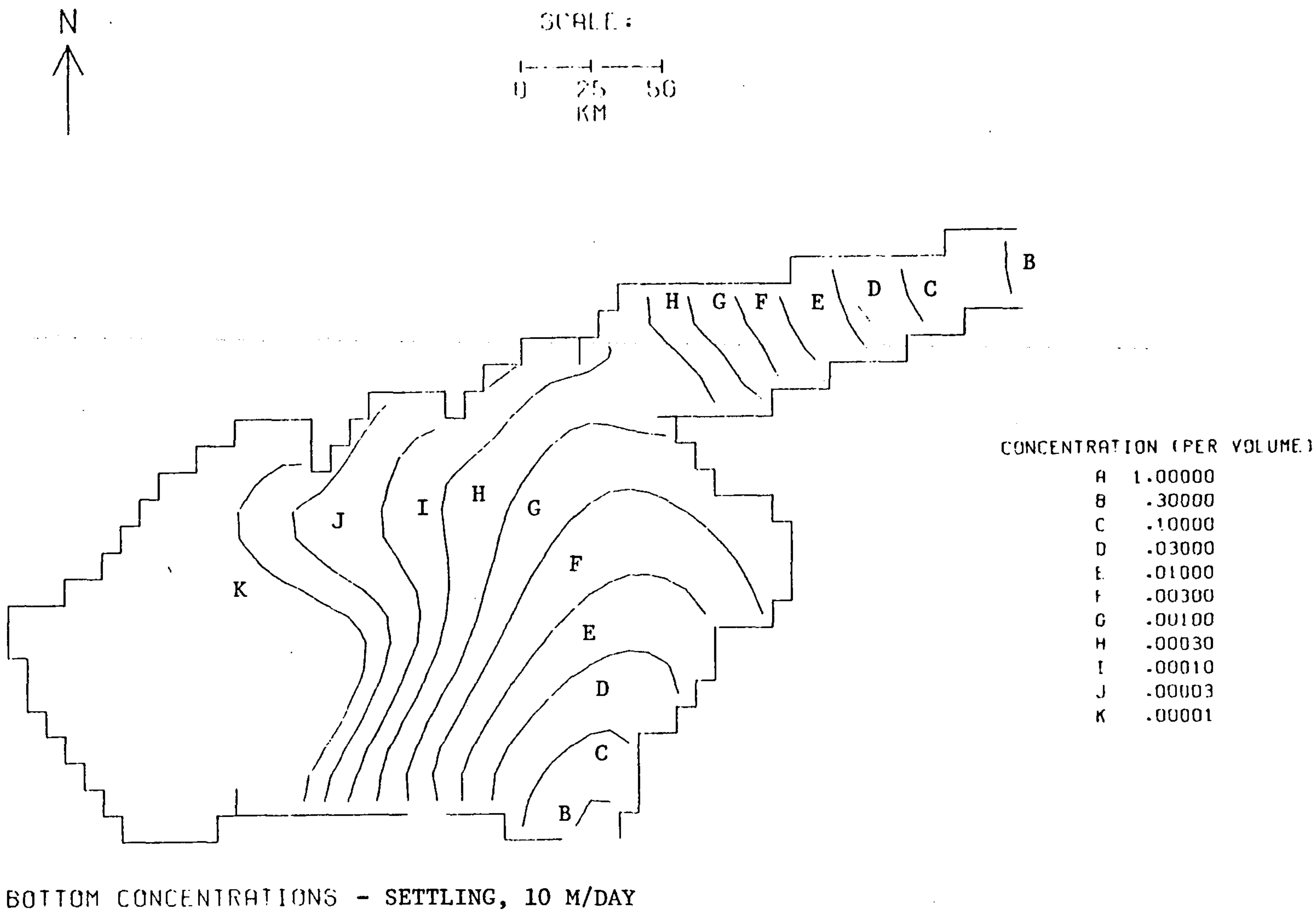
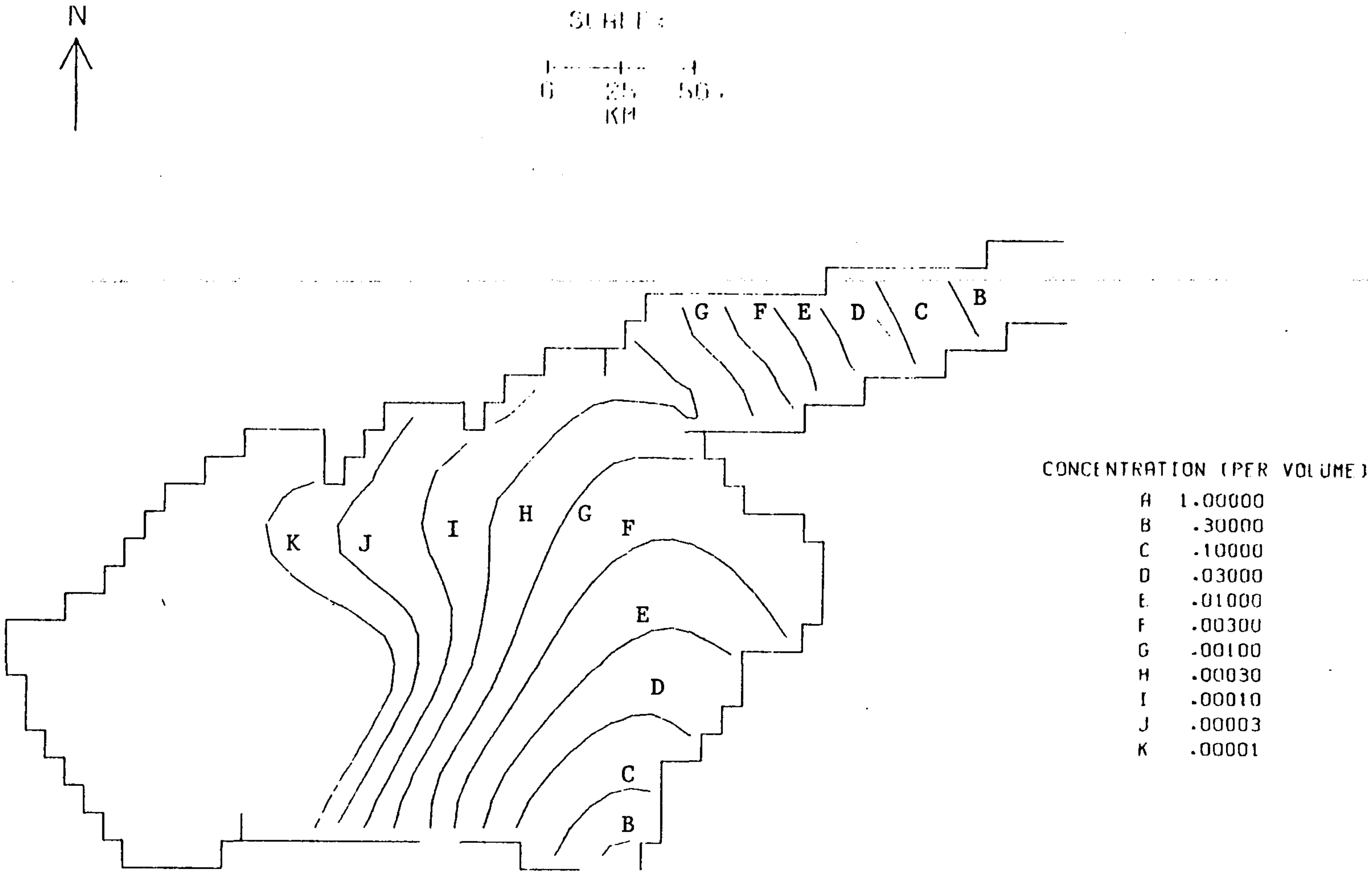
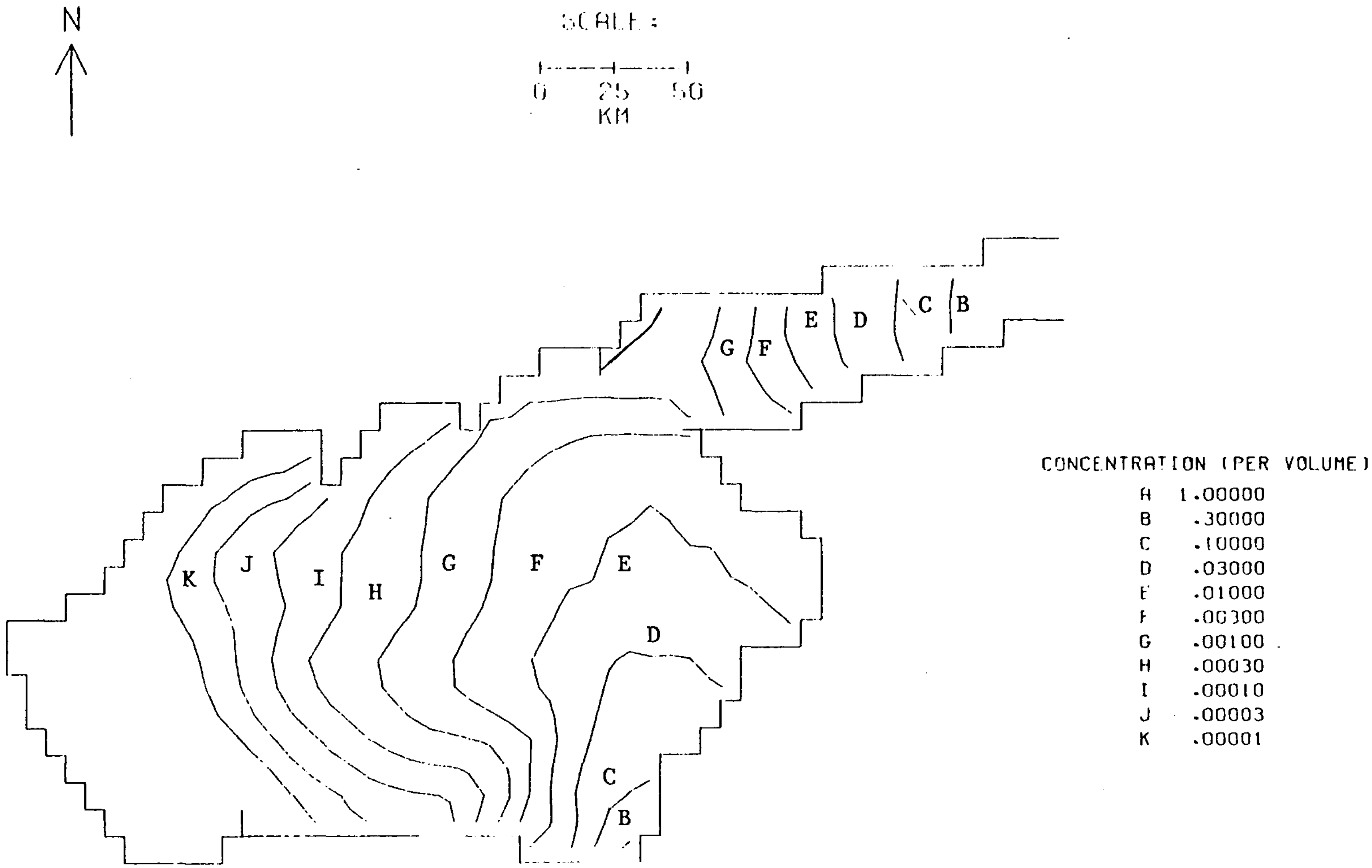


Figure C-17e. Case 1 dispersion model calculation for Sea of Azov after 28 days.



VERTICALLY AVERAGED CONCENTRATIONS - SETTLING, 10 M/DAY

Figure C-17f. Case 1 dispersion model calculation for Sea of Azov after 28 days.



SURFACE CONCENTRATIONS - NO SETTLING

Figure C-18a. Case 3 (variable wind) dispersion model calculation for Sea of Azov after 28 days.

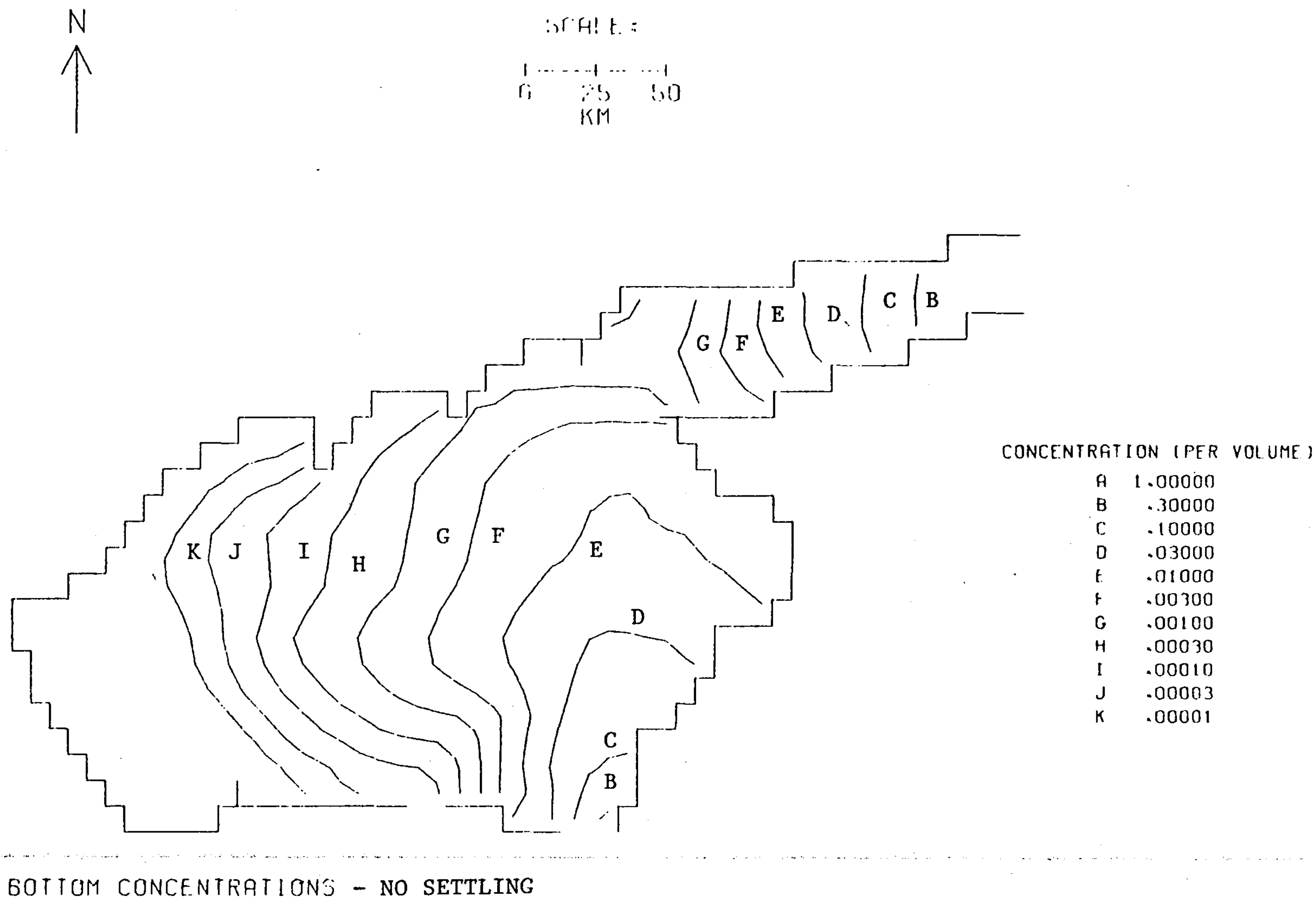
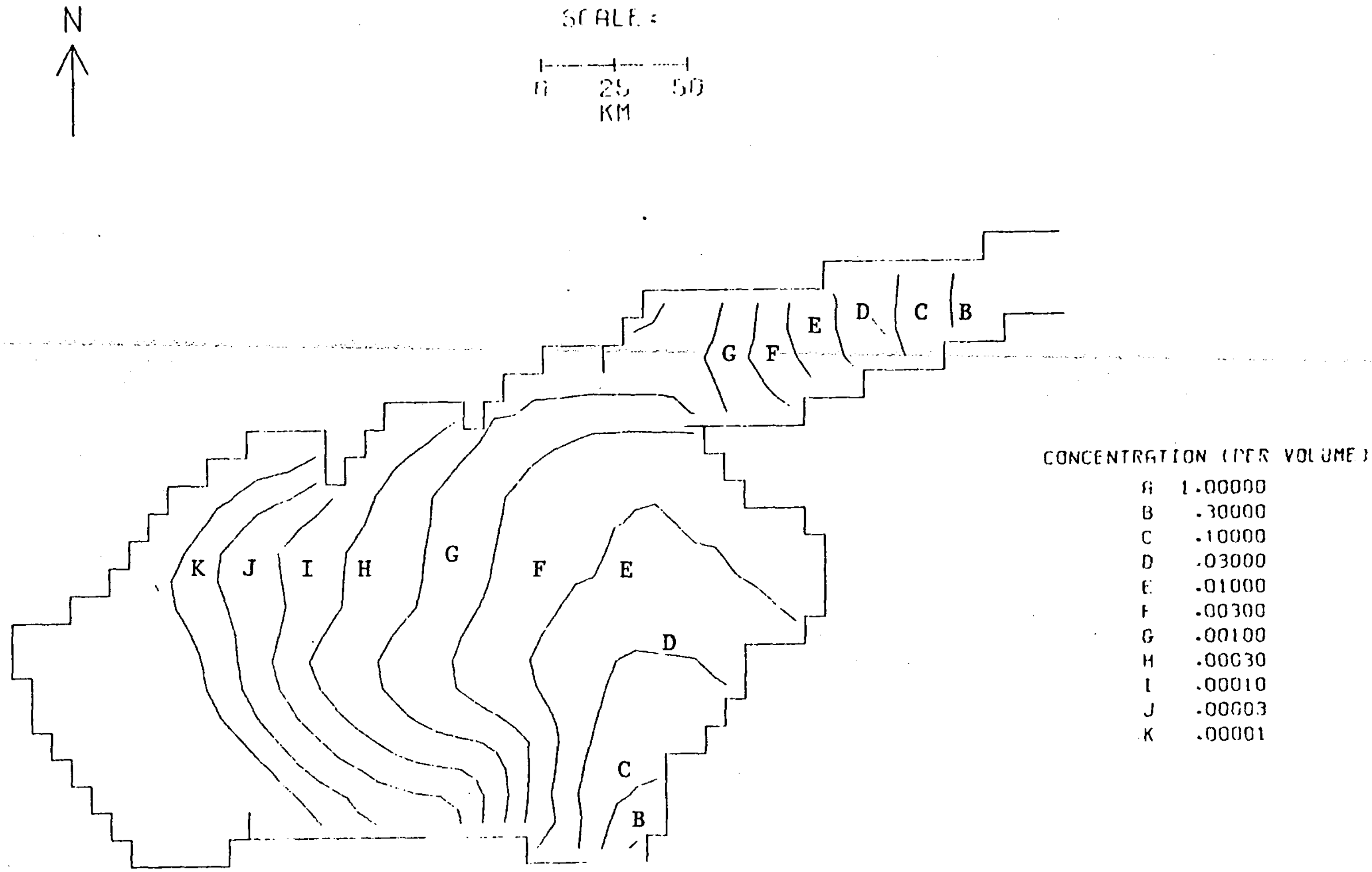
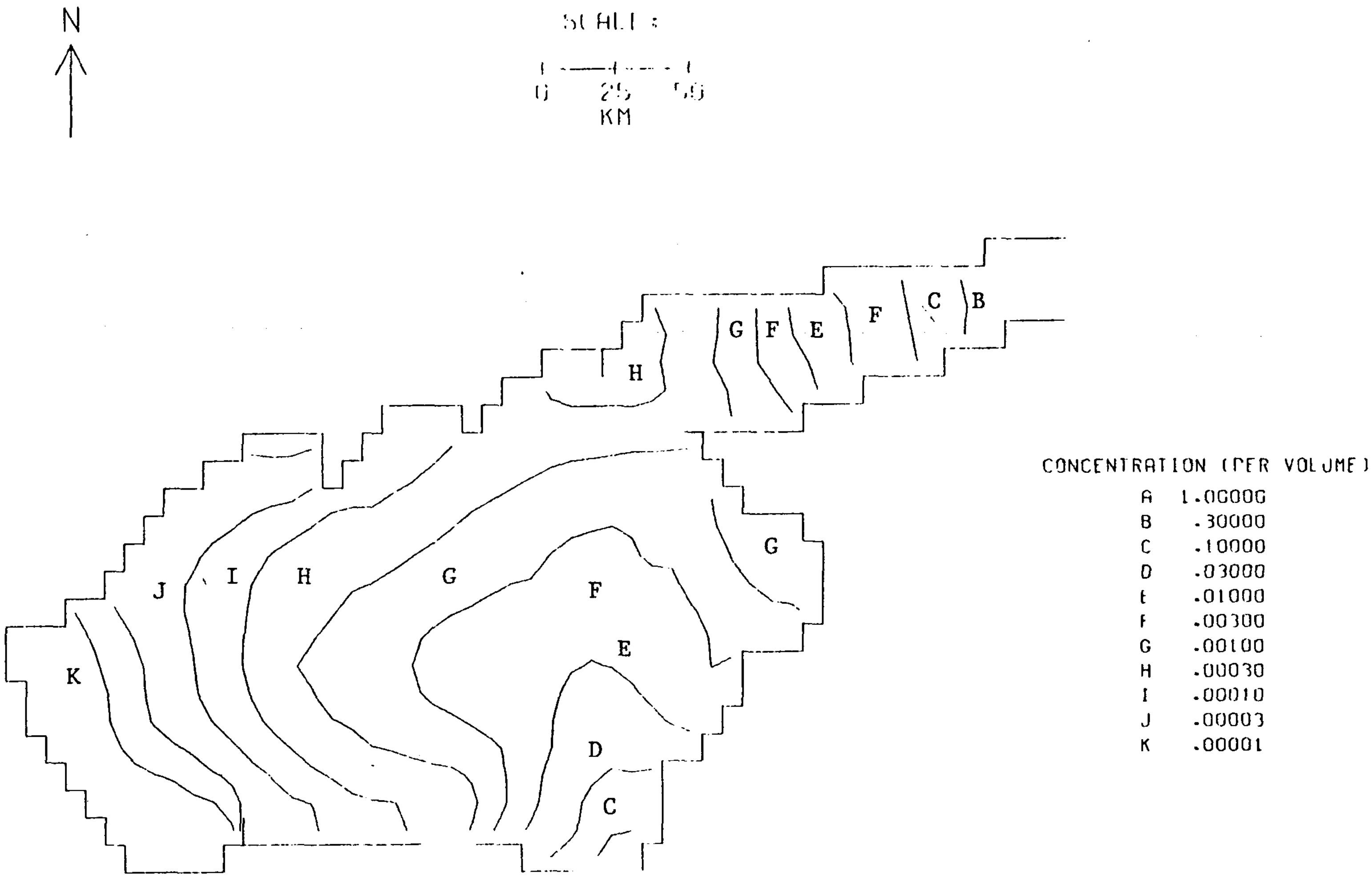


Figure C-18b. Case 3 (variable wind) dispersion model calculation for Sea of Azov after 28 days.



VERTICALLY AVERAGED CONCENTRATIONS - NO SETTLING

Figure C-18c. Case 3 (variable wind) dispersion model calculation for Sea of Azov after 28 days.



SURFACE CONCENTRATIONS - SETTLING, 10 M/DAY

Figure C-18d. Case 3 (variable wind) dispersion model calculation for Sea of Azov after 28 days.

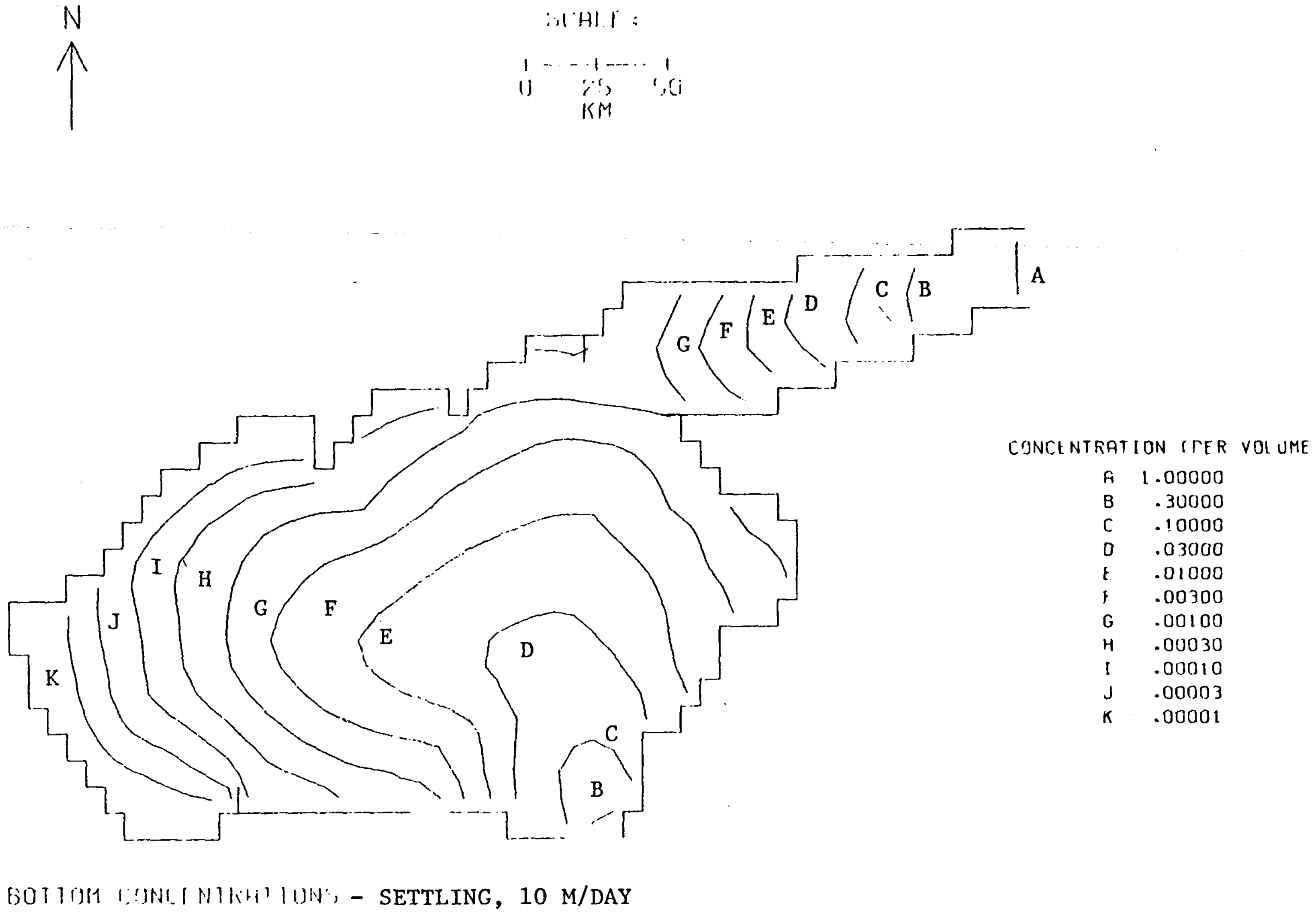
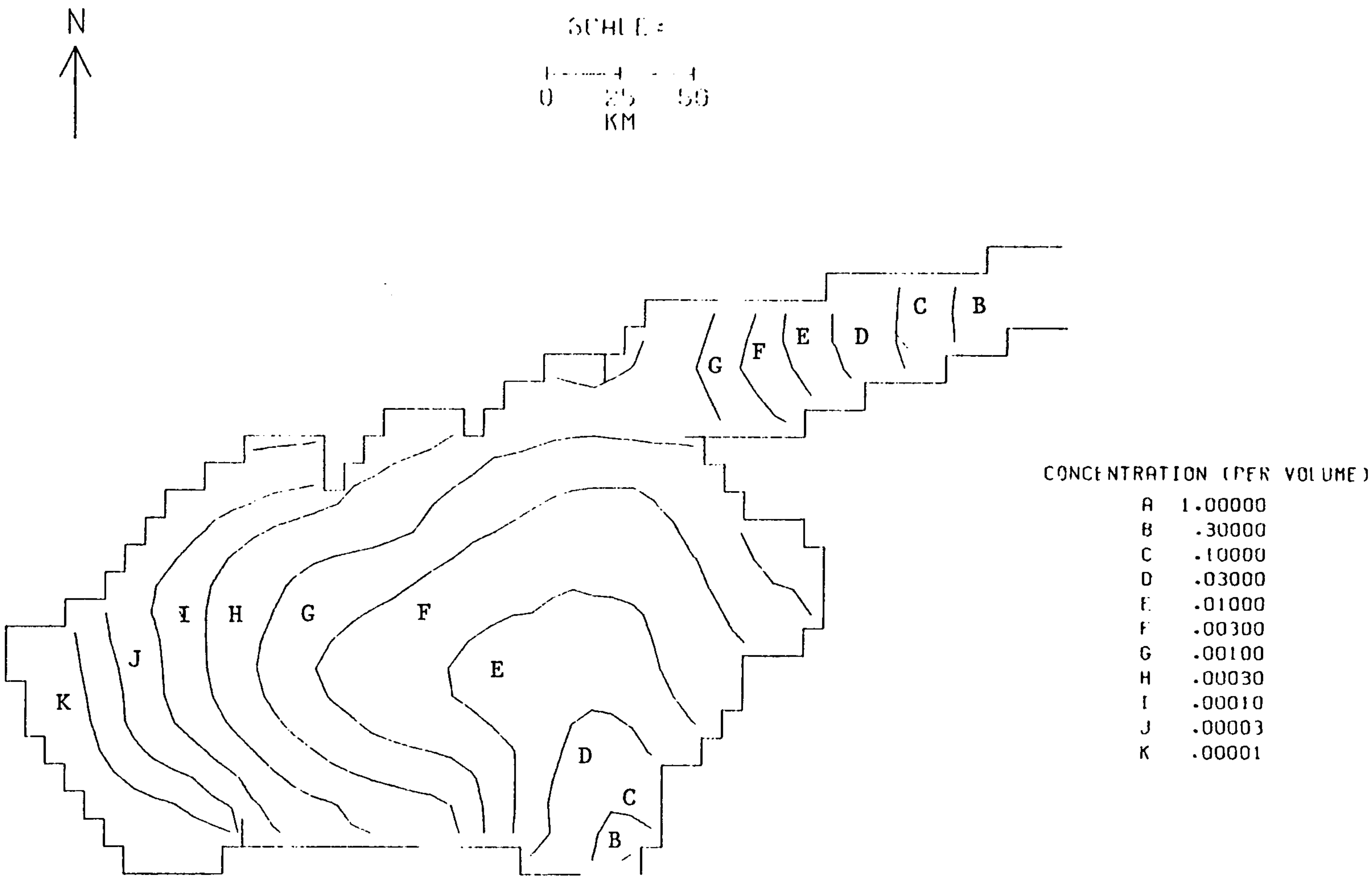


Figure C-18e. Case 3 (variable wind) dispersion model calculation for Sea of Azov after 28 days.



VERTICALLY AVERAGED CONCENTRATIONS - SETTLING, 10 M/DAY

Figure C-18f. Case 3 (variable wind) dispersion model calculation for Sea of Azov after 28 days.

APPENDIX D

METEOROLOGICAL, HYDROLOGICAL, AND CHEMICAL DATA FOR SELENGA SHALLOWS IN MAY-JUNE 1976.

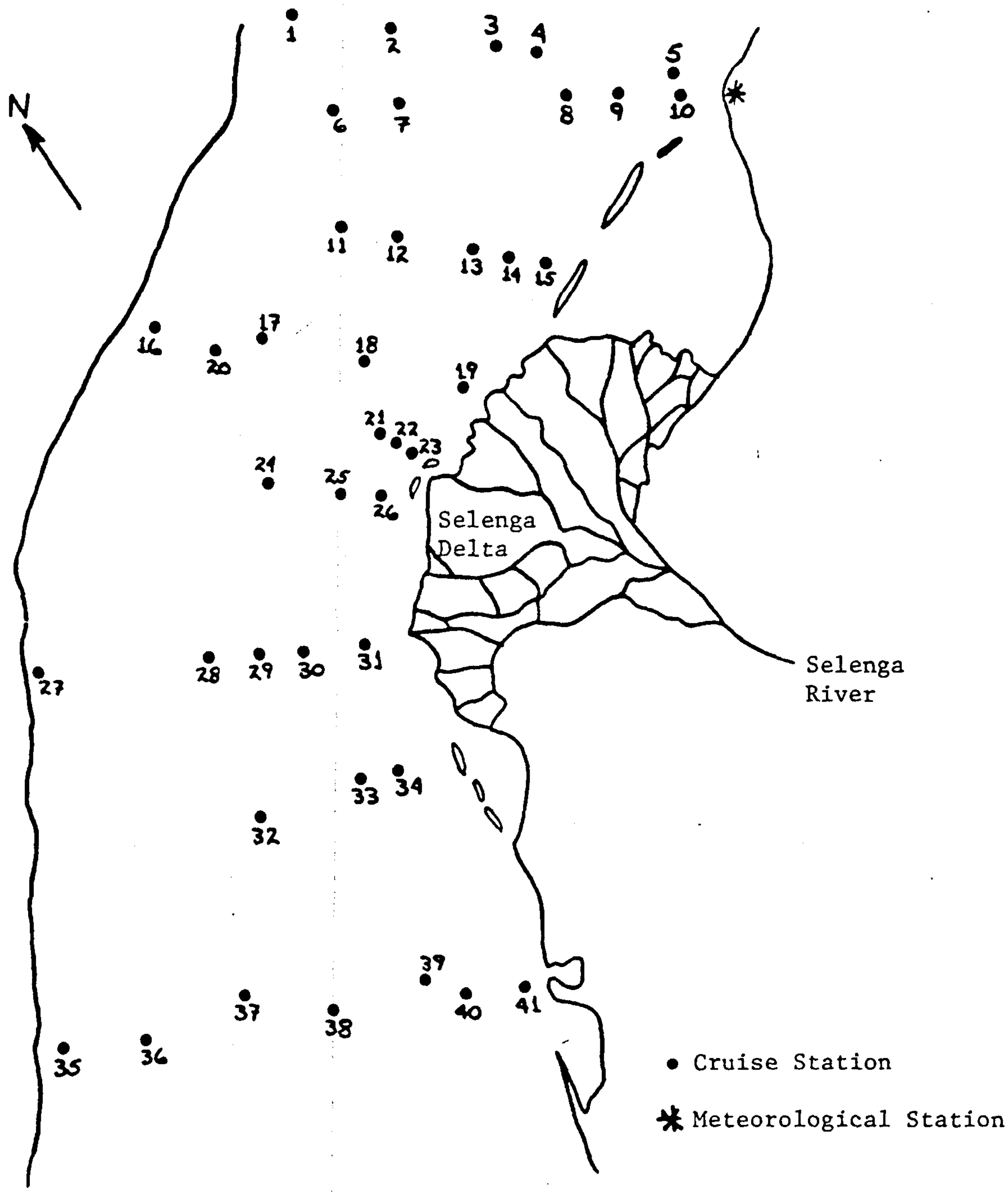


Figure D-1. Hydromet sampling stations in Selenga Shallows Region of Lake Baikal.

Table D-1

HYDROCHEMISTRY DATA FOR HYDROMET CRUISE ON MAY 28-29, 1976

STATION	DEPTH AT STATION (METERS)	SAMPLE DEPTH (METERS)	WATER COLOR	SUSPENDED SOLIDS (MG/L)
06	1150	0.5	1	2.1
		35	1	0.8
		85	1	0.9
		200	9	2.0
		1150	16	-
07	740	0.5	13	1.3
		35	13	2.8
		85	9	-
		200	5	1.2
		740	9	3.2
08	400	0.5	9	1.1
		35	0	-
		85	4	0.1
		200	0	0.1
		400	5	0.5
09	140	0.5	0	0.1
		35	2	0.8
		85	0	0.7
		140	1	1.2
10	25	0.5	0	3.2
		25	0	0.7
11	600	0.5	4	0.2
		35	0	0.4
		85	0	0.2
		200	0	0.1
		600	0	1.4
12	340	0.5	0	0.4
		35	0	0.5
		85	0	1.5
		200	0	0.5
		340	0	0.1

Table D-1 (continued)

HYDROCHEMISTRY DATA FOR HYDROMET CRUISE ON MAY 28-29, 1976

STATION	DEPTH AT STATION (METERS)	SAMPLE DEPTH (METERS)	WATER COLOR	SUSPENDED SOLIDS (MG/L)
13	365	0.5	0	0.1
		35	3	0.1
		85	0	0.1
		200	0	1.2
		365	-	-
14	200	0.5	0	0.5
		35	0	0.7
		85	0	0.1
		200	0	0.1
15	12	0.5	0	3.9
		12	0	2.6
17	600	0.5	0	0.9
		35	1	0.8
		85	0	0.6
		200	3	0.5
		600	0	0.6
18	195	0.5	1	0.1
		35	0	0.3
		85	3	0.2
		195	0	0.2
19	9	0.5	0	2.2
		9	0	7.0
24	300	0.5	0	1.2
		35	3	0.2
		85	0	0.1
		200	4	0.6
		300	0	0.1
25	100	0.5	3	0.3
		35	0	0.5
		100	4	0.4

Table D-1 (continued)

HYDROCHEMISTRY DATA FOR HYDROMET CRUISE ON MAY 28-29, 1976

STATION	DEPTH AT STATION (METERS)	SAMPLE DEPTH (METERS)	WATER COLOR	SUSPENDED SOLIDS (MG/L)
26	15	0.5	21	3.3
		15	10	3.3
27	300	0.5	0	0.4
		35	0	0.2
		85	0	3.5
		200	0	1.2
		300	0	0.6
29	180	0.5	13	1.0
		35	0	0.6
		85	0	0.6
		180	0	1.0
30	50	0.5	6	0.6
		25	5	1.4
		50	29	2.5
31	16	0.5	17	0.7
		16	21	0.9
32	185	0.5	1	2.7
		35	0	1.2
		85	0	0.7
		185	0	•
33	54	0.5	0	0.9
		25	0	2.1
		54	0	2.3
34	30	0.5	0	0.7
		30	1	0.9
37	400	0.5	0	2.9
		35	0	1.1
		85	0	1.4
		200	0	1.5
		400	0	0.4
39	275	0.5	0	1.5
		35	0	1.6
		85	0	1.0
		200	0	3.7
		275	•	•

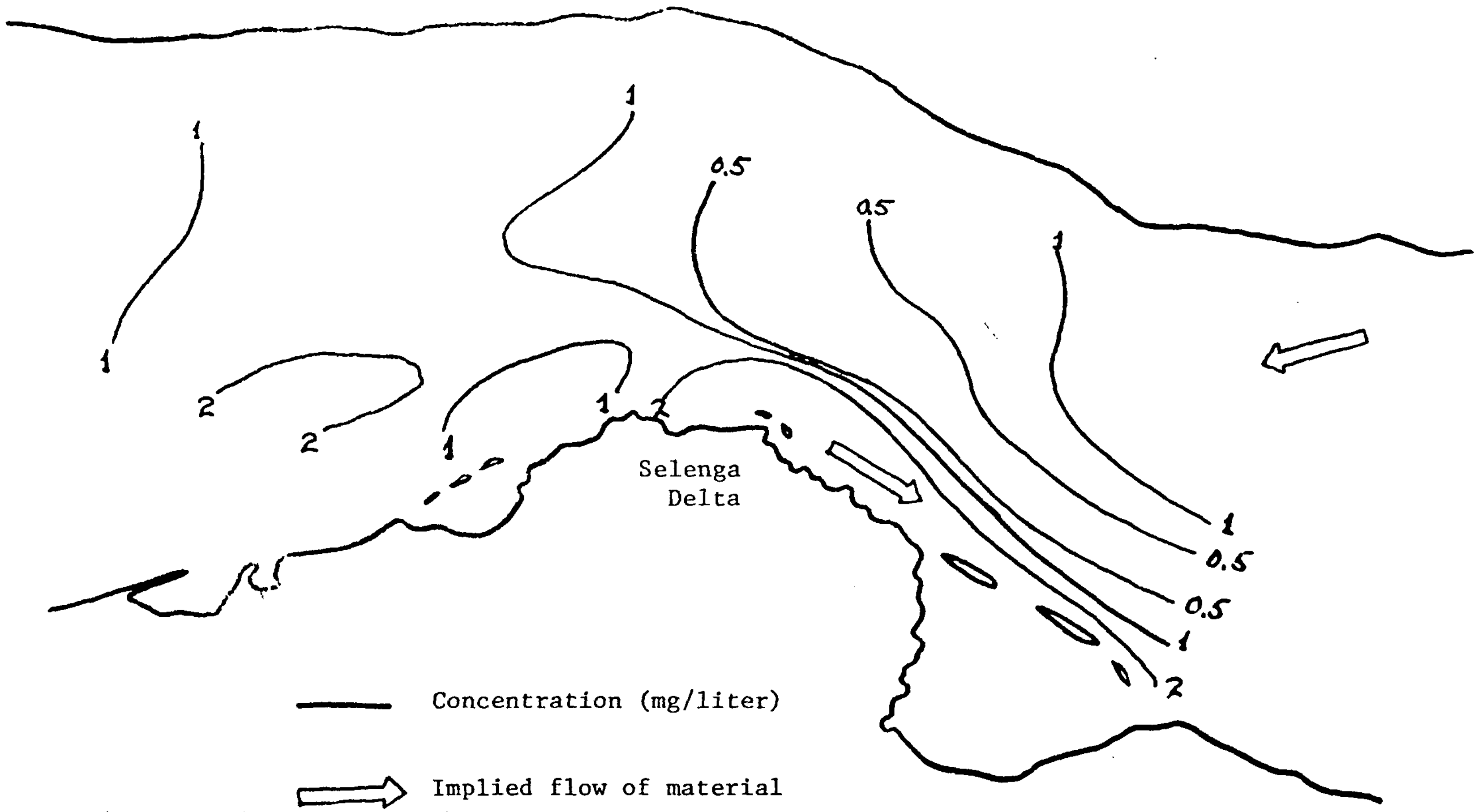


Figure D-2. Near surface concentrations of suspended material for Hydromet cruise of 28-29 May 1976.

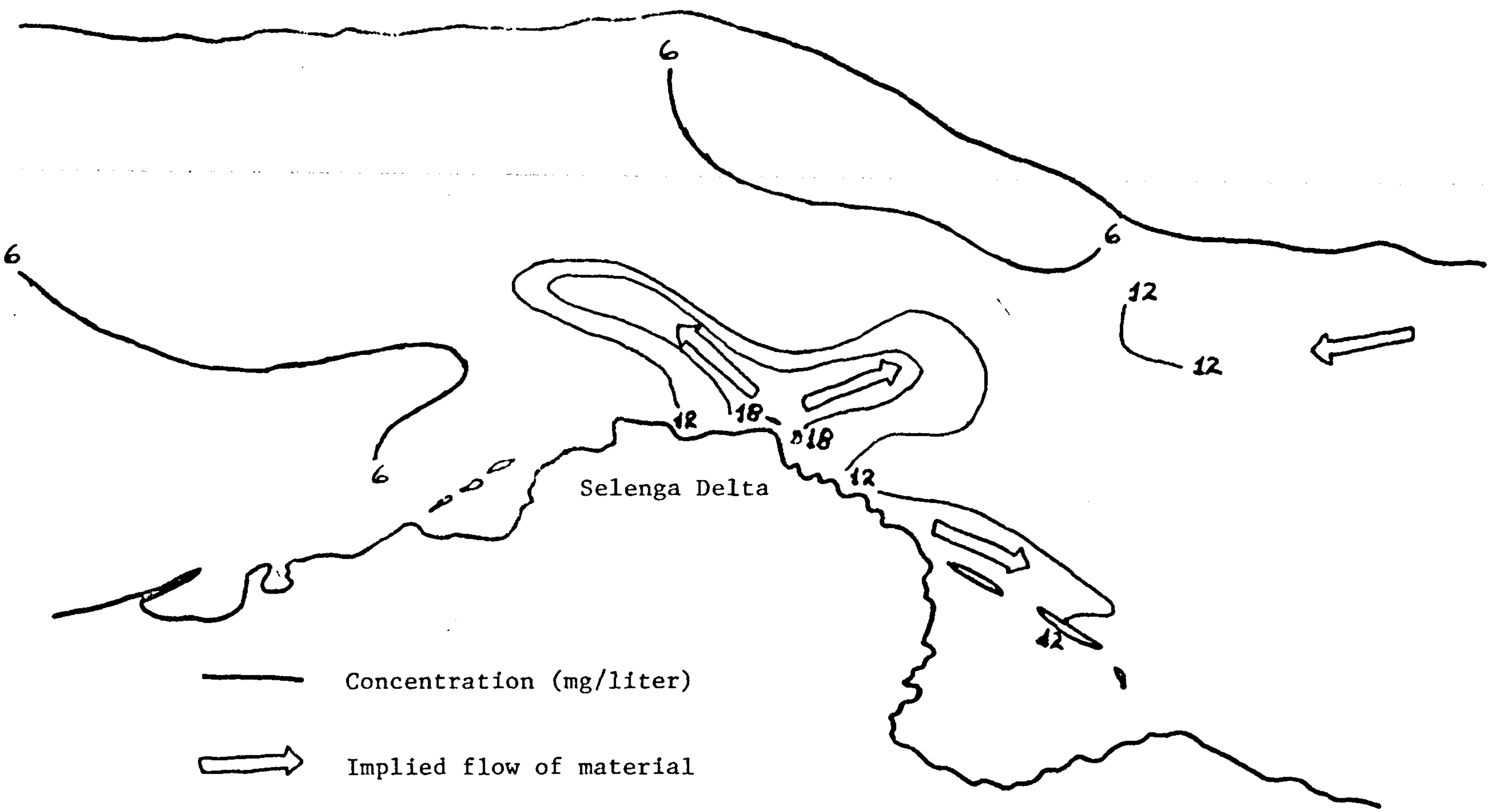


Figure D-3. Near surface concentrations of PO_4^{-3} for Hydromet cruise of 28-29 May 1976.

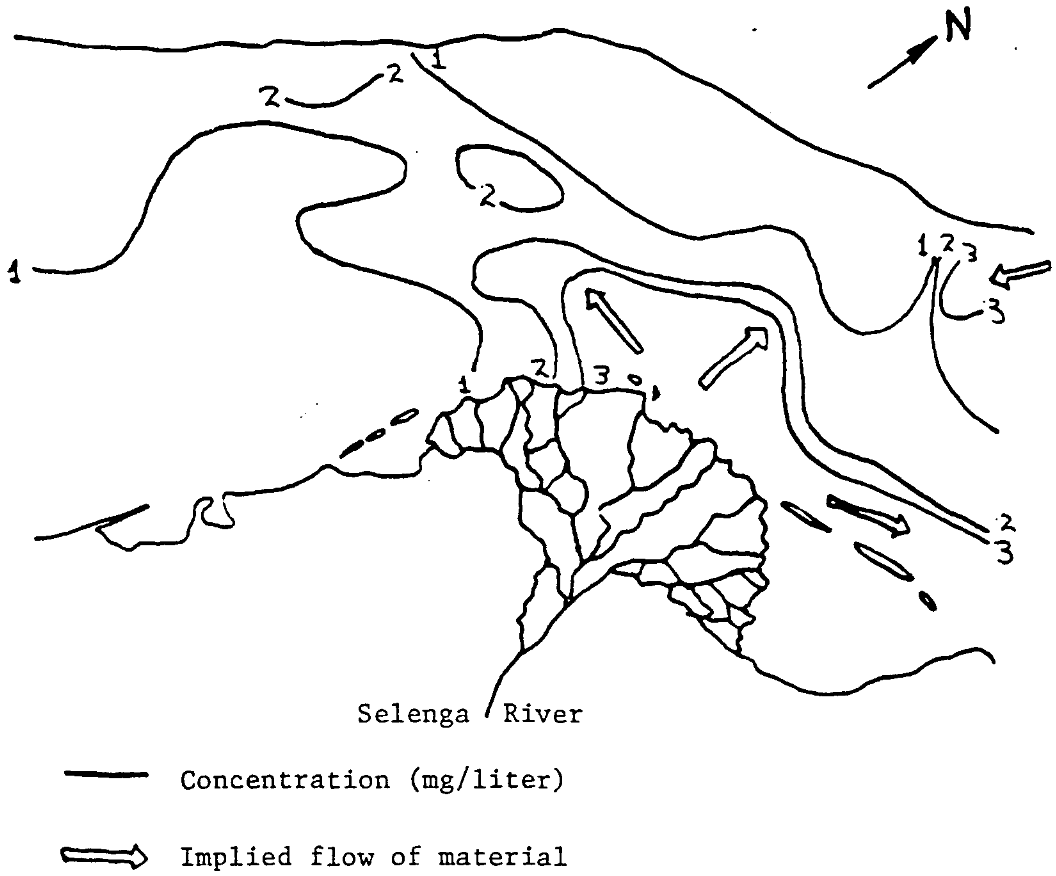


Figure D-4. Near surface concentrations of Cl^- and SO_4^{-2} for Hydromet cruise of 28-29 May 1976.

Table D-2

HYDROLOGY DATA TAKEN BY HYDROMET ON JUNE 22-23, 1976

STATION	DEPTH AT STATION (METERS)	SECCHI DEPTH (METERS)	SAMPLE DEPTH (METERS)	WATER TEMPERATURE (CENTIGRADE)	WIND DIRECTION AND SPEED (M/SEC)		WAVE DIRECTION	SEA STATE
01	1050	-	0.1	3.70	NE	3.8	NE	3
			5.	3.78				
			10.	3.77				
			20.	3.75				
			30.	3.73				
			50.	3.78				
			100.	3.73				
			200.	3.66				
02	1400	-	0.1	3.70	NE	3.7	NE	3
			5.	3.76				
			10.	3.74				
			20.	3.75				
			30.	3.70				
			50.	3.77				
			100.	3.67				
			200.	3.65				
03	850	-	0.1	3.70	NE	3.7	NE	3
			5.	3.74				
			10.	3.74				
			20.	3.72				
			30.	3.68				
			50.	3.72				
			100.	3.66				
			200.	3.61				
04	750	16.0	0.1	3.70	NNE	8.2	NNE	4
			5.	3.76				
			10.	3.75				
			20.	3.74				
			30.	3.71				
			50.	3.72				
			100.	3.71				
			200.	3.64				

Table D-2 (continued)

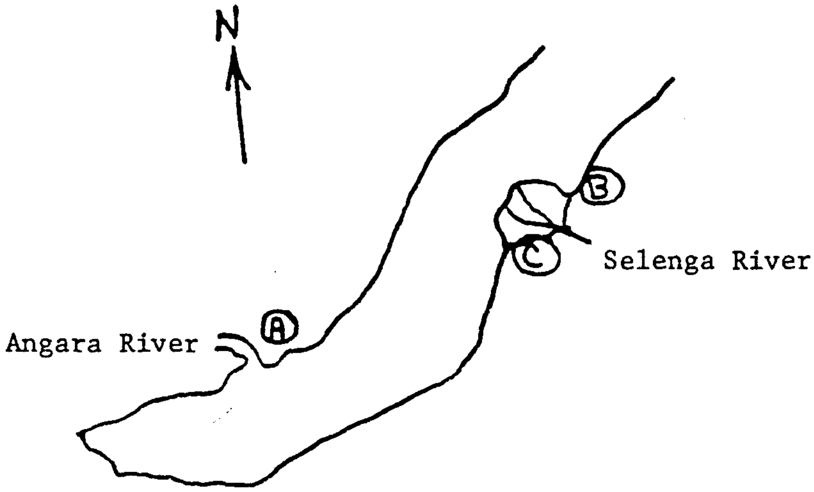
HYDROLOGY DATA TAKEN BY HYDROMET ON JUNE 22-23, 1976

STATION	DEPTH AT STATION (METERS)	SECCHI DEPTH (METERS)	SAMPLE DEPTH (METERS)	WATER TEMPERATURE (CENTIGRADE)	WIND DIRECTION AND SPEED (M/SEC)		WAVE DIRECTION	SEA STATE
05	60	7.5	0.1	8.70	NE	4.1	NE	3
			5.	4.64				
			10.	3.94				
			20.	3.90				
			30.	3.91				
			50.	3.92				
16	550	17.8	0.1	3.90	N	1.6	-	-
			5.	3.86				
			10.	3.88				
			20.	3.74				
			30.	3.70				
			50.	3.77				
			100.	3.69				
			200.	3.64				
20	650	16.5	0.1	3.90	NE	1.7	NE	3
			5.	3.88				
			10.	3.80				
			20.	3.74				
			30.	3.70				
			50.	3.75				
			100.	3.69				
			200.	3.59				
21	35	2.4	0.1	12.1	NE	3.4	NE	2
			5.	10.95				
			10.	5.24				
			15.	4.70				
			20.	4.46				
			30.	4.21				
22	23	3.2	0.1	9.40	NE	3.1	NE	1
			5.	8.66				
			10.	7.69				
			15.	7.22				
			20.	5.11				
23	13	2.8	0.1	11.2	NE	1.6	NE	1
			5.	7.48				
			10.	6.67				

Table D-2 (continued)

HYDROLOGY DATA TAKEN BY HYDROMET ON JUNE 22-23, 1976

STATION	DEPTH AT STATION (METERS)	SECCHI DEPTH (METERS)	SAMPLE DEPTH (METERS)	WATER TEMPERATURE (CENTIGRADE)	WIND DIRECTION AND SPEED (M/SEC)		WAVE DIRECTION	SEA STATE
35	450	21,5	0,1	5,8	NE	2,8	NE	1
			5.	5,29				
			10.	4,16				
			20.	3,95				
			30.	3,90				
			50.	3,94				
			100.	3,84				
			200.	3,72				
36	950	18,5	0,1	5,8	NE	2,7	NE	1
			5.	5,21				
			10.	4,03				
			20.	3,97				
			30.	3,93				
			50.	3,95				
			100.	3,84				
			200	3,61				
38	400	19,5	0,1	4,20	NE	3,4	NE	1
			5.	4,20				
			10.	4,10				
			20.	4,02				
			30.	3,92				
			50.	3,97				
			100.	3,85				
			200.	3,60				
40	120	20,5	0,1	3,80	NE	3,5	NE	1
			5.	3,74				
			10.	3,76				
			20.	3,73				
			30.	3,63				
			50.	3,71				
			100.	3,76				
41	22	13,5	0,1	5,10	NE	3,8	NE	1
			5.	5,2				
			10.	4,98				
			15.	4,62				



(A) Meteorological Station No. 1

(B) Meteorological Station No. 2

(C) Solar Radiation Station

Figure D-5. Location of Meteorological Stations.

WIND DIRECTION AND SPEED (M/SEC) AT SPECIFIED HOUR

DATE	1800	2100	0000	0300	0600	0900	1200	1500
05/20/76	SW 10	SSW 08	SW 06	SW 08	WSW 04	SW 08	SW 03	NW 02
05/21/76	SE 03	SSW 03	SW 05	SW 09	WSW 07	SW 07	SW 07	SW 05
05/22/76	SW 01	00	SSW 03	SW 05	W 03	W 04	N 04	SW 08
05/23/76	WSW 01	NW 03	W 04	WSW 07	W 07	WSW 05	SW 04	SW 06
05/24/76	SW 03	SW 02	SSE 02	E 03	SSE 07	S 03	ESE 03	NE 10
05/25/76	NE 01	NE 02	NE 01	NE 03	NNW 08	N 08	N 08	NNE 05
05/26/76	00	00	00	WSW 04	SSW 04	W 03	NW 05	NNW 05
05/27/76	SW 10	SSW 07	SW 07	SW 08	SW 08	SW 08	SW 04	NNW 01
05/28/76	E 01	E 01	E 01	SSW 10	W 05	NNW 04	SW 07	SW 05
05/29/76	SSW 03	S 03	SSE 02	SE 03	NNW 05	N 05	N 05	NE 04
05/30/76	E 01	E 01	SW 01	00	NE 05	NE 07	NE 09	SW 02
05/31/76	SW 05	SW 02	SW 05	SW 08	WSW 05	W 08	W 05	SW 01
06/01/76	W 01	SW 01	SW 03	WSW 07	SW 09	SSW 05	NNW 02	WSW 02
06/02/76	SW 01	00	N 01	NNE 01	NE 14	WSW 14	WSW 06	NNW 08
06/03/76	NW 01	NW 01	W 05	SW 03	SW 05	SW 05	SW 05	SW 03
06/04/76	SW 05	SW 03	SW 04	WSW 05	SW 05	W 04	N 05	NE 07
06/05/76	E 03	NE 04	NE 07	SE 04	SSW 03	SSW 05	SW 10	NW 07
06/06/76	NW 07	NW 04	NNW 05	W 05	SW 10	SW 09	SW 09	SW 07
06/07/76	SW 01	00	SSN 01	SSW 01	W 03	W 03	SW 01	SSW 01
06/08/76	SSW 01	00	00	SW 04	W 04	WSW 07	SW 05	W 01
06/09/76	SW 03	W 07	S 02	WSW 01	NW 03	NW 05	N 05	NE 01
06/10/76	NE 01	00	SW 01	SSW 01	W 03	NW 03	N 03	N 01
06/11/76	SW 03	S 01	00	SSE 01	NNE 10	N 10	N 08	SW 03
06/12/76	SSW 03	NW 07	SSW 05	SSW 03	SW 10	SW 03	SW 05	SW 09
06/13/76	SW 10	WNW 18	WSW 10	WNW 08	W 05	SW 07	SW 09	SSW 07
06/14/76	W 05	SW 01	S 04	SW 05	SW 05	WSW 10	WSW 10	SSW 10
06/15/76	S 05	S 01	SSW 01	S 03	W 02	W 03	W 01	W 01
06/16/76	NNE 01	00	00	SSW 03	SSW 03	W 01	NNW 03	NE 01
06/17/76	00	00	ESE 02	E 02	NE 05	NNE 07	NNE 08	NNE 06
06/18/76	NE 01	NE 01	SSW 01	SW 05	SW 09	SW 08	SW 07	SW 06
06/19/76	SW 05	SSW 08	SSW 04	SW 06	SW 08	SW 09	SW 07	WSW 07
06/20/76	SW 05	S 04	S 01	SSW 02	SW 06	SSW 05	SW 06	SW 03

NOTE 1) A '00' FOR WIND SPEED INDICATES CALM CONDITIONS

2) READINGS START AT 1800 HOUR OF PREVIOUS DAY

Table D-3. Wind data at meteorological station No. 1.

WIND DIRECTION AND SPEED (M/SEC) AT SPECIFIED HOUR

DATE	1800	2100	0000	0300	0600	0900	1200	1500
05/20/76	SSW 06	SSW 05	SSW 04	S 03	WSW 05	S 06	NW 04	ENE 02
05/21/76	SE 01	SE 01	S 04	SW 05	W 05	W 06	SW 03	SW 02
05/22/76	SE 02	SE 01	SE 01	SSW 01	WSW 04	WNW 03	NNE 03	NE 01
05/23/76	ESE 06	SW 01	SW 04	SW 05	SW 07	SW 05	WSW 01	SW 01
05/24/76	S 01	SE 01	SSE 01	SE 01	NE 08	NE 07	NE 10	NE 08
05/25/76	NNE 06	NE 06	NE 07	NE 01	NNE 07	NNE 05	NNE 06	NNE 05
05/26/76	NE 01	NE 03	00	WSW 01	W 02	W 02	00	00
05/27/76	00	S 03	SE 02	W 01	WSW 06	WSW 05	WSW 04	SE 03
05/28/76	S 02	SE 03	00	SSW 03	WSW 07	SSW 01	SW 07	WSW 06
05/29/76	SSE 02	SE 03	SE 03	SE 01	NNE 02	NNE 04	NNE 04	NE 08
05/30/76	NE 06	NE 05	NE 05	NE 04	NE 10	ENE 01	WNE 10	NE 10
05/31/76	NE 03	ESE 03	SSE 03	SSE 01	W 01	NNE 05	W 03	
06/01/76	SE 03	SE 03	SE 04	00	WSW 06	WSW 06	W 02	NE 05
06/02/76	WSW 02	SSE 02	SE 01	SSW 01	WSW 06	SW 08	SW 04	WNW 06
06/03/76	SW 02	SW 07	00	SW 02	WSW 06	WSW 10	SW 10	WNW 04
06/04/76	SE 01	00	SE 02	SE 01	SW 03	NE 04	NE 04	NE 06
06/05/76	NE 01	NE 05	NNE 07	NNE 05	SW 08	W 05	SW 01	SW 01
06/06/76	SW 02	SSE 01	WNW 05	SW 03	SW 05	WSW 04	WNW 03	NW 04
06/07/76	00	00	W 03	00	NW 02	NW 00	N 01	00
06/08/76	ESE 01	00	SE 01	00	NW 02	WNW 05	WSW 03	SW 01
06/09/76	NE 08	S 03	S 02	NNE 01	NNE 06	NNE 05	NE 07	00
06/10/76	00	NE 04	NE 04	00	NNW 01	NNW 03	NE 04	NNE 06
06/11/76	NW 02	00	SSE 02	NNE 04	N 05	NNE 07	NNE 07	N 05
06/12/76	NNE 02	00	S 05	SSE 03	SW 05	SW 05	00	00
06/13/76	S 04	S 05	S 03	00	WSW 04	WSW 04	WSW 03	SSW 04
06/14/76	00	SSW 04	W 03	00	WSW 05	W 04	WSW 05	SW 05
06/15/76	ESE 03	SE 01	SE 02	SW 03	WSW 05	W 05	WNW 02	WNW 04
06/16/76	00	SW 02	SW 02	W 03	NW 03	NNE 02	NNE 02	NNE 01
06/17/76	S 01	S 03	S 03	NNE 02	NE 03	NNE 04	NNE 08	NNE 07
06/18/76	00	00	SE 04	SSE 03	WSW 05	W 05	WSW 06	SW 07
06/19/76	S 05	S 05	SSW 03	S 04	WSW 06	W 06	N 05	00
06/20/76	00	00	SE 01	E 01	NE 02	WSW 06	NNE 05	00

NOTE 1) A '00' FOR WIND SPEED INDICATES CALM CONDITIONS

2) READINGS START AT 1800 HOUR OF PREVIOUS DAY

Table D-4. Wind data at meteorological station No. 2.

SOLAR RADIATION (CAL/CM**2-MIN) AT SPECIFIED HOUR

DATE	0630 DIRECT	0630 TOTAL	0930 DIRECT	0930 TOTAL	1230 DIRECT	1230 TOTAL	1530 DIRECT	1530 TOTAL	1830 DIRECT	1830 TOTAL
05/20/76		0.13	0.37	0.88	0.63	1.22	0.69	0.93	0.08	0.24
05/21/76		0.11		0.09		0.32		0.30	0.11	0.19
05/22/76	0.30	0.52	0.36	1.00		0.78		0.53		0.08
05/23/76		0.01		0.09		0.19	0.66	0.94	0.13	0.26
05/24/76	0.41	0.52	0.17	0.78	0.37	1.08		0.34		0.03
05/25/76	0.11	0.30	0.95	1.10	0.23	0.58	0.76	0.88	0.01	0.10
05/26/76	0.30	0.46	0.76	1.26		0.07		0.08		0.01
05/27/76	0.37	0.48	0.96	1.12	1.10	1.27	0.71	0.86	0.04	0.17
05/28/76		0.26		0.41		0.33	0.78	0.92	0.15	0.23
05/29/76		0.25		0.37		0.47		0.40		0.11
05/30/76	0.30	0.47	0.61	1.01	0.35	1.01	0.22	0.66	0.00	0.13
05/31/76	0.36	0.50	0.98	1.11	1.13	1.35	0.50	0.77	0.09	0.18
06/01/76	0.35	0.46	0.95	1.11	1.13	1.28	0.67	1.0	0.01	0.11
06/02/76	0.35	0.47	0.58	0.91	1.02	1.26	0.56	0.78		1.01
06/03/76		0.31		0.22		0.67	0.33	0.74	0.09	0.17
06/04/76	0.37	0.49	0.97	1.13	1.18	1.33	0.75	0.89		0.12
06/05/76		0.21		0.55		0.16		0.06		0.02
06/06/76		0.26	0.85	1.18	1.20	1.34	0.76	0.91	0.16	0.31
06/07/76	0.37	0.49	0.18	0.58	1.15	1.32	0.74	0.89	0.08	0.18
06/08/76	0.16	0.35	0.88	1.07	1.09	1.27	0.56	0.76	0.15	0.24
06/09/76	0.27	0.45	0.68	0.96	1.02	1.25	0.64	0.85	0.9	0.18
06/10/76	0.28	0.47	0.84	1.08	1.04	1.26	0.71	0.89	0.15	0.24
06/11/76	0.32	0.45	0.86	1.04	0.99	1.25	0.22	0.51	0.13	0.24
06/12/76		0.19		0.36		0.19		0.07		0.01
06/13/76		0.13		0.24		0.43		0.31		0.08
06/14/76		0.08	0.25	0.79	0.15	0.85		0.37		0.13
06/15/76		0.16		0.22		0.66		0.39		0.14
06/16/76		0.22		0.53		0.58	0.51	0.93		0.09
06/17/76	0.04	0.30	0.21	0.67		0.30		0.18	0.14	0.35
06/18/76	0.44	0.54	1.05	1.17	1.19	1.29	0.85	0.95	0.17	0.25
06/19/76		0.17		0.65	1.14	1.29	0.45	0.61	0.15	0.24
06/20/76	0.10	0.33		0.25		0.39	0.67	1.03	0.18	0.26

NOTE THAT A BLANK INDICATES NO DATA AVAILABLE

Table D-5. Solar Radiation Data.

TABLE D-6. WIND INFORMATION IN JUNE-JULY 1975

Month		Frequency (%) of wind directions (P) and average wind velocity (m/sec) (S)																Wind velocity (m/sec)		Frequency of calm periods
		N	NNE	NE	ENE	E	ESE	SE	SSE	S	SSW	SW	WSW	W	WNW	NW	NNW	Average	Maximum	(%)
									Sukhaya Station											
June	(P)	1	21	7	2	0	1	2	6	6	19	10	17	4	1	0	2	3.4	14	14
	(S)	2.0	4.2	5.5	3.5		1.0	1.8	2.5	2.6	4.2	4.0	4.7	2.4	3.7	3.0	2.6			
July	(P)	1	22	12	0	0	1	3	12	8	11	5	12	7	1	2	3	2.8	10	13
	(S)	3.0	3.3	3.2			1.0	1.7	2.2	2.6	3.9	3.7	4.5	3.2	1.7	2.2	2.5			
									Babushkin Station											
June	(P)	1	4	3	1	1	3	5	1	1	0	5	24	39	5	4	0	3.1	16	16
	(S)	1.3	1.8	1.3	1.7	1.5	1.8	2.5	3.0	1.0		2.5	4.1	4.9	2.3	1.4				
July	(P)	2	1	3	4	2	1	9	3	2	1	6	28	30	6	4	1	2.5	18	20
		1.0	1.5	1.5	1.4	1.2	1.5	2.6	2.7	2.2	2.0	1.4	4.2	4.1	1.7	1.0	1.5			

Note: Results are presented at two meteorological stations which are located on the eastern shore of Lake Baikal. Babushkin station is located south of the Selenga River mouth and Sukhaya station is north of Proval Bay. For each month, the upper line is the percent frequency of wind directions and the lower line is the average wind velocity.

TABLE D-7. NUMBER OF OCCURANCES OF WIND VELOCITY GRADATIONS FOR JUNE-JULY 1975.

Month	Gradation of wind velocity (m/sec)							
	0-1	2-3	4-5	6-7	8-9	10-11	12-13	14-15
				Sukhaya Station				
June	62	75	54	38	5	5	1	0
July	76	93	55	20	3	1	0	0
				Babushkin Station				
June	78	70	46	35	8	3	0	0
July	106	72	46	13	5	6	0	0

Note: Station locations ame as in Table D-6.

TECHNICAL REPORT DATA

(Please read Instructions on the reverse before completing)

1. REPORT NO.	2.	3. RECIPIENT'S ACCESSION NO.

4. TITLE AND SUBTITLE	5. REPORT DATE
RESULTS OF A JOINT U.S.A./U.S.S.R. HYDRODYNAMIC AND TRANSPORT MODELING PROJECT, APPENDICES B, C, AND D.	6. PERFORMING ORGANIZATION CODE
7. AUTHOR(S) John F. Paul, William L. Richardson, Alexandr B. Grostko (Rostov State University, USSR), Anton A. Matveyev (Hydrochemical Institute, Hydromet, USSR)	8. PERFORMING ORGANIZATION REPORT NO.
9. PERFORMING ORGANIZATION NAME AND ADDRESS Large Lakes Research Station Environmental Research Laboratory-Duluth Grosse Ile, Michigan 48138	10. PROGRAM ELEMENT NO. 1BA769 11. CONTRACT/GRANT NO.
12. SPONSORING AGENCY NAME AND ADDRESS Environmental Research Laboratory-Duluth Office of Research and Development U.S. Environmental Protection Agency Duluth, Minnesota 55804	13. TYPE OF REPORT AND PERIOD COVERED Final 14. SPONSORING AGENCY CODE EPA/600/03

15. SUPPLEMENTARY NOTES

Performed as part of project 02.02-12 (Water Quality in Lakes and Estuaries) of U.S.A./U.S.S.R. Environmental Agreement.

16. ABSTRACT

A joint modeling project with scientists from the U.S.A. and U.S.S.R. has been accomplished. The three geographical areas investigated include Lake Baikal and the Sea of Azov in the U.S.S.R. and Saginaw Bay, Lake Huron in the U.S.A. The modeling approaches ranged from those employing material and mass conservation to describe water movement to those involving solution of the complete three-dimensional hydrodynamic equations. The model calculations were compared to available data and, in all cases, reasonable agreement was obtained.

This portion of the report includes Appendices B, C, and D for the main study, published as EPA-600/3-79-015.

This report covers a period from May 1977 to December 1977, and work was completed as of April 1978.

17. KEY WORDS AND DOCUMENT ANALYSIS

a. DESCRIPTORS	b. IDENTIFIERS/OPEN ENDED TERMS	c. COSATI Field/Group
Hydrodynamics Mathematical models Circulation Lakes	Lake Baikal Sea of Azov Saginaw Bay Wind Driven Circulation U.S.A/U.S.S.R. Environmental Agreement	08/H 20/D

18. DISTRIBUTION STATEMENT	19. SECURITY CLASS *(This Report)*	21. NO. OF PAGES
RELEASE TO PUBLIC	UNCLASSIFIED	250
	20. SECURITY CLASS *(This page)*	22. PRICE
	UNCLASSIFIED	

EPA Form 2220-1 (9-73)