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TITLE: The Role of Excessive Water Withdrawals on the Aggravation of the Black Sea

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UNITED STATES GLOBAL STRATEGY COUNCIL

WASHINGTON, D.C.

The Role of Excessive Water Withdrawals on the Aggravation of the Black Sea

by

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Prepared for

The National Council for
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Washington, D.C.

EXECUTIVE SUMMARY

Prior to the extensive impoundment of rivers of the southern European slope of the USSR, the oceanographic regime of the Black Sea, the world's largest inland water body, was controlled mainly by excess fresh water influx from the rivers, plus precipitation, over losses due to evaporation. This surplus affected water exchanges between the Black and Mediterranean Seas via the Turkish Strait system. Poor in diversity, but very productive Black Sea biota evolved under to the "harmonious" operation of the major large-scale physical, chemical, and biological processes during the last 7,000 to 10,000 years.

At the end of this period, the oxic-anoxic interface reached its balance, which coincided with the established intrusion of Mediterranean water. Now, the "natural harmony" of the Black Sea has been disrupted not only in the coastal and estuarine habitats, but in the entire sea.

The major reduction of river flow from the northern slope of the Black Sea began with the development of postwar Soviet water management projects. The impoundment of rivers was completed in the early 1970s. The run-off depletion was further compounded by development of a massive irrigation network. This, coupled with the increased nutrient, organic, and pollutant transports, led to anoxic events and mass mortalities of marine organisms in previously productive regions. Acute oxygen deficits also occurred in the Sea of Azov. In large part, therefore, this paper is a technical report on the hydrology of the Black and Azov Seas.

In spite of various conservation programs (industrial water recycling, better pollution control, more efficient irrigation, curtailment in hydro energy production, etc.) introduced in the late 1970s, the loss of fresh water increased so dramatically that some remedial measures to arrest the decline in water availability and fisheries in the lower reaches and estuaries have become necessary.

The ongoing fresh water diversions from the Black Sea and Sea of Azov have a profound effect on the oceanographic regime of the Marmara-Bosphorus Strait-Black Sea ecosystem. The flow modification affects oceanographic, ecologic, and sanitary conditions in the Seas. Circulatory patterns are modified on a large scale, including adjacent areas in both Seas. The current political and economic havoc, population unrest, and small civil wars do not give much hope that any attempt to preserve the Black Sea will occur in the near future. The new bordering republics are nearing military, economic, and political anarchy. Such considerations should cause political leaders to think hard about risk assessment of the present situation in the entire Black Sea basin. The most acute potential danger is of a catastrophic release and possible explosion of hydrogen sulphide gas (page 46).

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ACKNOWLEDGEMENTS

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ABSTRACT

This project analyzes the role of the modification of run-off on the ecology of the Black Sea. Particular attention is given to evaluation of the Black Sea's potential if the current water development policy in this crucial and internationally sensitive area will prevail in pursuing strictly national, local aims.

The project also identifies environmental risks regarding structural transformation of the Black Sea and illustrates the links between excessive water utilization and the sustainable capabilities of marine natural resources. This study may shed considerable light on the cause-and-effect variables in the stagnating of the sea and the impact of these conditions on biological productivity of the marine environment and public well being.

I. INTRODUCTION

Prior to the extensive impoundment of rivers of the Southern European slope of the USSR, the oceanographic regime of the Black Sea, the world's largest inland water body (Figure 1), was controlled mainly by excess fresh water influx from the rivers, plus precipitation, over losses due to evaporation (Table 1). This surplus has affected water exchange between the Black and Mediterranean Seas via the Turkish Strait system (Figure 2). The only natural obstacle to water flows between the two seas was and is the narrow (0.76-3.60 km width) and shallow (32-34 m deep at its sill) Bosphorus Strait. However, subsequent water withdrawals for irrigation, municipalities, and industries have begun to modify the Black Sea thermohaline structure. As a result, the marine biota has started to experience significant negative changes. This study addresses the effect of the current water management (Rozengurt, 1989,1991) and its impact on the physical, chemical, and biological properties of the Black Sea; special attention is paid to analysis of the role of the marine environment's transformation on the future of living conditions of surrounding populace.

TABLE 1 - MAJOR ITEMS OF THE BLACK SEA WATER BUDGET (KM^3/YEAR)

	Möller (1928)	Bruevich (1960)	Solyankin (taken from Alekin, 1966)	Bogdanova (1969)		Möller (1928)	Bruevich (1960)	Solyankin (taken from Alekin, 1966)	Bogdanova (1969)
River Run-off	328	350	346*	--	Evaporation	354	350	332	--
Precipitation	231	225	119	--	Outflow through the Bosphorus	398	400	340	357
Influx from the Bosphorus	193	175	176	174	Outflow into the Azov Sea	--	--	32	--
Influx from the Azov Sea	--	--	53		TOTAL	752	750	704	--
TOTAL	752	750	694	--					
Discrepancy		-	10	--					

* River flows into the Azov Sea are excluded.

The descriptions and conclusions are based on the existing historical data set, statistical relationships and specific mechanisms of the water and salt exchange over the southern and northern sills of the Bosphorus Strait.

A. Large-Scale Thermohaline Structure and Dynamic Mechanisms

The relatively low salinity (182 g/Liter) of the Black Sea surface layer is caused by an excess of the integrated sum of run-off plus precipitation over losses due to surface evaporation (Table 1). However, this fresh water surplus has less strong impact on salinity of water masses underlying the surface layer (100 to 200 m thickness, down to 2,000 m plus) because of the sharp density discontinuity, or the permanent halocline (PHC), between the two major water bodies (Figure 3). This phenomenon is derivative of a well-pronounced seasonal thermohaline (STC) because of strong heating in spring-summer (curves 3 and 4). Another element of thermohaline structure, the so-called cold intermediate layer (CIL), is well defined throughout the sea (the core temperature is usually 1.0-2.0°C lower than water during the cold period). This layer is formed during the winter vertical mixing, known as inverse temperature stratification. The PHC and STC obstruct the vertical mixing and isolate waters below 150 to 200 m (or the so called chemocline [CC] or Pycnocline defined in Figure 3) from sources of oxygen. As a result, the major bulk of the Black Sea water is stagnant, anoxic, and essentially lifeless. The sustained yield of hydrogen sulfide (H_2S) is maintained by sulphate reduction below the CC and by decomposition of proteinaceous substances settling down to the anoxic zone (Skopintsev, 1975; Sorokin 1983). Thus, the high rate of vertical mixing ensured a sufficient amount of oxygen only in the upper layer, from the surface to 75 to 100 meters depth.

FIGURE 1

Major Rivers, Estuarine Regions, and Associated Geographic Settings

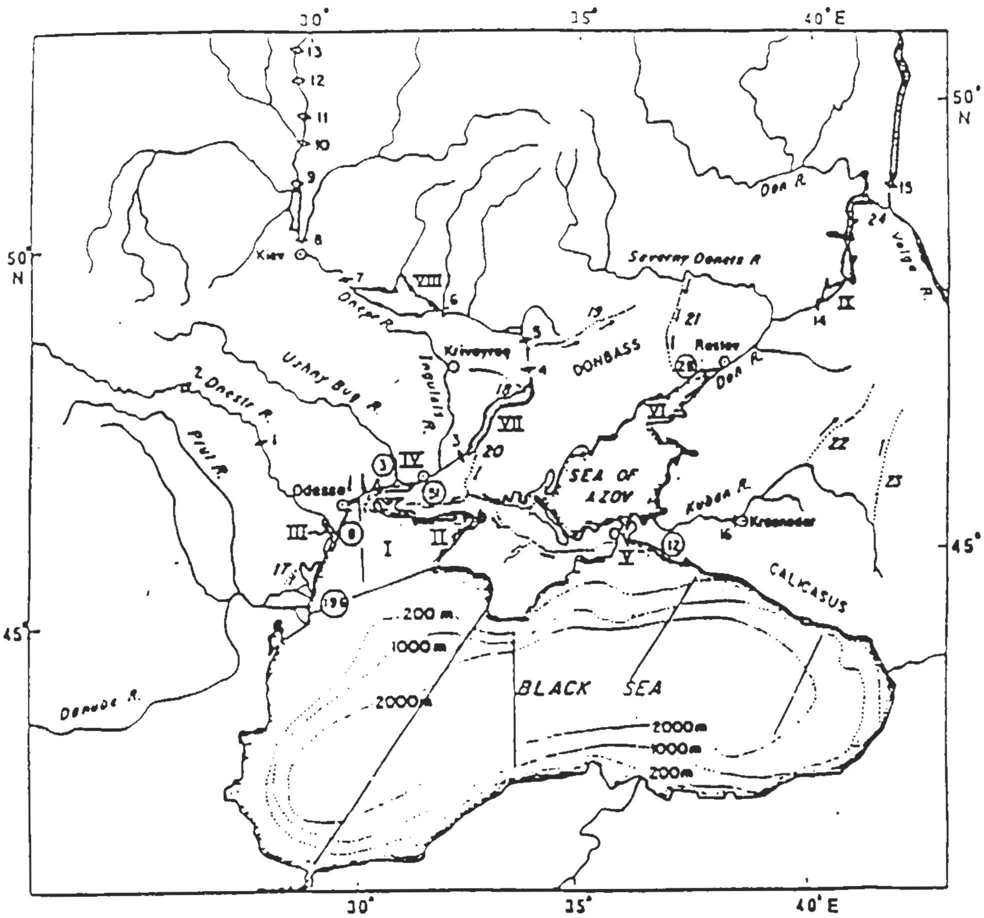


FIG.I. MAJOR RIVERS, ESTUARINE REGIONS AND ASSOCIATED GEOGRAPHIC SETTINGS OF THE BLACK SEA MENTIONED IN THE STUDY, AS WELL AS HYDROPOWER PLANTS (diamonds) AND IRRIGATIONAL SYSTEMS (dotted lines with arrows). STRAIGHT LINES ARE CROSS SECTIONS OF REGULAR OBSERVATIONS.

LEGEND

I - IX WATER BODIES

I. NORTHERN BLACK SEA
II. KARKINITSKY ZALIV (BAY)
III. DNIESTER ESTUARY
IV. DNIEPER ESTUARY
V. KERCH STRAIT
VI. TAGANRUGSKY ZALIV (BAY)
VII. KAKHOVSKOYE VDKHR (vodokhranilistse - storage lake)
VIII. KREMERCHUGSKOYE VDKHR
IX. TSIMLIANSKOYE VDKHR

I - 16 HYDROPOWER STATIONS

1. DUBOSSARY
2. MOGILEV PODOL'SKY (under construction)
3. KAKHOVKA
4. DNEPROGES
5. DNEPRODERZHINSK
6. KREMENCHUG
7. KANEV
8. KIEV
9. LUBECK
10. RECHITSA
11. ZHLOBIN
12. VILIAKHOVKA
13. MOGILEV
14. TSIMLYANSK
15. VOLGOGRAD
16. KRASNODAR

17 - 24 IRRIGATION AND WATER SUPPLY CHANNELS

17. DANUBE
18. DNEPR - KRIVOYROG
19. DNEPR - DONBASS
20. DNEPR - CRIMEA
21. SEVERNYDONETS - DONBASS
22. NEVINNOMYSSKY
23. KUBAN - KALALIS
24. VOLGA - DON

THE ARROWS NEAR CANALS SHOW THE DIRECTION OF FRESH WATER DISTRIBUTION.

ANNUAL RIVER WATER DISCHARGE IN km^3/YEAR AS SHOWN IN ENCIRCLED NUMBERS.

FIGURE 2

Turkish Strait System

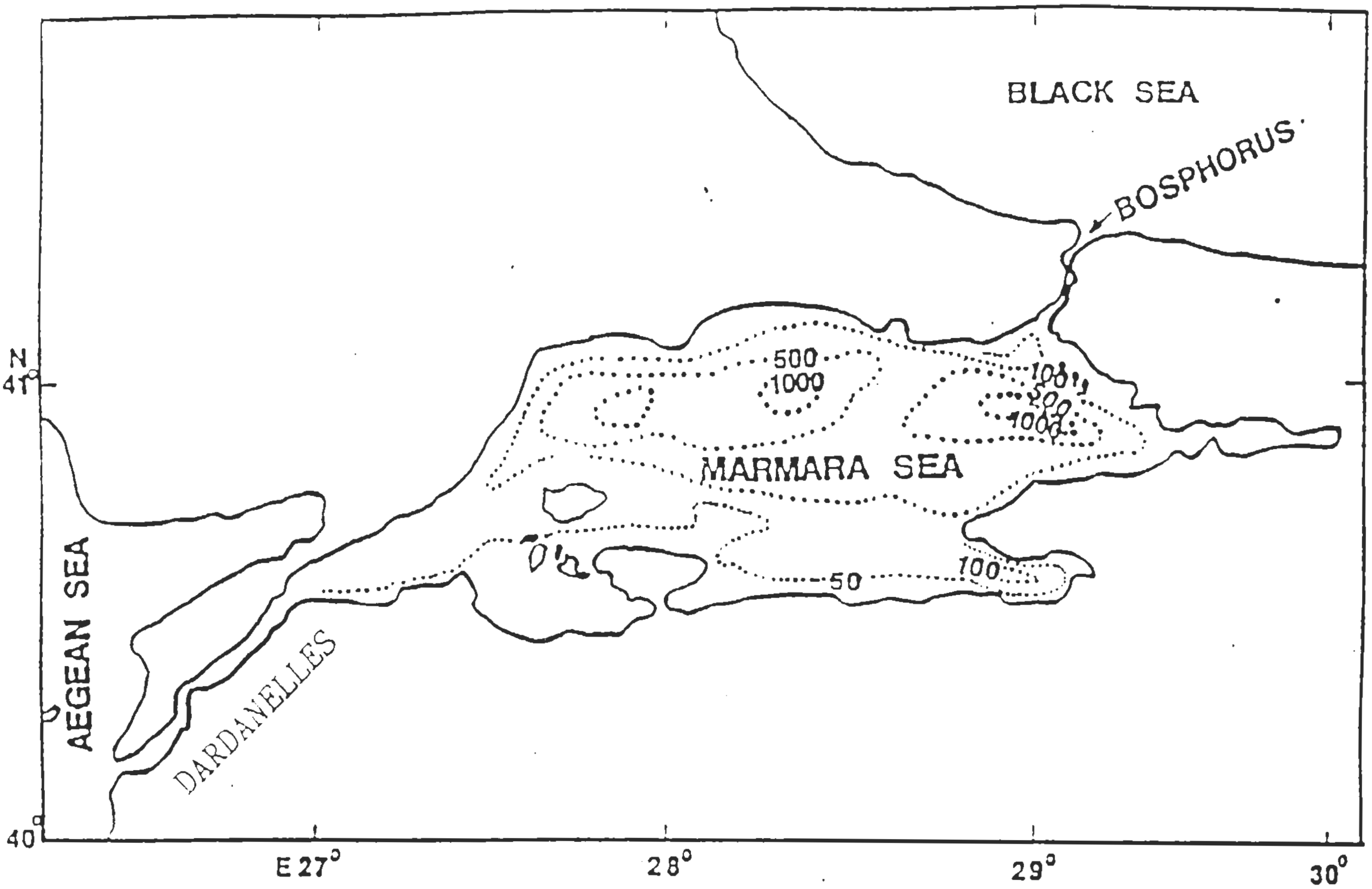


FIG. 2. TURKISH STRAIT SYSTEM
(DEPTH IN METERS)

The upper life-sustaining layer is remarkably patchy. The bulk of marine life is concentrated i the vicinity of the sea shelf, particularly in the Northwestern Shelf (NWS) and the Sea of Azov. (The latter is a part of the Black Sea basin and the recipient of the Don and Kuban river flows entering the Black Sea through the Sea of Azov - Kerch Strait ecosystem.)

The circulation patterns of the Black Sea's upper layer (Figure 4) consist of three well defined gyres: 1) cyclonic in the western part, 2) cyclonic and 3) anticyclonic in the eastern part. The nature of these gyres are mostly geostrophic (Neuman, 1943; Bol'shakov, et at, 1964; Filippov, 1968; Blatov. et al, 1980). The mainstream, which is frequently referred to as the Principal Black Sea Current, is 40-80 km wide and encircles nearly around the sea at a distance of 20-150 km from the coastline. Geostrophic circulation is more intense in winter, when its velocity reaches 40 to 45 cm per second, particularly below the seasonal thermocline (Blatov, et al, 1980).

Instrumental measurements (Filippov, 1968; Boguslavsky, et al, 1976) indicate that actual average velocities in the mainstream may be larger than purely geostrophic velocities (Figure 4 inset). Despite the presence of seasonal patterns in water transport, two major cyclonic gyres are well-pronounced throughout the year, and their circulatory patterns are presumably related to frequent average cyclonic wind-shear over the sea (Chernyakova, 1967).

The major flow patterns induce transverse motions associated with the Coriolis effect. The centers of the cyclonic gyres exhibit well defined, dome-shaped hills in isolines of property fields suc as temperature, salinity, oxygen, and H_2S concentrations (e.g. Blatov, et al, 1983). At the outer portions of the gyres, the downward motions prevail. This slow transverse motion (vertical velocities can hardly exceed 10^{-4} cm s^{-1} (Tolmazin and Rozengurt, 1965) is one of the most important mixing mechanisms, acting to a depth of 300 m. Below this depth, horizontal property gradients are barely detectable (Filippov, 1968), except for some local and transient effects.

FIGURE 3

Average Vertical Thermohaline Structure

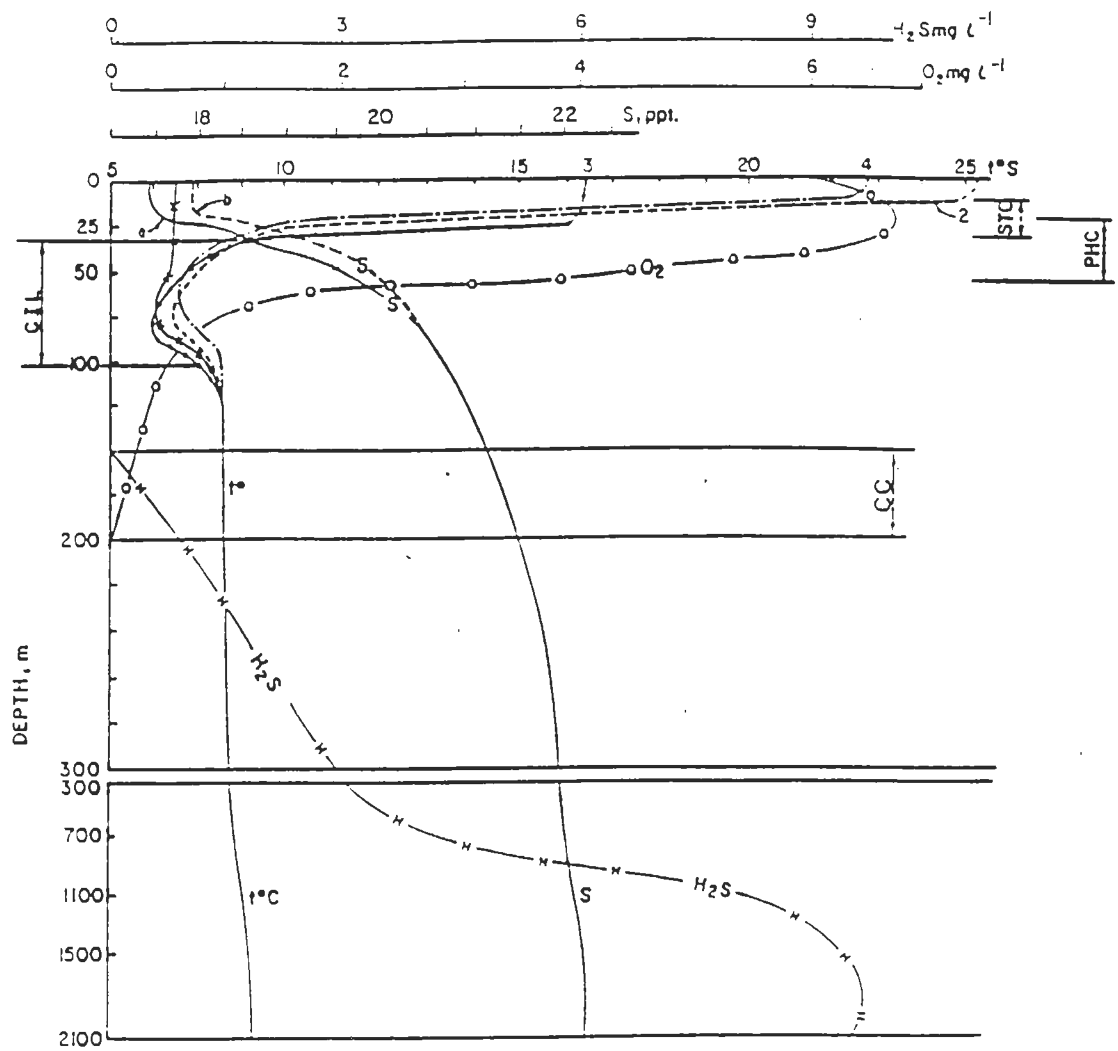


Fig. 3 Average Vertical Thermohaline Structure of the Black Sea (and associated terminology). Vertical distribution of temperature T^oC in various months (1-June, 2-August, 3-November, 4-February), salinity, S ppt (a-summer, b-winter), oxygen O_2, and hydrogen sulfide H_2S. Permanent halinocline (PHC) is the layer of sharp vertical salinity gradient, seasonal thermocline (STC) is the spring-summer discontinuity below the wind-mixed layer; cold intermediate layer (CIL) is the layer of the lowest temperature, a remnant of winter convection in the shelf zones; chemocline (CC) is the boundary layer between aerobic and anoxic zones which usually coincides with the layer of lowest mixing rate due to wind-induced and geostrophic currents. These abbreviations are used throughout the text.

FIGURE 4

Diagram of Current in the Upper Layer

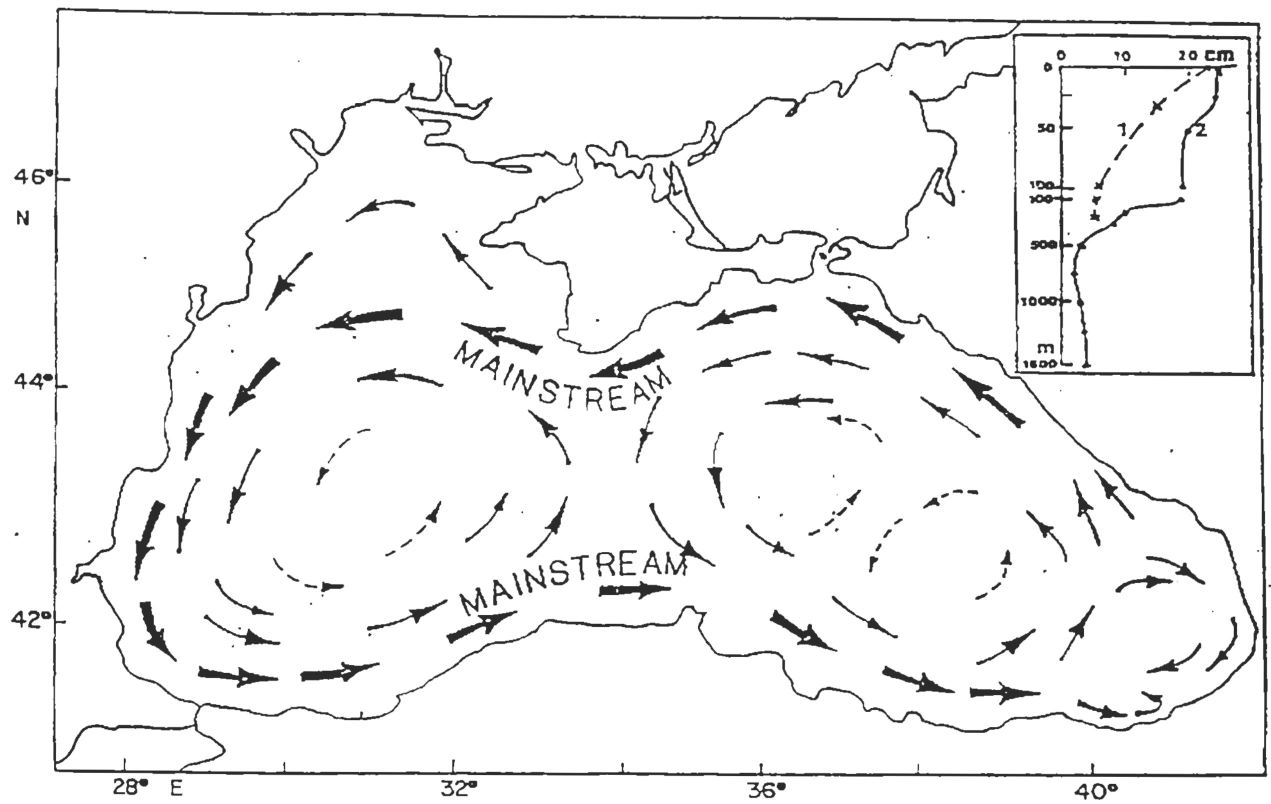


FIG. 4.

Diagram of current in the upper layer (down to the lower boundary of PHC). Based on the geostrophic computations of Neumann (1943); Bol'shakov, et. al. (1964); Filippov (1968); Blatov et. al. (1980) and sparse spot current measurements (Boguslavski, et. al., 1976)

Inset: average geostrophic (1) and actual velocity (2) profiles in the mainstream. The most stable currents are shown by the thick arrows. The dashed arrows are very unstable, variable currents.

Another important transport mechanism, which is mostly horizontal, is associated with spreading of the cold waters from the NWS in the CIL (Figure 3).

In February-March, the average temperature in the NWS ranges from 2° to 4°C (Tolmazin, et al, 1969) and gradually increases south and southeast reaching 6°C in the southeastern corner of the sea (Blatov, et al, 1983). In April, with the onset of the warm season, the horizontal differences in surface temperature reduced to 1 to 2°C but at the peak of the summer the gradient increases to 3 to 4°C. Following this increase, the seasonal themocline is formed, and the CIL is the only reminder of the intensity of vertical convection and horizontal advection during the preceding winter. The displacement of the lower and upper 8°C isothermal surfaces defines the boundaries of the CIL.

During the cold period, which coincides with low river flow, the NWS waters grow denser than much warmer water masses of the southern region. As a result, they descend along the slope off the NWS. The hypothesized rate of descending motion equals 10^{-5} to 10^{-4} cm per second. The intrusions of cold waters are detected by peculiar shapes of the isotherms that reveal wedgelike distribution of temperature along the prevailing currents. In strong winters, the descending flow may suppress the CIL lower boundary (a remnant from the previous winters). This facilitates the downward motion to depths deeper than simple convective overturn. In these cases, cold and oxygen-laden water reduces H_2S boundary to depths of 400-500 m (Bol'shakov, et al, 1964). The cold water discharging from the Kerch Strait is much less effective than the enormous NWS outflow, but the Azov outflow exerts a similar effect on oxygen enrichment of the Eastern Black Sea.

The NWS circulatory patterns entrain this cold water toward the Rumanian, Bulgarian, and Turkish coasts (Figure 4). Minimum temperature in the core of the CIL is 6.5-7.0°C. The cold water comes closer to the surface in the centers of the gyres, but the CIL is less pronounced in these areas. Eventually, the bulk of winter water tends to be accumulated in the far southeastern corner of the sea (the warmest place in the Black Sea) known as the "ultimate sink" for the cold waters. Their descending remnants form the deepest and largest pool, which may be trapped for a long period of time before starting its way along the northern mainstream. Circulatory features here are less stable than in other parts of the sea, but once evolved they develop a so-called local anticyclonic gyre (Filippov, 1968) which deepens the lower boundary of the CIL to 200 to 500 m (as opposed to 1200 m elsewhere along the mainstream). This anticyclonic gyre may last for several months.

Since the most substantial variables in property of different water masses (river flows, cold mixed, brackish waters from the NWS, and Mediterranean salty waters) have typified the western part of the sea, the PHC average depth does not exceed 60-80 m, whereas in the eastern part and near the Crimea the PHC penetrates as low as 100-120 m. The role of Mediterranean waters in the formation of the Black Sea thermohaline structure will be discussed later.

The rate of vertical mixing in various parts of the sea demonstrates that appreciable turbulent diffusive flux is felt slightly below the CC only in the mainstream (down to 300 m; Bogdanova, 1959; Tolmazin, et al, 1967). Below this zone, the water masses are very homogeneous because of slow motions and insufficient vertical mixing (Vladimirtsev, 1967). Note that their gaseous regime is lethal for all but specific bacteria (Leonov, 1960).

A distinct plume of saltier Mediterranean water was always observed northwest of the Bosphorus entrance (Figures 2 and 8). The Mediterranean effluent resembles a wedge of salt water contracted to the sea bed (vertical spreading does not exceed 7-8 m). The 20 g/Liter isohaline is considered as the boundary of the plume. Within these limits, the width of the flow at the southern boundary of the study area varies from 5 to 30 km. The plume rarely exceeds 50 km in length, and it is typified by very stable velocity up to the point of final dilution.

Farther down, along the continental slope, the Mediterranean waters are barely detectable by slightly elevated temperature and salinity for the Mediterranean water slowly descends and mixes with the ambient along the mainstream. At a distance of 800-900 km from their origin, the traces of salty and warm water are found as deep as 300-400 m. Analysis of radiocarbon water aging (Ostlund, 1974) underscores that the "youngest" water of 780 to 980 years occupies the "ultimate sink" (Figure 7), and the oldest Mediterranean water of 2,200 years is located in the central part of the Black Sea. Apparently the very diluted Mediterranean water is transported beneath the CIL and gradually sinks along its descent to the southeastern corner.

II. SOME CHEMICAL PHENOMENA AND BIOLOGICAL PROPERTIES

The Black Sea is the world's largest meromictic basin, i.e. it contains the greatest amount of anoxic water on the planet below the highly stable chemocline (CC). This determines the chemical and biological uniqueness of the Black Sea basin. The ionic composition of the Black Sea is similar to that in the ocean with the exception of the carbonate ion (Skopintzev, 1975). The concentration of CO_3^{2-} increases downward from 0.46% of the total salt content in the upper layer to 0.95% in the anoxic layer vs. 0.207% in the ocean. Excess CO_3^{2-} is caused by the large carbonate influx of river flows and the production of large quantities of carbon dioxide during anoxic decomposition of organic matter.

The upper boundary of the CC coincides with a sharp vertical gradient in reduction-oxidation (redox) potential Eh (Figure 5) which drops from +150 to -50 mV (in the ocean Eh is positive everywhere). The notable decrease in the Eh gradient, in the middle of the CC, suggests that biological (microbial) oxidation of H_2S due to slow vertical mixing (turbulent or convective) largely overshadows the chemical oxidation. Above the CC, the redox potential reaches +350 to +430 mV which is associated with the "normal" dissolved O_2 concentration. In summer the O_2 maximum (130 to 140% saturation) is usually observed in the upper part of the CIL, apparently, due to the enhanced photosynthetic activities. In winter, the vertical concentration of O_2 is nearly uniform down to the layer boundary of seasonal convective overturn (Figure 3).

Below the CC the formation of H_2S (about 80-90% is SH^- and the rest is S^{2-}) is maintained by chemical-bacterial sulphate reduction (Figure 5).

Any oxygen-containing nutrients, such as NO_2^{2-}, NO_3^{2-} and PO_4^{2-}, which penetrate into the upper part of the anoxic zone, are rapidly decomposed by thiobacilli, which use O_2 for respiration. However, the anoxic zone has accumulated large amounts of ammonia and silicate (two to five times more than in deep oceanic waters) as well as organic forms of N, C, and P. Note that these compounds potentially could have been used in the food chain if they had been brought into the upper photic zone by vertical movements.

It is widely believed that the unusually high nutrient concentration in the photic zone far away from the major nutrient sources (rivers and estuaries) is maintained by the slow outcrop of deep water in the cyclonic centers and transverse circulation, described above (Figure 4). It is partially supported by the marked peak in particulate manganese at the layer of 60 to 150 meters above the oxygen-zero level (Figure 5 - Brewer and Spenser, 1974). Similar phenomena were observed for iron oxides. Some other aspects of subtle chemical-microbrial interactions will be shown later.

A. Biology

A diversely poor, but very productive Black Sea biota has evolved due to a "harmonious" operation of the major large-scale physical, chemical, and biological processes during the last

7,000 to 10,000 years. At the end of this period, the oxic-anoxic interface reached its balanced position which coincided with the established intrusion of Mediterranean water.

Faunistic and microbiological studies in the Black Sea revealed rather complex chemical-biological interactions of matter and energy fluxes between various trophic levels of the food web, and spatial distribution of flora and fauna in connection with major sources of fresh, brackish, and marine waters.

The rate of biological productivity of the Black Sea was known to be much higher than in the ocean. For example, out of 550 billion tons of primary production of the world ocean, 415 billion tons or 75% are utilized by various organisms. Pelagic species consume 68% of the above amount, whereas 7% is used by the benthic forms. In the Black Sea, the annual primary production used to reach 1.5 billion tons, but 78% was consumed by pelagic and benthic organisms. The Black Sea fish constituted 0.2% of the total primary production, whereas in the ocean, it was equal only 0.051% (Karpevich, 1968).

B. Microflora

Microbial processes in the Black Sea are playing a rather more exceptional role in the marine environment than do those in any other sea, for bacteria are distributed in more than 80% of the Sea's volume, often where other organisms cannot survive. Bacterial production of biomass, which can be readily assimilated by protozoa and filtering plankton, is not so important by itself for life in the sea, but its role is vitally significant in maintaining the abundance of sulphur, carbon, nitrogen, etc. that the micro-organisms consume.

The amount of heterotrophic bacteria is abundant in the upper oxygen layer but their quantity is decreasing from the coastal (particularly in the river-affected areas) to the central parts of the sea. In the vertical direction, the maximum microbial concentration and production is noted in 1) the upper thin film (known as hyponeuston) mostly due to detritus brought by drainage from the land, 2) in the STC, acting as a screen for light suspended organic material, and 3) close to the lower boundary of the redox gradient zone, where the basic maximum of thiobacilli and methane-oxidizing bacteria actively participate in chemosynthesis production (oxidation of H_2S, Mn^2+, F^2+, CH_4, and other compounds released upward from the anoxic zone).

In the upper layer of the anoxic zone, the principal production of H_2S from SO_4^{2}- occurs due to surface reduction by abundant anaerobic bacteria (Figure 5).

The sources of organic matter are dead phytoplankton, zooplankton, and other detritus particulate produced during chemosynthesis in the redox gradient zone. The rate of sulphate reduction is about 6 mg H_2S M^{-3} day $^{-1}$.

Except for the areas along the continental slope, sulphate reduction in the water column is negligibly small. In the near-bottom water, the source of organic matter is debris precipitated to the sea bed. The rate of sulphate reduction in this layer is 10 mg H_2S m^{-3} day^{-1}. Other oxides, such as MnO_2, and compounds of iron, cobalt, and zinc (Brewer and Spenser, 1974), are also reduced to the corresponding anions $M_n^{2}+$ (Figure 5), Fe^2+, Fe^3+, Co^++, etc. In the same zone general production of H_2S is estimated at 20 $gm^{-2}yr^{-1}$ or 7 x 10^6 tons yr^{-1} (Sorokin, 1964).

The upward expansion of the anoxic zone is effectively barred by processes of chemosynthesis above the zone (Figure 5). Estimates indicate that the annual rate of H_2S oxidation is 150-100 $gm^{-2}yr^{-1}$ (Aizatullin and Skopintzev, 1974), which is several times more than the H_2S production. This disparity is attributed to insufficiency of the data base and, perhaps, additional H_2S production from the ancient organic sedimentary deposits.

FIGURE 5

Chemical-Microbiological Interactions

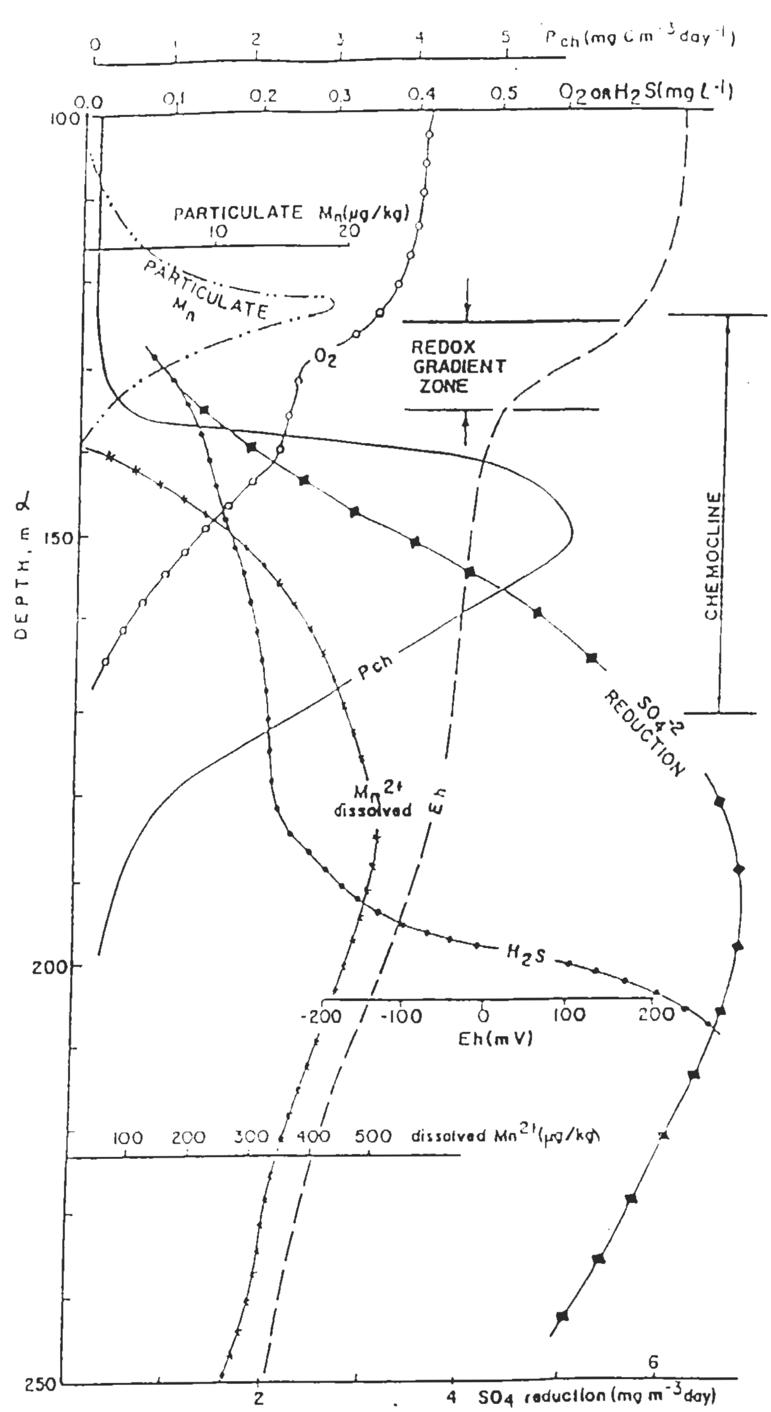


Fig. 5 Chemical-microbiological interactions around the chemocline as revealed by the vertical distributions of O_2, H_2S, P_{ch} (rate of chemosynthesis production), redox potential Eh(mV), particulate and dissolved Mn, and the rate of SO_4^{-2} reduction of anaerobic bacteria. (Brewer and Spenser, 1974).

The processes of chemical and microbiological oxidations of H_2S in situ are not equivalent so far as the energetics of the ecosystem are concerned. The energy produced by H_2S oxidation, which can be used via microbial chemosynthesis by the ecosystem (curve Phc, Figure 5) is greater than that produced by oxidation of an equivalent amount of organic matter. During chemical oxidation, this energy is lost as heat. The additional biomass produced during chemosynthesis is partially used by filtering zooplankton and by protozoa. Sulfur and carbon cycles are maintained by microorganisms.

C. Phytoplankton and Zooplankton

This, the largest source of primary production, consists mostly of a wide variety of euryhaline diatom species. They flourish within a salinity range of 16 to 18 g/L. Their composition and biomass production are coastal and seasonal. The major sources of high production are coastal waters, primarily river flows (Figure 6) enriching the surface layer with nutrients. The circulation patterns clearly influence the spatial phytoplankton distribution. Existence of phytoplankton in nutritionally depleted central parts of the sea suggests that some organic material may enter the food web from the anoxic zone via chemosynthesis.

In the pelagic food chains of the Black Sea, the most important species of zooplankton are the copepoda. In coastal waters they compose 50 to 70% of the total zooplankton biomass. Another important group is larvae of various benthic organisms and fish.

The pelagic zooplankton consist of several species of the thermophilic (warm-loving) non-migration group which tends to inhabit the upper warm layers, and a psychrophilic, more active group attached to colder waters down to 150-170 m. These two groups are well separated by the STC in summer, and only during pronounced upwelling can the psychrophilic group approach coastal waters rich in nutrients and phytoplankton (Koval, et al, 1967).

FIGURE 6

Primary Production by Phytoplankton

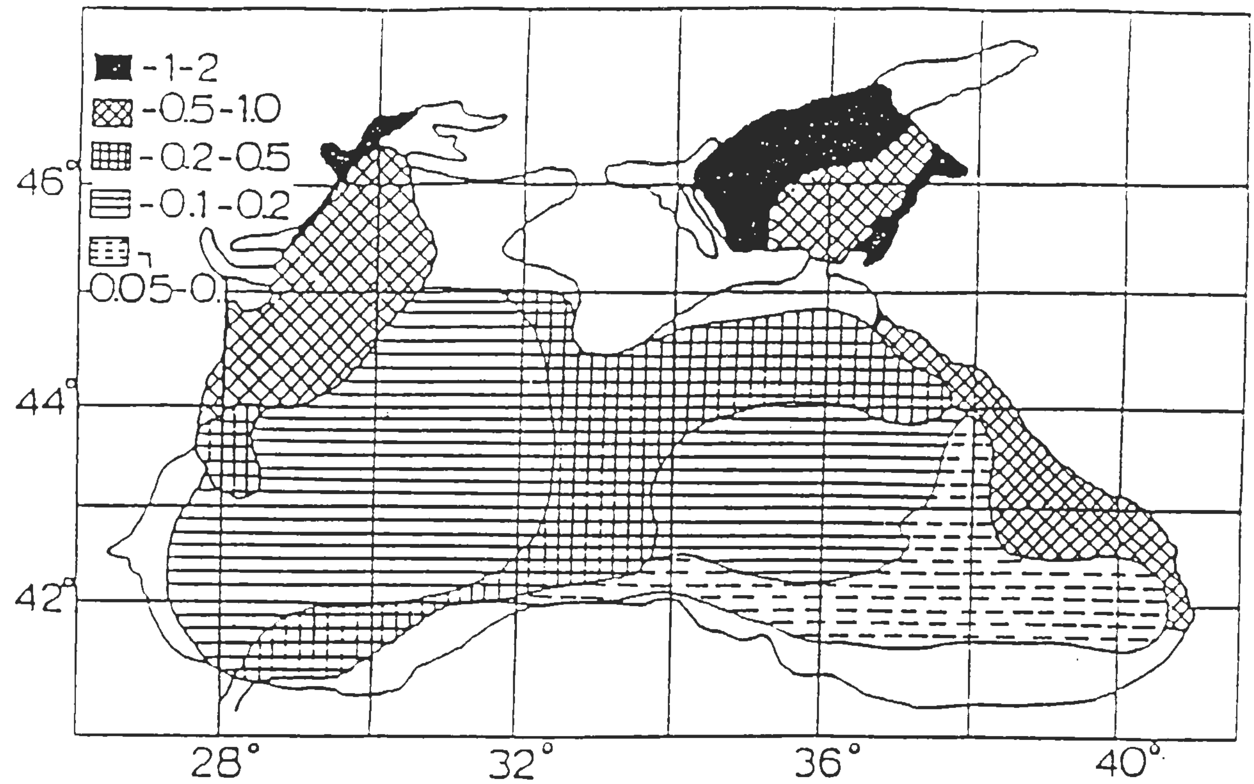


Fig. 6 Primary production by phytoplankton in the Black Sea ($g\ C\ m^{-2}\ day^{-1}$) in August-October (modified after Sorokin, 1964; and Finenko, 1967)

D. Fish Population

Distribution of life in the Mediterranean and the Black Sea is closely linked with the dissimilarities in physical and hydrochemical properties in the two basins. Qualitatively abundant stenohaline Mediterranean flora becomes markedly impoverished in the Black Sea (Zenkevich, 1963). Of more than 6,000 Mediterranean species, only 1,500 are tolerant to the harsh environmental stresses of the Black Sea, and only 200 are found in the Azov Sea. Native Pontic and relict euryhaline (less sensitive to salinity variation) communities in the Black Sea are much less diverse than in the Mediterranean.

Commonly distinguished are four major groups of 180 species of fishes populating the Black Sea (Zenkevich, 1963; Vinogradov, et al., 1967). One distinct community consists of fresh-water organisms which inhabit river mouths and low salinity zones of the sea. These semi-anadromous fishes cannot survive in salt water, and enter the sea only during a flood period.

Another community consists of native Pontic (sometimes called Caspian) fauna, which developed in the basin after the Tertiary Period and adapted to considerable changes in the Black Sea's brackish water environment. Among them the most valuable are anadromous fishes which enter rivers in spring for spawning, but otherwise prefer low salinity areas of the sea. Among this group the best known are beluga, sturgeon, sevruga, and several species of herring.

Since the time of the Ice Age, a small community of 8 species, a relic of the Arctic migrations, has flourished in the Black Sea. They prefer cold waters below the seasonal thermocline and breed in the late fall or winter. The most frequently caught from this group is sprat.

Finally, the most numerous group is the Mediterranean migrants. They inhabit the upper 150-180 ı layer of the sea. Out of 117 species, only 60 breed in the Black Sea. The most well-known are comber scombrus (mackerel), Sarda sarda (bonito), and three species of Mugilidae (mullet) and some thers.

The fish of the first two groups inhabit the Sea of Azov and the NWS, while the other two groups ›refer the salt waters of the open sea. However, numerous Mediterranean groups use the NWS as ›reeding and nursery grounds. The majority of the Black Sea fish spend the entire summer and a part ›f the fall in the NWS, leaving it only with the onset of cold weather. Some species, like anchovy, nigrate from the Black Sea through the Kerch Strait to the Sea of Azov. The latter is used as feeding ʒrounds. Two major species of Mugilidae use shallow lagoons of the NWS (Figure 2).

Rich vegetation, high biomass of benthos, and dense pelagic plankton provide plenty of food for the young and adult forms of fish and shellfish species in shallow estuarine regions. For instance, NWS macrozoobenthos produces biomass 0.4 kg/m^2 on average, which is 60% more than in other shelf zones of the Sea (Vinogradov and Zakutsky, 1967).

All groups of Black Sea fauna also exhibit peculiar morphological composition and physiological cycles compared to the same groups in the Mediterranean. Biological productivity, however, dramatically increases from west to east. For instance, benthic biomass in the eastern Mediterranean Sea reaches only a few grams per m^2, whereas in the Black Sea it amounts to 100-200 gr m^{-2} or more. The Sea of Azov used to have outstanding fish production (80 kg/ha), because of large quantities of nutrients brought by rivers, which were effectively utilized by all trophic groups in a short time. The Black Sea used to provide a fish yield of 13.2 kg/ha, whereas the Mediterranean Sea has only about 0.1 kg/ha. This gradual increase of biological productivity highlights peculiar patterns of the eastward spawning-feeding migration.

Aggregated statistics of overall biomass and production of various groups is shown in Table 2.

TABLE 2 - BIOMASS AND ANNUAL NET PRODUCTION OF THE MAIN ELEMENTS IN THE BIOLOGICAL STRUCTURE OF THE BLACK SEA

Structural Elements	Biomass, Wet	10^6 tons Ash-free	Production, Wet	10^6 tons Ash-free
Chemosynthesizing microbes	0.25	0.04	27.27	4.36
Microphyto benthos	0.50	0.03	54.50	3.27
Microphytes	16.00	2.72	17.00	3.00
Phytoplankton	3.70	0.31	1213.60	102.00
NOCTILUCA	5.60	0.09	40.88	0.64
Zooplankton				
phytophages	3.10	0.36	99.20	11.52
detritophages	0.80	0.04	35.04	1.76
predators	6.02	0.08	60.80	1.27
Zoobenthos	23.80	0.81	53.60	2.00
pelagic	1.38	0.25	10.74	18.25
Bacteria				
benthic	2.03	0.36	74.09	13.14
planktophages	0.54	0.11	0.59	0.12
Fishes				
benthophages	0.08	0.02	0.09	0.03

Note that since the 1960s, (Puzanov, 1965) about 150 new, typical Mediterranean species have been found in the formerly brackish areas, which suggests that this process has intensified due to fresh water withdrawals from the Black Sea and Sea of Azov rivers.

The "natural harmony" of the Black Sea described earlier was disrupted not only in the coastal and estuarine habitats, but in the entire sea. It was not expected that the Mediterranean migrants, which only partially feed on the brackish-water plankton, could not survive in the Black Sea after the completion of the hydroenergy program. The first to go was the tasty Black Sea mackerel. Its whole stock of some 50,000 to 100,000 metric tons had disappeared by 1967, and has never recovered since. The experts thought it was due to rapid reproduction of predators such as bonito and bluefish, and concluded that the place of the mackerel would be taken by another high market-value fish, a scad with a stock of some 200,000 metric tons. But the scad also vanished, followed by bonito and bluefish. The only edible fish still being caught by numerous trawlers near the Kerch Strait are the anchovy, a small type of scad, and the less abundant sprat.

All marine species whose sustained yield and reproduction cannot be maintained by artificial propagation (e.g. some Arctic relics) have been brought to the brink of extinction. No replacements in free "niches" of the highest forms of living resources are possible to attain without a long process of evolution or adaptation.

The major reduction of river flow from the northern slope of the Black Sea began with the discharge development of postwar Soviet water management projects. The impoundment of rivers was completed in the early 1970s.

The run-off depletion was further compounded by massive development of irrigation networks. An immediate effect of the water withdrawals from the Dniester and Dnieper, and the diversion of over 28% of the Danube spring run-off, can be characterized by the following chain of events. Powerful spring floods lasting 25-40 days, typical for the natural conditions of the Black Sea rivers, were replaced by two smaller peaks of river discharge of much longer periods. One of them (in winter - early spring) is caused by intense hydroenergy generation and weir discharges through the cascade of storage reservoirs. Another is associated with the spring flood, modified by refilling of storages. This has strengthened the summer pycnocline which has inhibited vertical mixing of coastal waters. As a result, the rate of natural purification of the entire coastal system has been reduced 7 to 12 times. This, coupled with the increased nutrient, organic, and pollutant transports, has led to anoxic events and mass mortalities of marine organisms in previously productive regions. Acute oxygen deficits also occurred frequently in the Sea of Azov.

Dams and irrigation networks not only worsened the water quantity problems, but they created a water quality problem. Agricultural run-off and irrigational seepage, carrying large quantities of fertilizers, pesticides, and organic wash-outs from the cropland, disrupted food webs in the receiving basins, causing drastic changes in nutrient and biogenic supply to estuaries and coastal waters (Denisova, 1979). Ultimately, less fresh water reached the Black Sea and the quality of the water that did reach it deteriorated (Zhuravieva, Simonov, and Belyaev, 1972; Rozengurt, 1974, 1991; Krotov, 1976; Zaitsev, 1989).

In practice, voluminous fluxes of nutrient ions (NO_3^{-2}, NO_2^{2}-m P_{-4}^{2}-m etc.) and fresh organic matter during the natural spring freshets have been replaced by fertilizers, soil outwash, and decaying remnants of flora from the fields and livestock yards. Early phytoplankton blooms in the string of storages caused eutrophication, which further depleted nutrients so vital for marine biota. The low-lying marshes no longer are covered by water and are drying up. The dredging in the Danube delta strengthened salt wedges in the navigational channels that severely depleted the brackish water habitat of key species, especially semi-anadromous and anadromous Danube and sea fishery. As a result, the Soviet coastal fishery, based on the catch of these valuable fish, nearly ceased to exist.

In spite of various conservation programs (industrial water recycling, better pollution control, more efficient irrigation, curtailment in hydroenergy production, etc.) introduced in the late 1970s, losses of fresh water increased so dramatically (Table 3) that some remedial measures to arrest the decline in water availability and fisheries in the lower reaches and estuaries became necessary. Several proposals have been suggested (Lagutin and Tolmazin, 1965; Osmer, 1973; Rozengurt and Tolmazin, 1976; Ponomarenko, 1980; Kochina and Ratkovich, 1983) for restriction or cessation of water exchange between the Black Sea and the river-affected areas such as the Dnieper and Dniester estuaries, and the Azov Sea (Figure 7). A project for complete partitioning of the Azov Sea from the Black Sea was widely discussed in the 1970s and was severely rebuffed by the author at one of the meetings held under the auspices of the Council of Ministers in 1974.

TABLE 3 - APPROXIMATE REDUCTION OF ANNUAL RIVERFLOW OF THE BLACK SEA RIVERS (THE NORTHERN SLOPE) AS A RESULT OF ECONOMIC ACTIVITIES

			Reduction of Annual Discharge for Average Flow Conditions					
			1971 - 1975		*1981 - 1985*		*1991 - 2000*	
River	Natural Water Reserves km³	Run-off in the Mouths km³	km³	% of Total at the Mouth	km³	% of Total at the Mouth	Annual km³	% of Total at the Mouth
Don	27.9	27.9	5.4	19	7.6	27	12.0	43
Kuban'	13.4	11.7	4.3	39	5.4	49	3.3	25
Dnieper	53.5	53.5	13.0	24	28	52	30	59
Dniester	9.3	9.3	1.9	20	3.7	40	3.2	30

Sources: Bronfman, et al (1979), Vendrov (1979), Ponomarenko (1981), Tolmazin (1985), and Rozengurt (1991)

Forecasts show that by the year 2000, the water consumption in the Dniester and Dnieper basins will exceed available water resources in years of subnormal wetness (Rozengurt, 1991). The same will be typical for the Danube water reserve. In practice, the four decades unbalanced water development and made it impossible to prevent the complete destruction of the productive 75 m upper layer across the sea. The man-induced trends in the reduction of the flow further aggravated the water quality and ecological properties of the NWS. Modifications in the vertical density structure have affected the sea-wide chemosynthesis and the thermohaline structures in the coastal waters, and entire mechanisms of the cold water spreading and oxygen enrichment of the CIL.

FIGURE 7

Projects to Regulate Water and Salt Exchange

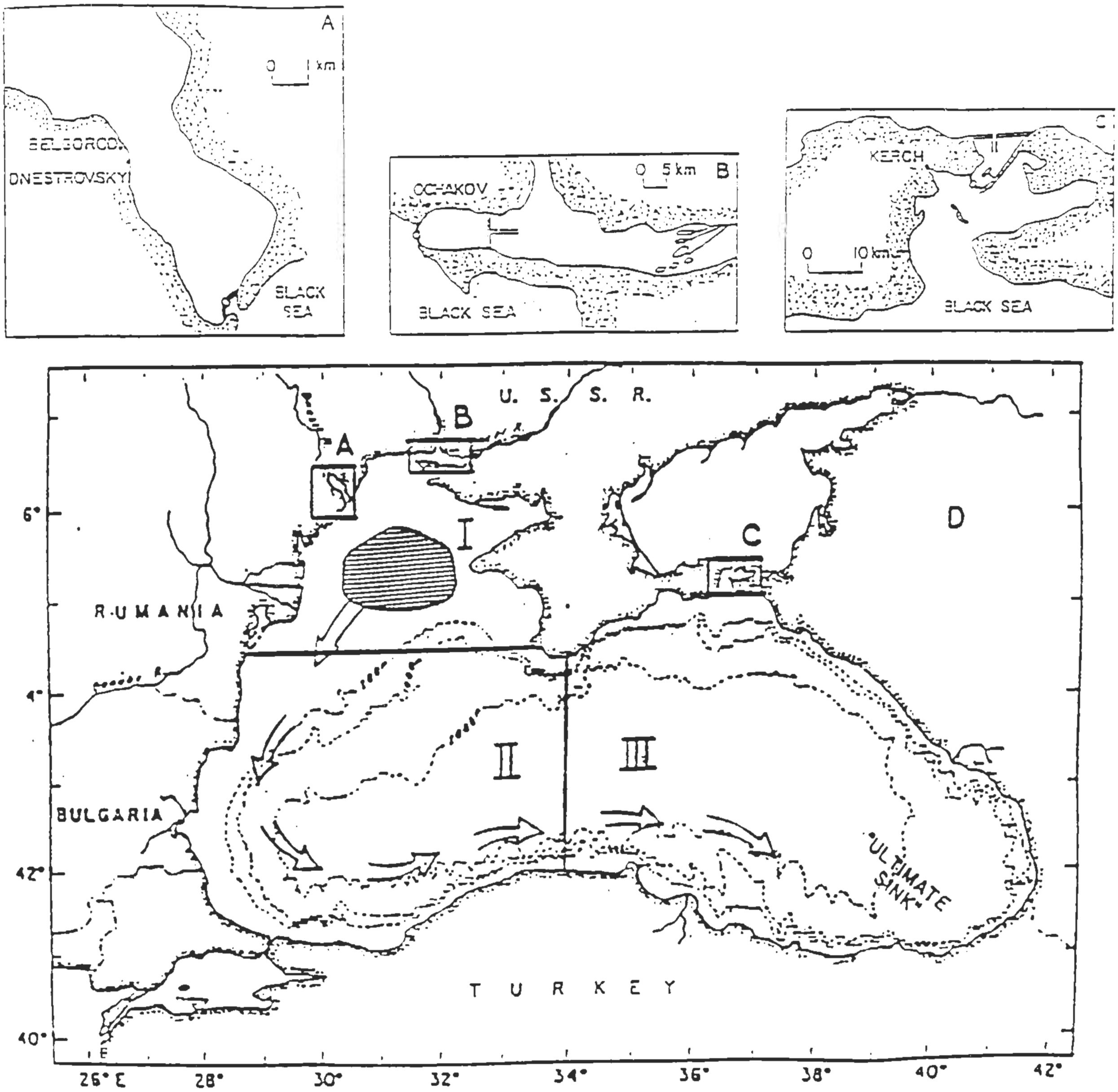


Fig. 7. Projects to regulate water and salt exchange between the Black Sea and the Dniester (A) and the Dnieper (B) estuaries and the Azov Sea (C). Earlier schemes to use combinations of dikes and long canals (Rozengurt and Tolmazin, 1976) are still considered for the Dniester estuary and the Azov Sea. More recent proposals refer to complete sectioning off of the Dnieper estuary and the Azov Sea (Ponomarenko, 1980; Kochina and Rathovich, 1983); however, only the Dnieper project is now undergoing technical and economic justification (Baksheyev and Laskavyi, 1983). (D) various regions of the Black Sea referred to in the text. The shaded area is the zone of cold water formation. Transport of the cold water in the CIL is shown by arrows (Filippov, 1968; Boguslavsky, et. al., 1976).

Existing correlations between the average salinity (S_I) of the upper 200 m layer in the northwestern corner (Region I, Figure 7D) and the average river flow discharge (Blatov, et al, 1980) indicate that the curtailment of runoff (Q) by 50-70 km^3Sec yr^{-1} (anticipated at the year of 2000) will cause the steady increase of S_I by 0.85 - 1.2 ppt. At the same time, the vertical salinity gradients will apparently decrease, particularly in the cold period, and hence more intense convective overturn will be the most likely outcome. The flow of cold water in the CIL from its major source (Figure 7D) will noticeably intensify.

Similar correlations for the western and eastern parts (Regions II and III) show that in 5-10 year intervals (after river flow reduction) salinity in the 200 m layer will increase by 0.35 - 0.45 ppt.

The stabilization period for this process, defined as a time shift of the best correlation, is 15-7 years. The fall convection will deepen everywhere. Increasing turbulent mixing in more homogeneous water may disperse the CIL in winter while the cold water takes its track (Figure 7D) towards the "ultimate sink." This effect very rarely occurs now. Enhanced convective overturn and the transverse circulation mechanism (Section I) may lower the oxic-anoxic interface and facilitate upward extraction of nutrients and chemosynthesis favorable to life. It is not ruled out that the vertical overturn will start earlier in the fall due to salinity convection, particularly in the southeastern corner (the "ultimate sink"), where the evaporation rate is high even during fall cooling. This process will warm the Black Sea water to a large depth, and warmer water will occupy the CIL, gradually spreading vertically. This process may take 10-15 years for stabilization after the initial impact of the onset of lower fresh water availability in the sea.

It will not be until the entire Black Sea is warmed, due to the increased role of Mediterranean water (see next section) that the heat budget of the sea will start to change.

Evaporation from the warmer sea surface will increase, and the intensity of saline convection may surpass the depth of the winter conjecture overturn. Then the amount of heat stored during the long warm period will suffice to create a permanent thermocline. At the end of this period, which may last from tens to a hundred years or more, depending on the mixing of the Mediterranean effluent, the oceanographic regime of the Black Sea, at least at its southern and southeastern regions, will resemble that of the Mediterranean. As in the latter, the diversity of life in the new Black Sea will substantially increase, but the productivity will shrink (Vinogradov and Tolmazin, 1968).

III. THE ROLE OF RUN-OFF REDUCTION ON THE WESTERN BLACK SEA-BOSPHORUS STRAIT ECOSYSTEM

As was shown in the pre-project period, the function of the basic marine mechanisms could be described as follows. During the winter intensive convection and gravitational sinking of cold water down to the anoxic zone causes a rather active vertical mass exchange. With the onset of spring-summer warming, the STC radically slows down the rate of vertical mixing, thus activating the process of bacterial chemosynthesis below and within the CC. Therefore, the amount of fresh organic matter and nutrients available for accumulation by the low trophic level organisms is increased. The STC also vertically separates the thermophilic species from the psychrophilic species of zooplankton. Powerful and short spring river floods bring enormous quantities of nutrients and detritus from the drainage areas. These substances rapidly circulate in the shallow upper layer, causing phytoplankton bloom and attracting numerous semi-anadromous and anadromous fish to the coastal waters, estuaries, lagoons, and rivers for spawning and breeding. In the late spring and summer schools of fish (the Mediterranean migrants in the upper strata and the Arctic relics down below) also rush towards the shallow NWS and the Kerch Strait for feeding. With the onset of cold seasons, the Mediterranean fish migrate south, whereas anadromous (Pontic) fish migrate into the deeper shelved areas for the entire winter. All this smoothly operating machinery has been partially destroyed by the Soviet river flow diversions.

The chronic fresh water deficit slowed down the water exchange, for the cumulative losses in run-off have resulted in a gradual decrease in the surface slope, which has been, since time immemorial, the major source of the upper layer entraining circulation in the Bosphorus.

Arguably, the nearly stable two-layered density and southbound/northbound circulation structure in the strait area are entirely the products of hydraulic head, whose origin is linked to excess of fresh water over evaporation. Subsequently, the less dense Black Sea waters occupied the surface layer and directed its motion to the Marmara Sea. At the same time, the marked density imbalance between the Black and Marmara Seas is pushing the denser Mediterranean water to the Black Sea along the strait's bed.

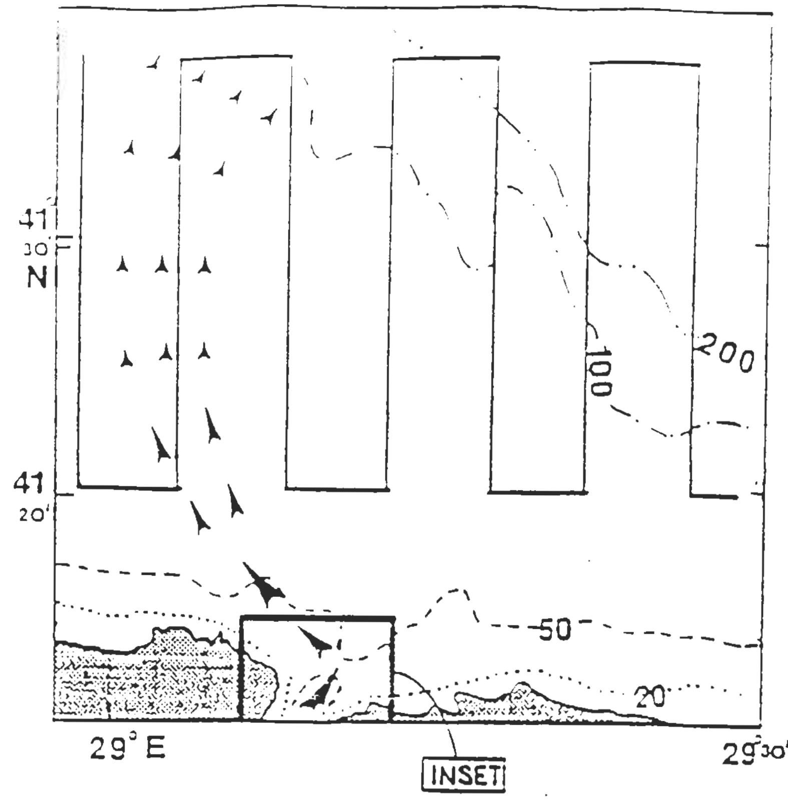
These major features of salt and water balance behavior still exist, but the decline of run-off has triggered a drop of the average sea level from 5 cm (1945-1976) to 10-12 cm (1990) in comparison with the period of 1923-1944. (The massive impoundment of rivers was not the issue at that time. Blatov, et al, 1980: Tolmazin, 1985).

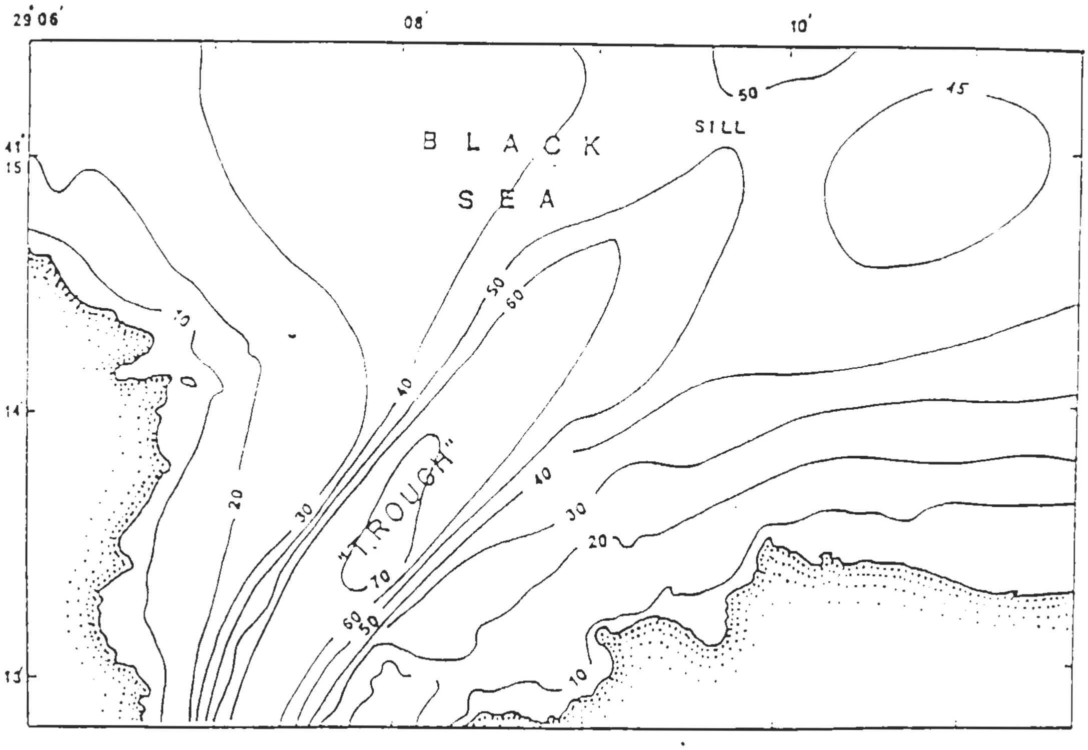
Therefore, the hydraulic head in the strait decreased from about 35 cm (Gunnerson and Ozturgut, 1974) to 23 cm over a 30 km length. This has facilitated and may further facilitate far-reaching implications for the oceanographic regime of the entire Black Sea-Bosphorus-Marmara Sea ecosystem. Their insidious development may be better understood if one introduces some specifics of the flow dynamics in the strait and its immediate vicinities.

The thermohaline structure and water exchange in the Bosphorus when the role of wind-forcing is insufficient are controlled by simultaneous interaction of the following elements of circulatory mechanisms:

FIGURE 8

Bathymetry





INSET

Fig. 8 Bathymetry (meters). Routes of Research Cruises and near-field spreading of the Mediterranean flow on the Black Sea shelf north of the Bosphorus. (Inset: Close-up of bathymetry in the vicinity of the northern entrance)

1) The discharge of the upper flow nearly twice exceeds the incoming Mediterranian water masses (Table 1). This triggers substantial entrainment of deep water masses which intensifies the turbulent friction and mixing through the interface. Subsequently, the latter gradually loses its strength. At the same time, a well-defined sill north of the Bosphorus (Figure 8 - inset) largely exercises hydraulic control over the surface, intermediate, and deep flows in the entire Turkish strait system whereas the southern sill affects mainly the deep flow because this sill is underneath the strait's major interface (Moller, 1928; Cecen, et al, 1981).

2) Numerous field studies and publications (Bogdanova, et al, 1967; Bogdanova, 1969) indicate that the overflow onto the shelf occurs nearly regularly; its well-defined plume of high-salinity water has been found far north off the northern Bosphorus sill (Bogdanova, et al, 1967).

3) The turbulent momentum transport several times exceeds the mass transport along the strait. As a result, a wide separation of the density and current interfaces occurs, whose displacement may reach 21 m depth at the northern end of the strait (Figure 9). Consequently, at both ends, the water masses are entrained into the opposing flows, some parts of which are reverted back to the sea of origin. This mechanism explains why, before leaving the strait, the wedges of water masses become very thin, but largely retain sharp vertical discontinuity.

4) In the "trough" north of the strait (Figure 8 - inset) the flows in the upper layer are wide enough, in comparison to the strait flows. Their turbulent friction generates appreciable resistance to the underlying dense water flow. In such conditions the stationary accelerations and rotational effects may dominate the overflow process. Bottom irregularities such as the sill or the depression in the channel can induce an upstream (or downstream) response within

the interface. The latter may cause marked transverse irregularities, even separation of the dense flow from the channel floor. This flow can be traced over a distance of 15-25 km (Figure 8).

Hence, the vertical stratification along the strait becomes extremely sharp (Bogdanova and Tolmazin, 1967). During such episodes, the Mediterranean plume spreads over the entire Black Sea shelf (Bogdanova, 1969). Persistent southerlies and southeasterlies (29% of occurrences) do not reverse, but significantly modify the flow patterns pertaining under no-wind conditions. The upper southbound flow may substantially decrease its forcing or even cease to exist, whereas the undercurrent increases its strength and volume, which causes considerable mixing through the density interface. During such episodes, vertical shear effects may cause the development of lenses of elevated salinity and temperature, which propagate far away along the continental slope (Bogdanova, 1969).

Today, fresh water depletion in the Black Sea hydrophysical balance has caused weakening of the predominantly two-layered flow and density structure in the Bosphorus. As a result, the height of surface slope is decreasing; consequently, the Mediterranean effluent is growing stronger. Under such conditions wind forcing has become the major contributor to the net water exchange in the strait while in the past when the gravitational circulation dominated.

It is assumed that under calm atmospheric conditions the Mediterranean water may retain its characteristics over much longer distances than now along the Anatolian mainstream and reach the CC with a sufficient amount of dissolved O_2. This may contribute to the chemical oxidation of deep waters in detriment to microbial oxidation. In other words, along the Anatolian coast (in the mainstream, Figure 4), the ancient deposits of nutrients in the formerly anoxic zone will be converted into insoluble compounds and lost to the life cycles. This process may expand the oxygen the zone down to 200 m and enhance organic precipitates from above and organic release from sediments on the continental slope.

Regarding the effect of wind, during southern storm-surge episodes which occur 3-7 times a year, large volumes (3-12 km^3) of undiluted Mediterranean water may descend to the stagnant zone whose depth may vary 250 to 1000 m; therefore, a vertical stratification is strengthened. At the same time, given the immensity of the anoxic zone (4.2 to 4.4 x 10^5 km^3), the occasional injections of salty "blobs" observed in recent years may not affect the concentration of H_2S in the abyss. On the contrary, the incoming flow starts gradually displacing upward the anoxic water, which makes the surrounding environment lethal (Rozengurt, 1991) .

In addition, an estimated 40 to 60 x 10^6 m^3 yr^{-1} of sewage and industrial waste were discharged into the Bosphorus, Golden Horn, and Sea of Marmara through 123 major and 500 minor drains. Only part of the sewage is undergoing primary treatment (Gunnerson and Ozturgut, 1972; Gunnerson, 1974). Raw sewage contains large amounts of suspended solids as well as coliform bacteria, including pathogenic bacteria and viruses, and is characterized by high biological oxygen demand (BOD). Unfortunately, these wastes may find their way to the Black Sea for river run-off and hydraulic head both have nearly vanished.

The increase of extremes in salinity variables in the plume over the shelf caused a strong environmental stress on the fauna of the Black Sea. The stenohaline fauna have experienced severe depletion; moreover, they cannot survive during occasional salt water intrusions. Repeated episodes of mass mortalities and secondary organic pollution are typical outcomes in the coastal areas.

From theory it is assumed that the initial enhanced influx of the Mediterranean water will slightly diminish at the end of about a 10-year period, because the salinity - temperature gradients in the strait will decrease.

FIGURE 9

Schematic Presentation

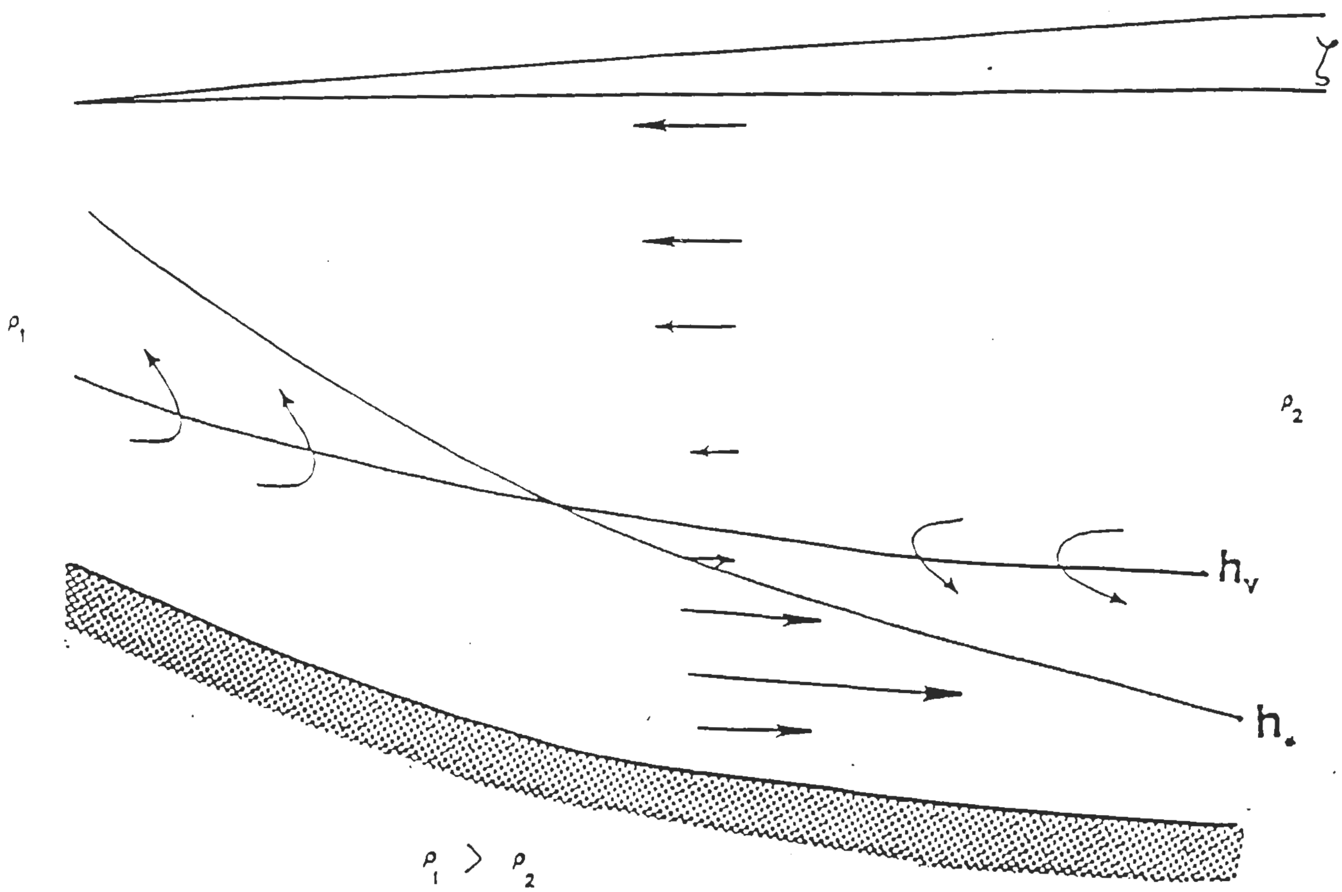


Fig. 9 Schematic presentation of the velocity profile, surface of no-motion h_v and density interface along the Bosphorus at a given surface slope (ζ is the surface elevation at the northern end). (after Tolmazin, 1981)

IV. CONCLUSIONS

The ongoing fresh water diversions in the Black Sea and Sea of Azov have a profound effect on the oceanographic regime of the Marmara-Bosphorus Strait-Black Sea ecosystem. The flow modification affected oceanographic, ecologic, and sanitary conditions in the sea. The circulatory patterns are modified on a larger scale, including adjacent areas in both seas.

Although the first scientific description of the Black Sea was published in 1890-1891 by N. Andrusov and A. Lebedintsev, from time immemorial it had been known that only a small part of its volume is able to sustain life (Zenkevich, 1963). The sea biota inhabited about 4.2% of its volume (volume = 547,015 km^3, area = 420,325 km^2, average depth = 1,301 meters, maximum depth = 2,245 meters) which encompasses the upper water masses between 0 to 150 meters depth. About 163 species of 110 fish out of 2,000 sea organisms occupy this life-sustaining surface layer. In the 1930s the average commercial catch equaled 450,000 tons of which about 250,000 tons were caught by Soviet fisheries. Note that at that time the integrated run-off from the Black Sea watershed exceeded 350 to 400 km^3 per year.

The rest of the sea is a lifeless water body saturated with hydrogen sulfide up to 9 mL/Liter (Skopintsev, 1975), known to be lethal for all living creatures with the exception of some anaerobic bacteria (Figure 10A). The simplified vertical structure of the Black Sea water masses was formed about 5,000 to 7,000 years ago (Leonov, 1960; Degens and Ross, 1974; Sorokin, 1983). The origins of this phenomenon can be explained by the following description of the mechanism of interjection and interaction between the higher salinity and density of Mediterranean flow entering the Black Sea through the Bosphorus Strait, and the lower salinity and density of the sea surface water masses diluted for millenia by run-off from the Black Sea watershed (1,864,000 km^2).

As was said, the Mediterranean flow, after exiting from the Bosphorus Strait, descends along the continental slope and fills the deepest area of the Black Sea's abyssal plain, by which the water masses tend to be displaced gradually upward. This displacement and, therefore, renewal of sea water below 125 to 200 meters takes by different estimations 300 to 500 or 2,500 years (Tolmazin and Rozengurt, 1965; Tolmazin, 1985). At the same time, the surface water body is entrained in active mixing induced by wind circulation and the excess of the sum of run-off and rainfall over evaporation from the sea surface (Leonov, 1960; Rozengurt and Sitnekov, 1973; Rozengurt and Tolmazin, 1976). Being a permanent feature of the sea regime for a thousand years, this increment of freshwater balance was able to reduce the salinity of the surface layer in comparison with the deep layer. As a result, two layers of density discontinuity (pycnocline) were formed over the entire sea. The first and most distinctive layer occupied the depth of 10 to 30 meters, while the second pycnocline was situated at the depth of 75 to 100 meters (maximum thickness in the spring, minimum in the winter). Despite their seasonal fluctuations these layers not only significantly restricted vertical mixing between surface and deep water masses but also served as guards against penetration of stagnant deep waters which are known to be lethal to the potential living environment (Bogdanova, 1969; Filippov, 1968).

Since the late 1970s, however, the boundary of the water layer poisoned by hydrogen sulphide has risen from a depth of 200 meters to 50 to 85 meters (Vinogradov, 1988; Spiridonov, 1989). Note that the appearance of this ominous sign of pending ecological disaster appeared to be related to the cumulative losses of fresh water discharged to the Black and Azov Sea totalling up to 650 and 450 km^3, respectively (1,100 km^3 is equal to the volume of the Northwestern Black Sea or nearly four times the volume of the Sea of Azov).

As was mentioned above, the NWBS cold waters play an important role in the transport mechanisms controlling the large-scale thermocline structure and gaseous regime of the upper and intermediate layers of the entire sea. Needless to say, in the recent past the lower boundary of the cold, oxygen-laden and denser intermediate layer occupied the depths of 120 to 150 meters over two-thirds of the sea, and even sank to 400 to 500 m in its western region during early spring. Such a vertical water transport carried millions of tons of oxygen whose chemical interaction resulted in reducing the concentration of hydrogen sulfide (H_2S) in these layers to an analytical zero (Bol'shakov et al., 1964). In conjunction with the average circulation patterns the advance of these deep water masses from their sources in the north to the easternmost corner of the sea was well-outlined by the 6.6° C isotherm; oxygen concentration equal to but not less than 2.5 to 4.0 mg/L at depths over 100 meters (Tolmazin, 1985). Correspondingly, down to this depth the Black Sea water masses were teeming with fish and dolphins.

Today it appears, however, that the cumulative lack of spring run-off (its integrated losses have exceeded 1,000 km^3 since the 1960s) has depleted formerly oxygen-laden cold water layers and weakened the intensity of vertical mixing in the layer of 0-200 meters. This has hampered oxygen renewal and increased the duration of detention time up to several hundred days. In turn, the rise of hydrogen sulfide concentration in the layer of 50 to 100 meters was triggered (Faslchuk and Ayzatullin, 1986; Leonov and Ayzatullin, 1987). Subsequently, the hypoxic water masses moved up to the lower boundaries of the photic zones. Correspondingly, the intrusion of poisoned deep water to the shallows of the northwestern and other areas of the Black Sea has caused mass mortality of shelf zone biota. In practice, this development has started to menace the entire Black Sea.

FIGURE 10

Vertical Stratification of Water Masses

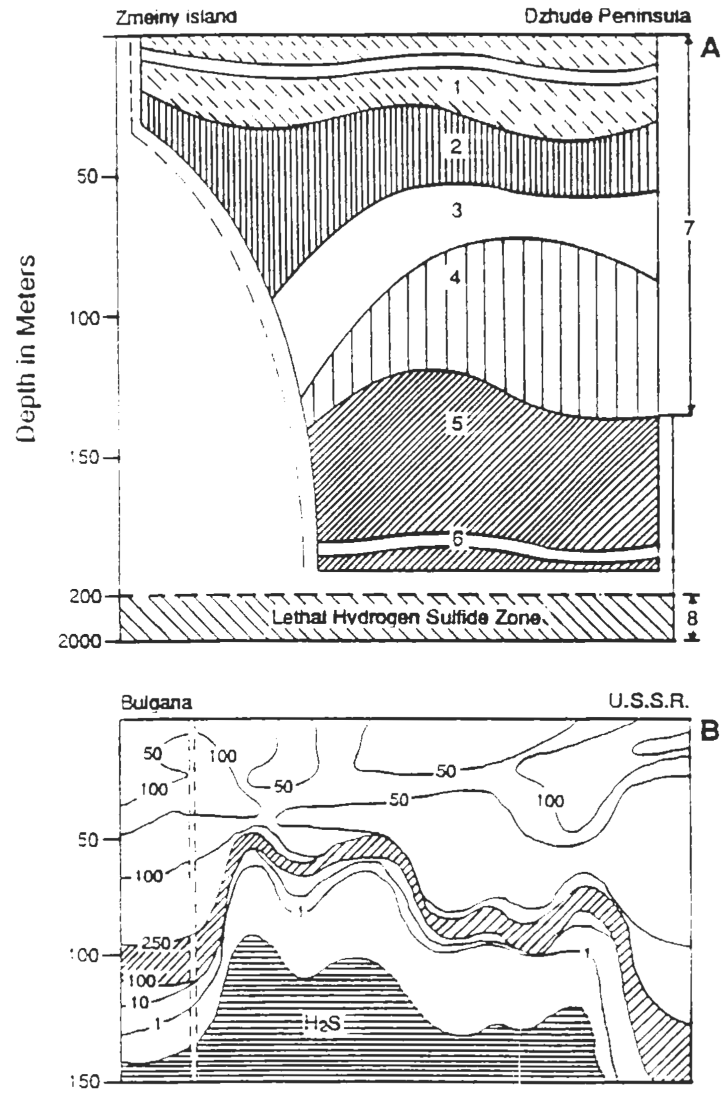


FIGURE 10 Vertical stratification of water masses in the central part of Black Sea (A) and, (B) vertical distribution of mesoplankton biomass (kal/m^3). Legend A: (1) Upper Mixed Layer: Seasonal thermocline and picnocline; (2) Intermediate Cold Layer; (3) Zone of Ancient Marine Picnocline; (4) Zone of Low Oxygen Concentration; (5) The Expanding Zone of Recent Increase of Hydrogen Sulfide (H_2S); (6) Zone of Substainable Oxygen Concentration and Living Resources (annual extremes of some oceanographic parameters : t^oC=6-26; S (gram / L)=17-22.5; O_2=0.2-8.8 ml / Liter); (7) Combined Life Sustaining Zones; and (8) Lethal Hydrogen Sulfide Zone, H_2S=2-9 ml/Liter. *Source:* Modified after Leonov, 1960; Vinogradov, 1990.

Soviet oceanographers speculate that less than 10% of the Black Sea's volume has been spared, for the time being, from this poisoning. However, decades of Soviet field observations (Vinogradov, 1990; Zaitsev, 1989) and the 1988 joint American-Turkish survey of the Black Sea (Murray and Izdar, 1989) have revealed that the poisonous subsurface layer is rising to the surface at a dangerous rate of 2 meters per year. Conceivably, if the rise of this poisonous layer continues unabated, it may bring about an unprecedented ecological catastrophe, since hydrogen sulfide in an undissolved gaseous state is highly lethal to human beings and is an acutely flammable gas. There are speculations that if hydrogen sulfide reaches the surface, any powerful detonator may trigger an explosion of enormous proportions. This in turn may destroy all living creatures in the sea and wipe out the human inhabitants of the former Soviet and Southern Europe.

This assumption may seem fantastic, but there is evidence that explosions on a much lesser scale have occurred in the past. For example, in 1927 a powerful earthquake measuring 8 on the Richter scale, with its epicenter beneath the Black Sea, hit the Crimean Peninsula. At the time, personnel from Soviet naval stations located near Sevastopol, Evpatoria, and Cape Lucul witnessed huge pillars of flame over the sea's surface. These flames were reported to be about 500 meters high and between 1,800 to 2,700 meters wide (Classified Report, Navy Archive, Leningrad, cited by Spiridonov, 1989). The appearance of this shocking event was explained by the fact that the tremendous power of the earthquake pushed ignited hydrogen sulphide gas beyond the surface of the sea. However, an oceanographer and corresponding member of the Academy of Science, M.E. Vinogradov, contends that these plumes of fire were linked to the leakage of methane from a series of small undersea volcanos (Vinogradov, 1990). According to Vinogradov, the water layer saturated with hydrogen sulfide will not be able to overcome the surface water pycnocline and, therefore, will be confined between this and a deep water pycnocline. This assumption is very fragile for the pycnocline strength is determined by the presence of brackish water whose surplus or deficit is strongly linked to river run-offs.

In light of such uncertainty, the possibility of the Black Sea emitting explosive, lethal gas into the atmosphere where it could ignite is not such an insane fantasy. Some Soviet scientists, fearful of this potential catastrophe, have been trying since 1975 to persuade the federal government to take some preventive measures. One of them rather incredulously proposed to pump the gas from the sea in order to extract its sulfur and generate electric power. Many believe that such measures may halt the rise of the sea's poisoned, lifeless layers to the surface, thereby decreasing the probability of a destructive environmental catastrophe.

However, the current political and economic havoc, population unrest, and small civil wars (Moldova vs Ukraine, Georgia vs Ackhazia, Ukraine vs Crimea Republic) do not give much hope that any attempts to preserve the Black Sea will occur in the near future. The new bordering republics are nearing military, economic, and political anarchy. Such considerations should cause political leaders to think hard about risk assessment of the present situation in the entire Black Sea basin.

The danger is that the Danube riparian countries and the South of the former Soviet Union will continue unbalanced inland water development; therefore, the living have little or no hope at all of stopping self-inflicted environmental anarchy.

It will take a very tough approach by western and American economic institutions toward the incessant aspiration for river impoundment of Czechoslovakia, Hungary, Rumania, and Ukraine in order to avoid an inexorable destruction of the most sophisticated environmental Mediterranean systems.

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