REPORT TO

NATIONAL COUNCIL FOR SOVIET AND EAST EUROPEAN RESEARCH

TITLE: SOVIET WATER POLICY AND ITS IMPLICATIONS FOR THE ECOLOGICAL-ECONOMIC DESTRUCTION OF THE CASPIAN SEA

AUTHOR: Michael A. Rozengurt
San Francisco State University

CONTRACTOR: San Francisco State University

PRINCIPAL INVESTIGATOR: Michael A. Rozengurt

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NOTE

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SUMMARY

For the last 25 years the Central Government of the U.S.S.R. has invested hundreds of billions of rubles to develop the energy network in the heart of the Russian land, consisting of a series of large hydroelectric power plants, large dams (the Volga-Kama Cascade) and vast impounded lakes. This development came in order to solve different tasks: 1. To make the gigantic local metallurgic industry independent from power sources outside the Russian republics; 2. To upgrade strategic internal waterways connecting Central Russia with other republics and the open seas, and through that to preserve in one hand more than 75% of the national cargo traffic; 3. To provide employment for millions through additional construction and redevelopment of light and heavy industry, thus attracting excess manpower from highly industrialized parts of the country; 4. To develop a highly productive agriculture, mainly for rice, on the Lower Volga arable lands, thus creating a mechanism by which areas traditionally growing rice, i.e., Central Asia, became dependent on the Central Government for their food supplies and were forced to produce mostly immense cotton crops to exchange for the rice.

This strategic multi-purpose development has excluded the environmental requirements of the Volga basin area, causing irremediable damage to riverine, estuarine and marine fisheries, deterioration of freshwater intakes along the course of the Volga River, salinization and desertification of the land.

As a result of these projects, the commercial landings, including the world's greatest valuable fishery have significantly decreased. For example, the commercial fishery of

Caspian herrings, yielding about 130,000-160,000 tonnes before construction of the dams, was reduced to 1,300 tonnes in the North Caspian area two decades later. The famous Russian sturgeon and stocks of other valuable fish were reduced 3-25 times and more in the entire sea. The direct losses accounting only for fisheries are in the order of 10-15 billion rubles.

The attempt to mitigate the precipitous decline of water quality and living resources through the construction of the sophisticated Volga Divider in the Delta, costing about 2.5-3.0 billion rubles, has further exacerbated the problem since the water withdrawals during the spring season are many times higher than the natural runoff fluctuations. One of the most serious implications of this development is that the Central Government needs to spend billions of dollars just for the preservation of whatever is left of the ecosystem. It is important to emphasize that these type of events are, to some extent, emerging in some estuaries of the U.S. Pacific Coast and Gulf of Mexico.

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1.0 Introduction

The Caspian Sea lies in the world's largest inland basin, (fig.1) extending from 47^{O} 43' to 54^{O} 51' E. The shortest distance between the Caspian Sea and the Back Sea basin (the nearest basin having open connection with the Mediterranean through it with the Atlantic Ocean) is across the Caucasus.

The northern and southern boundaries of the Caspian watershed are located between 62^{O} N and 35^{O} N, i.e., north of Leningrad and south of Teheran, and its area of 3.5×10^{6} km^{2} is about equal to 25% of the continental landmass of the USA.

This enormous basin extends from the subarctic to the subtropical regions. The climatological, morphometrical and geophysical features of this area are responsible for formation of the environment of the Caspian Sea and surrounding lands located hundreds of kilometers from its shoreline.

The average surface area of the Caspian Sea of 378,400 km^{2} constitutes 18% of total areas of all lakes of the World[1] about five times the surface area of Lake Superior or about 2.7 and 10.0 times the surface areas the Adriatic Sea and Sea of Azov, respectively, or roughly equal to the size of Great Britain (fig. 2).

The volume of the Caspian Sea (78.1×10^{3} km^{3}) accounts for 44% of the total volume of inland lakes of the world, and about 241 and 3.6 times the volume of the Sea of Azov (USSR) and the Baltic Sea, respectively.

Over 130 rivers and numerous streams discharge an average of almost 300 km^{3} per year (or 6% of the total natural runoff in the USSR) from which about 85% originates in the Volga-Kama

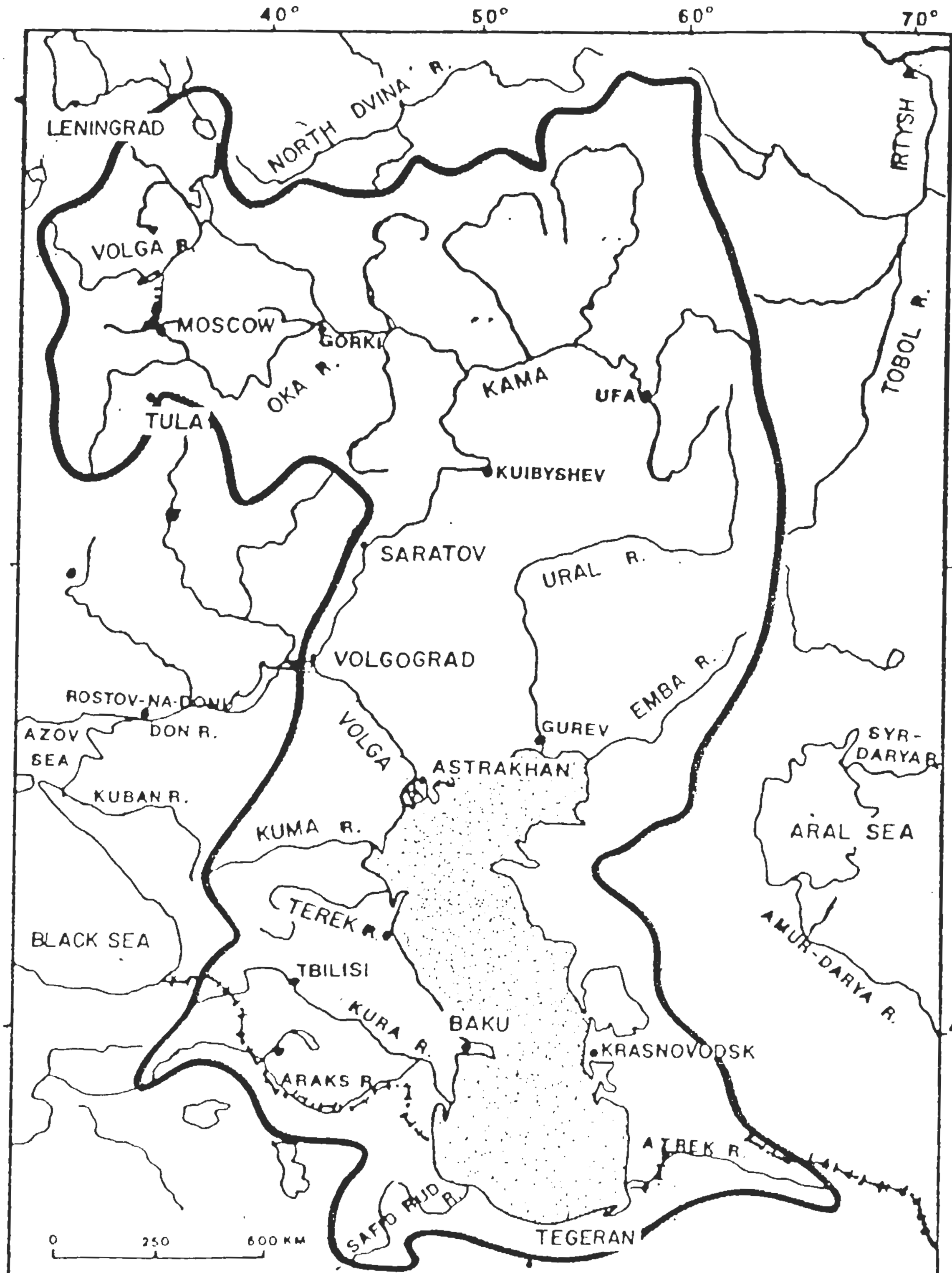
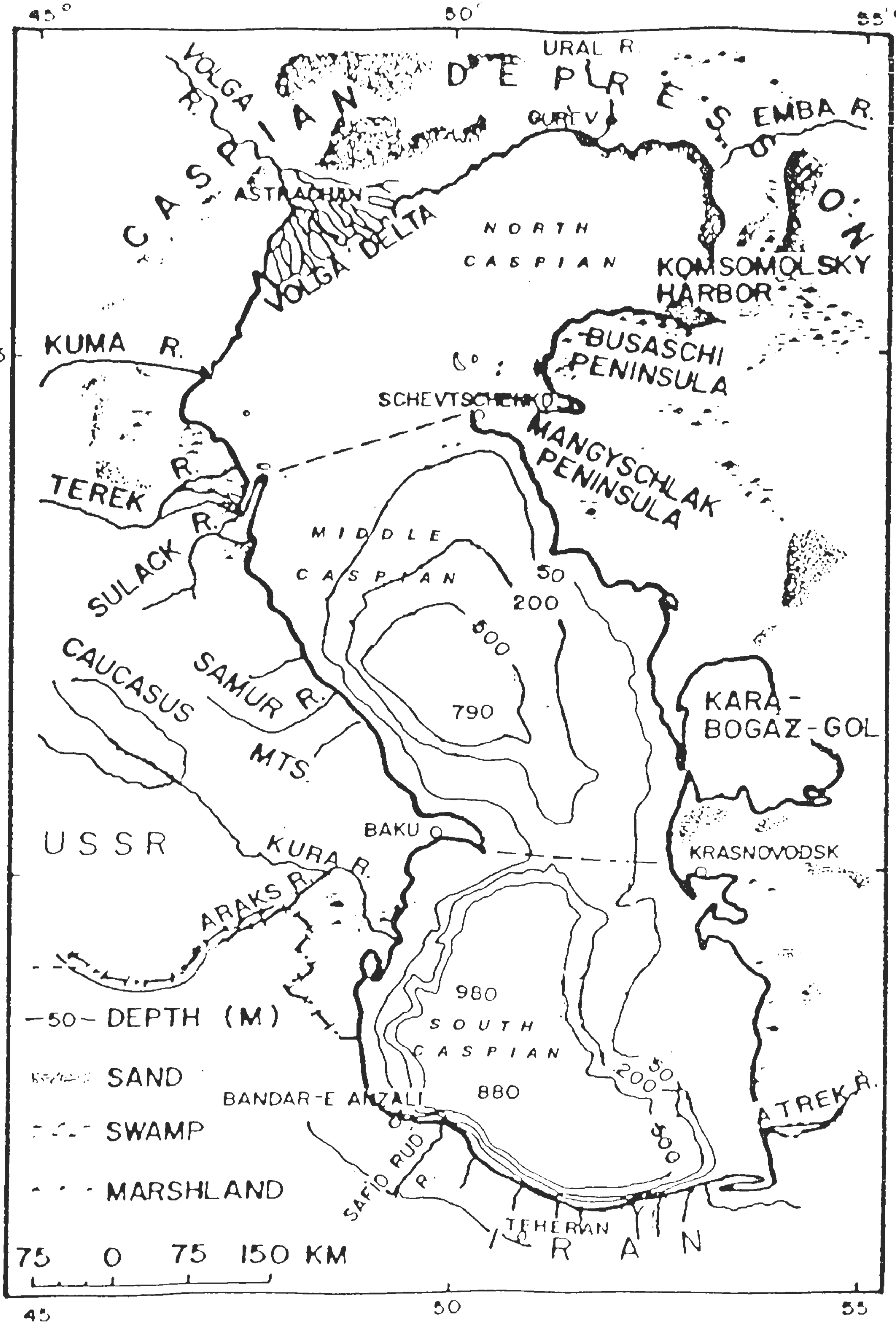


Fig. 1 The Caspian Sea watershed (modified after Shlyamin[6]).



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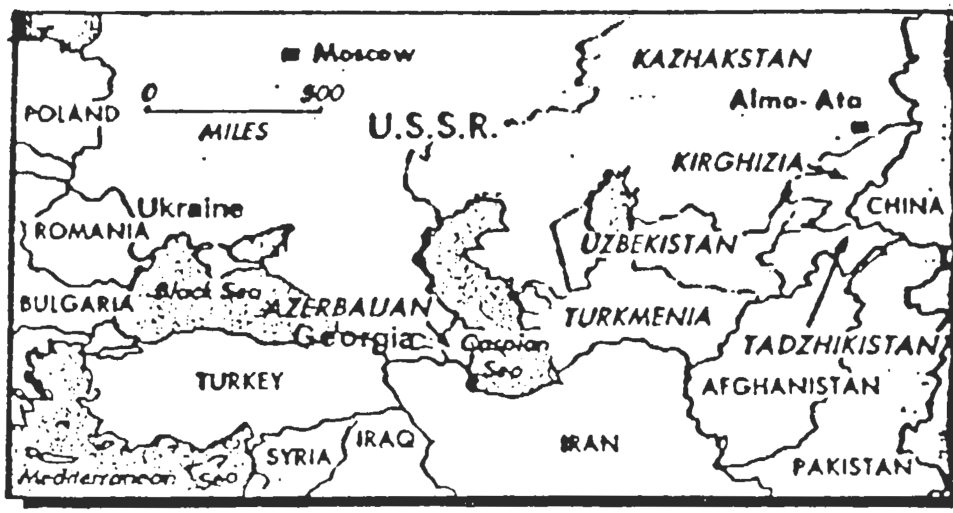


Fig. 3 The major republics of the USSR adjoined with the Caspian Sea basin.

TABLE 1

Some Morphometric Characteristic of the Caspian Sea

Basin	Watershed	Length	Max Mean Min Width	Area	Volume	Depth Mean	Depth Max	Natural Total Runoff
	$x10^3$ KM^2	KM	KM	$x10^3 KM^2$	$x10^3 KM^3$	M	M	KM^3
Caspian Sea	3,600	1,030	435 300 196	361-424	75-78.1	180-208	980-1025	200-460
Volga River	1,380	3,700	?	-	?	?	?	207-375
Entire Volga Delta	1,380	70-120	180-220	17-21	?	?	?	
North Caspian	?	?	?	81-197	0.4-0.7	4-5	20-25	207-375
Middle Caspian	?	?	?	137-154	25.7-26.3	170-213	790-800	?
Kara-* Bogaz-Gol	?	?	?	8-12	0.2-?	7-?	10-?	12-22
South Caspian	?	?	?	51-148	49.0-77.5	325-334	980-1025	8-18

298 KM^3 - Mean total modified runoff to the Caspian Sea, 1988-1977.

251 KM^3 - Volga-Kama River basin mean natural runoff, 1887-1962. Kama runoff 47% of total. The Volga Kama, Ural, Terek, Sulak, Kuma, Emba River flow is equal to 90% of total, (North Caspian), Samur (Middle Caspian), Kura, Safid Rud, Atrek and small rivers and streams (South Caspian) runoff is about 10%. (The range of fluctuation of mean morphometric sea characteristics reflects the influence of a fresh water balance on a rise or fall of sea level for the period 1929-1978.)

The Caspian Sea includes many islands of different sizes of which the total area equals 2,049 km^2 (North, Middle and South Caspian - 1,813 km^2, 71 and 165 km^2, respectively).

*Kara Bogaz-Gol has been separated from the Caspian Sea by the dam since 1980. The major goal was to stop the discharges from the sea to this basin, therefore, to accumulate more water for the Caspian basin (about 8-9 km^3 per year). The latest increase occurrence of abnormal wetness made this dam an unnecessary, expensive experiment. At present, the Kara Bogaz-Gol is drying up, its area shrunk almost 4 times. As a result, the chemical industry sustained a great deal of losses. The salinity concentration of its water ranges between 200-300 g/liter. Compiled from references 1, 2, 4, 6, 9, 10.

TABLE 2

Historical Fluctuations of the Caspian Sea Level, 1809-1985

Period, years	Mark of the sea level corresponding to mean ocean level (M)	Range of mean annual fluctuations of sea level (CM)	Mean fall/rise of sea level per year (CM)	Natural fall (rise) in sea level (CM)	Man's induced fall in sea level (CM)	Total reduction of sea level (CM)
1809-1914	-23.4-24.4	--	--	--	--	--
1809-1929	-26.96	±17	-2.7	-250	--	-250
1930-1941	?	?	-15.0	?	?	-188
1932-1940	-27.79	?	-9.9	-158	-10	-168
1940-1956	?	?	-11.9	-168	-34	-202
1942-1970	-28.47	±17	-2.0	?	?	-246
1956	?	?	?	?	-34	-202
1957-1977	-29.02	?	-4.6	?	?	-298
1932-1977	-29.02	?	-6.3	-160	-138	-298
1971-1977	-29.02	?	-8.0	?	?	-298
1978-1985	-27.97	?	13.0	105	?	-193

Note: Table compiled from 1-3, 12. The mean natural Volga River runoff 259 km^3 (1881-1929) and 208 km^3 (1930-1941), The average regulated runoff to the Caspian Sea basin: 240 km^3 (1970-1977) and 311 km^3 (1979-1982).

and Ural River basins and about 15% from the southern river drainages, the Terek, Sulak, Samur, Kura (the Caucasus region) and mountainous Iranian rivers and streams (Table 1).

Despite the impressive morphometric characteristics of the sea its area constitutes only 10.8% and 27.4% of the basin and Volga watershed, respectively. Therefore, any significant changes (climatological and man induced) over the watershed have a strong impact on the ecological conditions of the sea.

The major water users in the river basins are: agricultural (60%), hydroelectric power plants, industrial and municipal uses and commercial fisheries (in the Volga basin -- shipping).[2-10]

The special user of the Sea is the naval testing branch of the Caspian Fleet. It is important to emphasize that the Caspian Sea is widely used by classified naval institutions located in Leningrad, Gorki and Nikolaiev-City, to test modern navigation and oceanographic equipment and different types of engines. The Ba'il peninsula, 10 km south of the City of Baku, serves as a base for the Red Flag Caspian Fleet. The Caspian Sea provides a diversity of hydrological characteristics, namely, a wide range of water temperature and salinity conditions; an almost steady presence of highly developed thermo- and haloclines; internal waves; strong surface waves; upwelling and downwelling zones in the Eastern and Southern parts of the Sea; and a dense distribution of suspended matter, phyto- and zooplankton. All of these characteristics and its inland location, makes the Caspian Sea into an ideal testing ground.

The last three decades of extensive water development in significant parts of six republics of the USSR located in the sea watershed (USFSR, Azerbaijian, Armenia, Georgia, Kazakhstan and Turkmenistan) and in the Iranian coastal zone (fig. 3) with an aggregate population of more than 7.5×10^7 people have had deleterious effects on all aspects of the sea, its estuaries, freshwater intakes and fishery.[11-14]

1. Location/Geography. The Caspian Sea is located in the far south-eastern end of the European part of the USSR, along the boundary of Europe and Asia. This relict sea occupies the largest continental depression the water elevation of which is below the mean ocean levels of about -28m.

The Caspian Sea is usually divided into three sections (fig. 2)[5, 6, 7]: North, Middle (Central) and South. This division is based on morphometric, morphologic, physical, chemical and biological peculiarities and differences in the regions considered.

In turn, the North Caspian is divided into two parts: western and eastern, which differ in terms of their morphometric and regime characteristics and use.

The western part is deeper than the eastern, though their surfaces are almost equal. Their average and maximum depth are: 5.6 m and 25.0 m and 3.3 and 9.0, respectively.[1] Correspondingly, 63% of a total volume of the North Caspian confine in the western region. The latter is used for shipping through the deep Volga-Caspian canal (about 120 km in length) and serves as a major historical route for migration of anadromous fish (Bakhtemir tributary).

The North and Middle Caspian are separated by a submerged part of the Mangyschlak Peninsula, and Middle and South Caspian by the shoal of the Apsheron Peninsula (near the city of Baku).

The average depths of these regions 4.4, 192 and 34.5 m, respectively.

Out of 91,942 km^2 of the North Caspian total area of 90,129 km^2 is defined as the shoal covered by water. This region is the most important and productive area of the Caspian Sea, although its constitutes only 24% of a total area (376,345 km^2) and 0.5% volume of the Sea (78,081 km^3).[1]

The total area and volume of Middle Caspian constitutes 36.4% and 33.9%; South Caspian 39.3% and 65.6% of the total sea area and its volume, respectively.[1] Therefore, the area and the volume of the North Caspian is 1.5 and 67, and 1.6 and 127 times less than the average area and volume of Middle (137, 812 km^2 and 26,439 km^3) and South Caspian (148,640 km^2 and 51,245 km^3), respectively.

In the meantime, the ratio between the volume of the "normal" Volga basin runoff of 251 km^3 to the mean volumes of the western (249 km^3) and eastern (148 km^3) parts of North Caspian equals 1:1; 1.7:1.0 and 0.63:1. These ratios demonstrate the significance of the Volga discharges to the North Caspian regime which, in turn, provides adequate conditions for preservation of the unique and very resilient species of flora and fauna, adapted to the brackish water conditions since the historical past.[3, 5, 11]

The two hundred years of studies of the Caspian Sea have produced numerous conclusive evidence that the runoff from the Volga watershed, which covers 1.38 million km^2 (or almost 40% of a total area of the sea basin),[1] has been and will be a major factor (among climatological, geophysical and other factors) controlling the hydrological and biochemical structure of the sea, and therefore, intimately related to its biological productivity.

1.1 Sea level

Under natural conditions the value of an amplitude is determined by residual value of an algebraic sum, namely, runoff (Q) + precipitation (P) - evaporation (E) over the sea surface and duration of years of different wetness. For the period of 1900-1982, these elements of the freshwater balance of the Caspian Sea were equal to: Q=278.3 km^3, P=73.7 km^3 and E=375.5 km^3, or their residual is equal to -3.5 km^3.[1] Therefore, the drop in the sea level is inevitable. The presence of this negative value makes the Caspian Sea system very vulnerable to the climatological and anthropogenic disturbances. That is why the Volga runoff is, despite its volumes, looks like a rather limited source of water supply to the sea.

During the current century there were several drops in the level of the Caspian Sea (table 2) caused by the drought (1930-1941) or increased volumes of irretrievable water withdrawals (1950-1977) to meet agricultural needs and to fill in the storage facilities of hydropower plants. The effect of extensive water development compounded by a frequent recurrence of years of subnormal or even lower than subnormal precipitation (section 2) was devastating for the delta-sea ecosystem.

1.2 Water Masses

There are four major water masses whose displacement almost corresponds to the geophysical division of the sea, namely: North Caspian, Upper Caspian, Deep Middle Caspian and Deep South Caspian (fig. 4).[1, 5]

The North Caspian water masses, in turn, are divided into four zones: fresh, intermediate, brackish and sea (fig. 4a, table 3). The Volga runoff, superimposed by wind-induced circulation, determines the seasonal and average location and displacement, and intra-annual regime characteristics of these water masses. In general, the North Caspian water masses (fig. 5-7) are characterized by the highest horizontal and vertical gradients of seasonal temperature and salinity (density). Very complex gravitational and wind-induced circulations result in the pronounced development and advection of these zones with respect to longitude and latitude.

Such conditions result in the development of a strong thermocline and halocline, whose location coincides in space and time. Therefore, the vertical stability is pronounced.

The circulation patterns and associated hydrological structure of the Upper Caspian water masses are determined by: 1) water and salt exchange between the North and Middle Caspian, 2) the large scale wind drive and 3) seasonal and spatial variations in external heating or cooling of surface waters. The complex interaction of these factors gives rise to various energy-dissipating mechanisms (such as wind currents and waves; downwelling and upwelling; internal waves; turbulence, etc.) that effect and amplify water and salt transport between North and

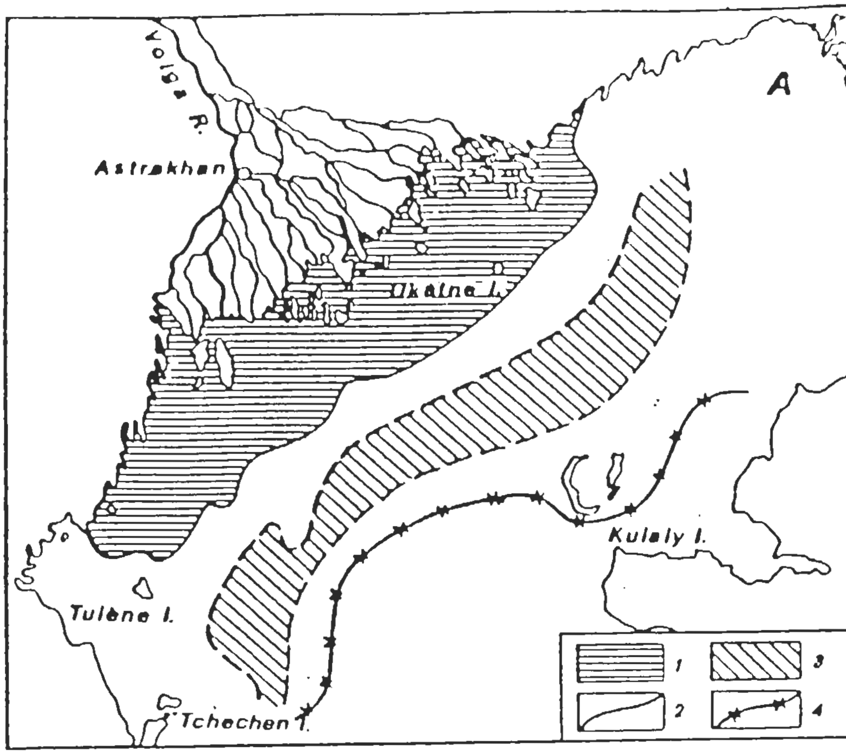
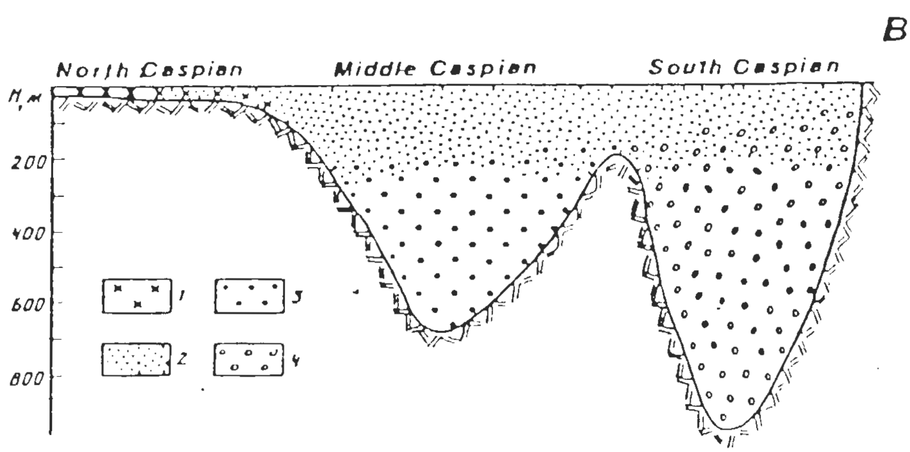


Fig. 4   A. Salinity zoning of the North Caspian Sea water masses adjacent to the Volga Delta: 1. River freshwater transition; 2. Boundary between transition and mixing of fresh and sea water; 3. Hydrological front within the mixed water zone; 4. Sea boundary of river water. (After Baydin and Kosarev[1])



B. Water masses of the Caspian Sea along the 51°E meridian: 1. North Caspian; 2. Upper Caspian; 3. Deep Middle Caspian; 4. Deep South Caspian. (After Baydin and Kosarev[1])

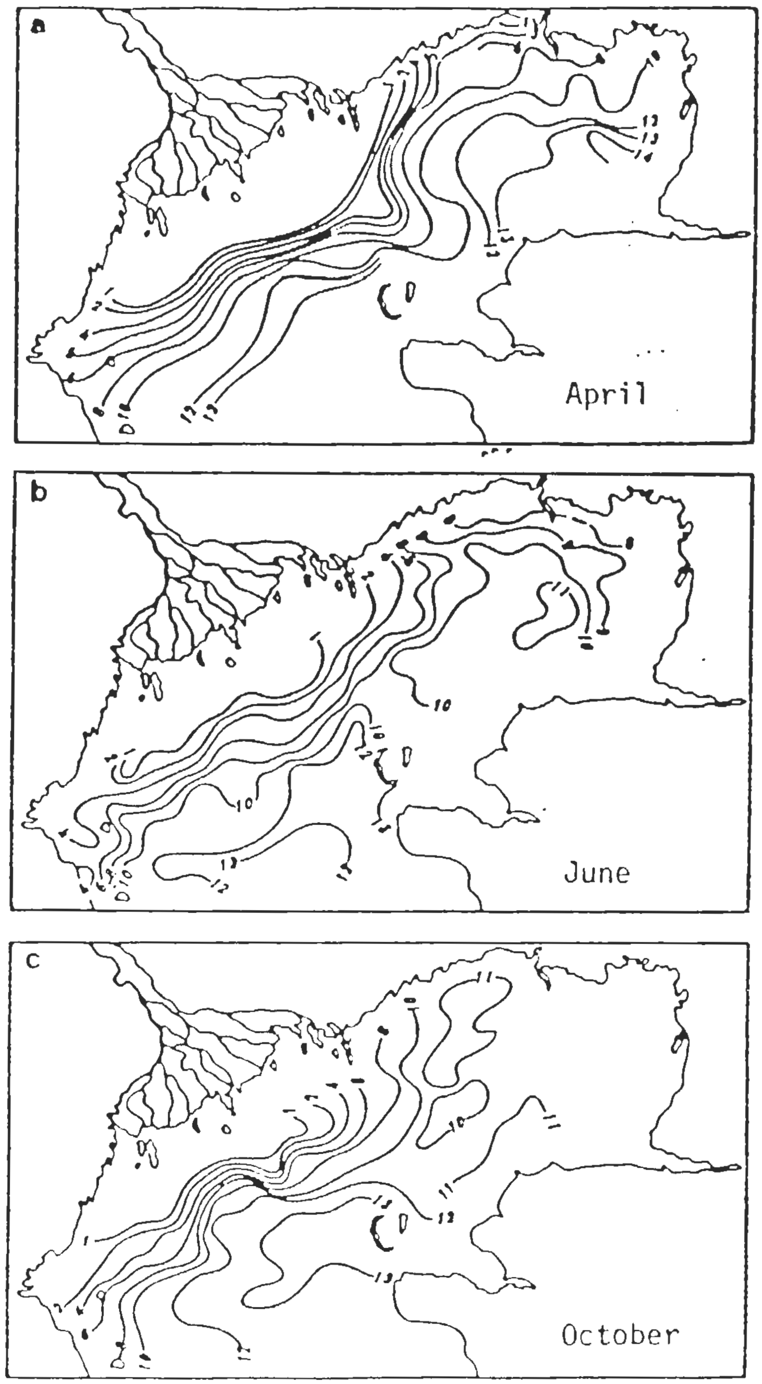


Fig. 5 Salinity distribution on the surface of the Caspian Sea in 1976.

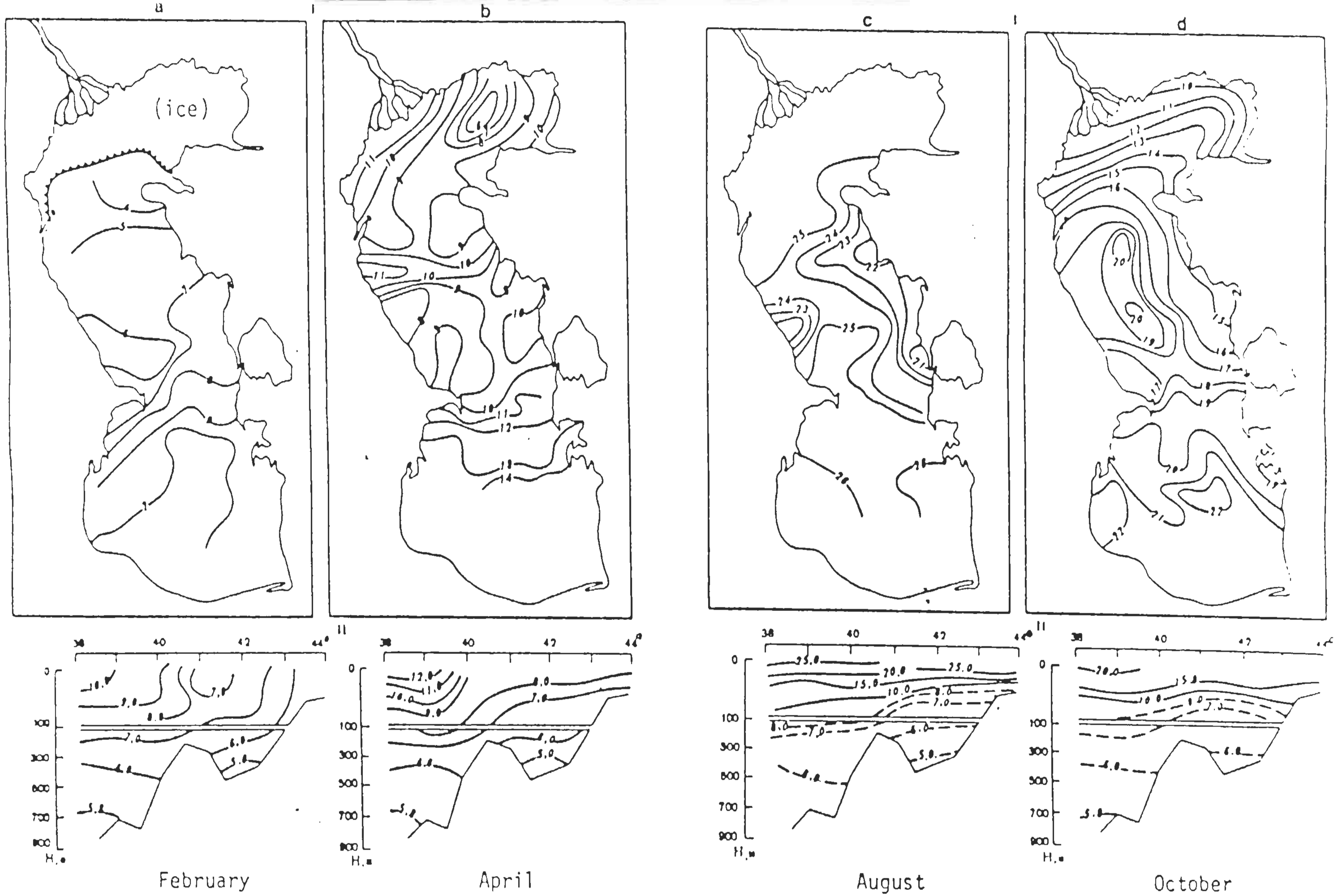
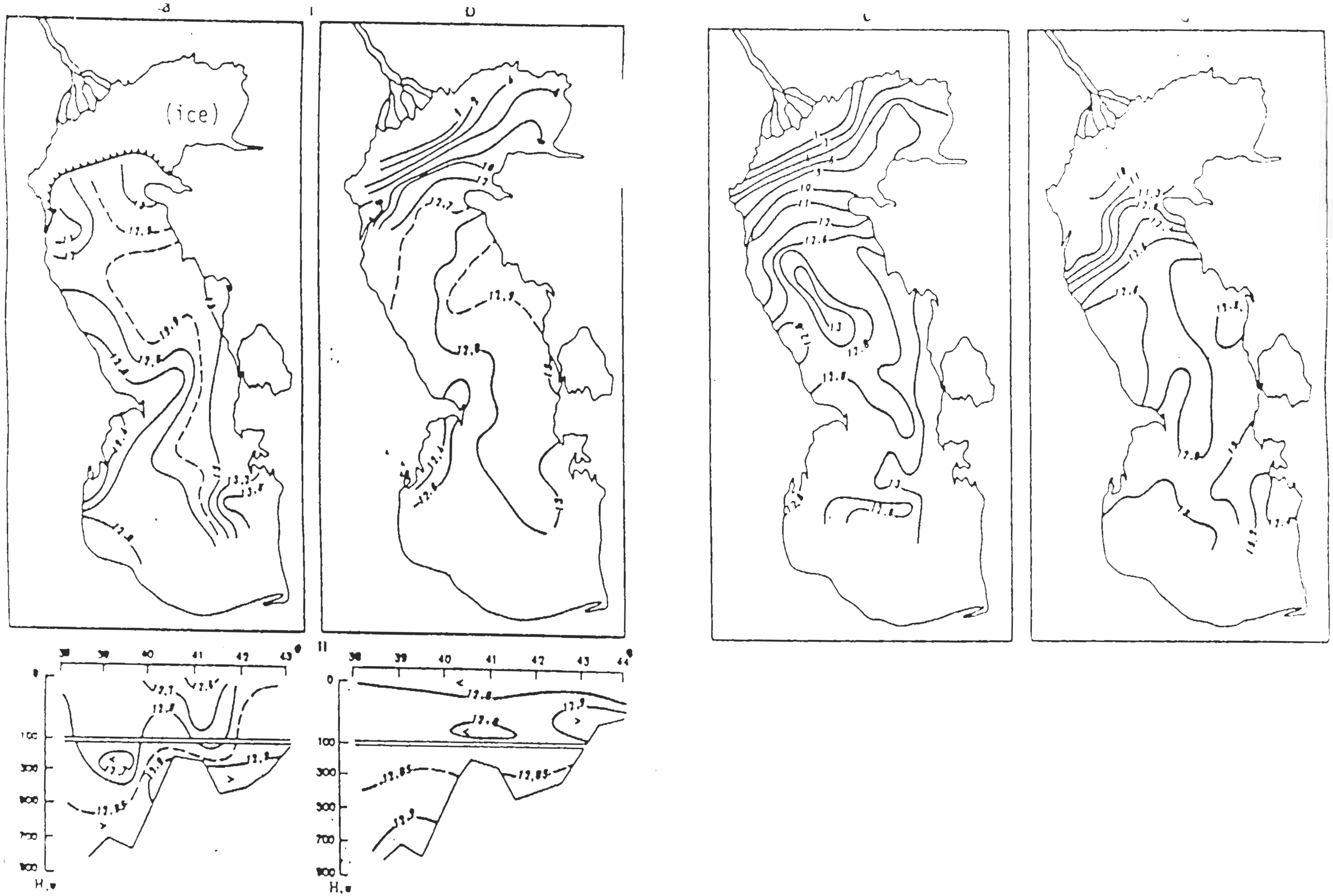


Fig. 6 Water temperature distribution on the surface of the Caspian Sea (I) and along the 51° meridian transection (II): a. February; b. April; c. August; d. October (After Baydin and Kosarev[1])



February April August October

Fig. 7 Salinity distribution on the surface of the Caspian Sea (I) and along the 51° meridian transection (II): (After Baydin and Kosarev[1])

TABLE 3

The fluctuations of the mean seasonal hydrological and chemical parameters of the Caspian Sea water masses (1964-1981)*

Season	$t^{o}C$	$^{o}/oo$ g/l	O_2 ml/l	pH	NH_4 mg-at/l	P mg-at/l	Si mg-at/l
	North Caspian (western part, surface)						
winter	-0.6- 4.0	?	?	?	?	?	?
spring	6.0-22.0	0.2-12.0	6.2-7.5	8.3-8.4	97.2-136.8	5.0-5.9	1324-1574
summer	21.0-26.0	1.0-13.0	4.9-6.9	8.5-8.7	64.8-100.8	5.0-5.3	1855-1883
autumn	0.0-23.0	1.0-12.0	5.6-8.7	8.4-8.5	100.8-102.6	5.6-5.6	1826-1855
	North Caspian (western part, bottom)						
winter	1.0- 4.0	?	?	?	?	?	?
spring	6.0-16.0	2.0-12.0	6.3-8.2	8.2-8.4	57.6-73.8	4.6-6.2	534-1152
summer	15.0-21.0	1.0-13.0	5.3-6.2	8.1-8.5	75.6-75.6	5.6-5.9	955-1236
autumn	1.0-16.0	1.0-12.0	6.7-7.0	8.3-8.4	86.4-99.0	5.3-5.6	702-815
	North Caspian (eastern surface)						
winter	-0.6- 3.0	?	?	?	?	?	?
spring	6.0-24.0	1.0-14.0	6.2-8.2	8.2-8.3	70.2-90.0	3.7-5.6	815-1630
summer	21.0-31.0	2.0-12.0	5.8-6.2	8.1-8.7	79.2-79.2	5.6-5.6	1545-1798
autumn	0.0-23.0	2.0-13.0	6.2-7.8	8.3-8.4	82.8-88.2	4.0-5.0	1742-1855
	North Caspian (eastern bottom)						
winter	-0.6- 3.0	?	?	?	?	?	?
spring	5.0-24.0	1.0-14.0	5.8-8.5	8.2-8.3	50.4-61.2	4.0-5.6	927-1377
summer	21.0-26.0	2.0-10.0	5.2-5.8	8.0-8.2	63.0-66.6	4.3-5.0	1264-1714
autumn	0.0-20.0	1.0-13.0	6.6-7.4	8.2-8.3	66.6-68.4	5.0-5.3	1321-1433

Table 3 (continued)

Season	t °C	°/oo	O_2 ml/l	pH	NH_4 mg-at/l	P mg-at/l	Si mg-at/l
				Upper Caspian (surface)			
winter	3.6- 7.2	12.5-13.3	7.5-8.4	8.42-?	20-?	12.7-14.9	389-455
spring	8.0-11.3	11.0-13.3	8.0-9.0	8.41-?	?	6.8- 9.7	334-601
summer	20.0-26	12.6-13.5	5.5-7.0	8.44-5	88-208	7.2-9.3	373-586
autumn	6.0-14.7	11.8-13.5	6.0-6.5	8.44-?	?	9.9-11.0	354-374
				Upper Caspian (200m)			
winter	5.0-5.5	13.0-13.1	6.0-6.5	8.22-?	5-?	17.9-?	1100-?
spring	4.5-5.9	13.0-13.1	6.5-6.0	8.19-?	?	28.5-?	571-?
summer	5.5-6.0	13.0-13.1	5.5-5.0	8.23-?	257-?	16.4-?	1035-?
autumn	5.8-6.0	13.0-13.1	3.5-4.5	8.25-?	?	20.6-?	1218-?
				Deep Middle Caspian (250 - 600m)			
winter	5.0-4.2	13.0-13.1	6.0-3.7	8.22-8.13	4.1-8.0	18.0-29.7	1200-1850
spring	6.0-5.0	13.0-13.1	5.5-4.3	8.19-8.20	?	29.0-30.3	770-1400
summer	6.5-5.0	13.1-13.2	5.0-4.0	8.23-8.18	250-181	7.0-36.2	750-1085
autumn	5.0-4.5	13.0-13.1	5.0-3.4	8.25-8.20	?	20.0-33.3	740-1442
				South Caspian (Surface)			
winter	7.0-10.3	12.5-13.0	7.0-7.8	8.48-?	31-41	9.1-9.8	335-302
spring	7.9-14.0	12.3-13.2	7.0-8.2	8.44-?	?	8.9-8.6	273-377
summer	25.0-29.0	12.6-13.6	5.0-6.0	8.44-?	131-146	7.5-8.7	304-404
autumn	12.0-19.0	12.3-13.5	6.0-8.0	8.50-?	?	2.6-5.3	88-210

Table 3 (Continued)

Season	Parameters t^oC	$^o/oo$	O_2 ml/l	pH	NH_4 mg-at/l	P mg-at/l	Si mg-at/l
			South Caspian (600-800m)				
winter	6.0-5.7	13.0-13.1	3.7-1.9	8.12-8.09	?	23.8-28.1	1530-1640
spring	6.0-5.9	12.9-13.0	2.0-2.5	8.02-8.01	?	60.6-57.0	1928-2000
summer	6.0-6.3	13.0-13.1	2.6-1.6	7.93-8.12	119-98	32.8-36.0	1564-1476
autumn	6.3-5.7	13.0-13.0	3.2-1.8	8.10-8.16	?	35.3-53.0	1410

*The table is compiled from Baidin and Kosarev[1]

North Caspian: surface (0-4m); bottom (deep waters)

a) t^oC, $^o/oo$, and O_2- mean monthly for winter (February); spring (April-June); summer (August) and autumn (October); 1960-1980.

b) NH_4, P and Si- mean monthly inorganic values; spring (April-June); summer (July, August) and autumn (September, October); 1955-1979, pH -for the same period

c) 60%, 25% and 15% of the North Caspian water masses have average weighted salinity concentration of 2-8$^o/oo$, <2$^o/oo$ and >10$^o/oo$, respectively.

Upper, Middle and South Caspian:

a) t^oC and $^o/oo$ (1968-1978); O_2 and pH (1964-1980) - mean monthly values.

b) NH_4 - summer and winter (1979-1981); P and Si - inorganic mean monthly values; winter (February); spring (April); summer (August) and autumn (November); 1964-1981.

TABLE 4

Characteristics of Hydropower Plants in the Volga-Kama Basins

Name of plant	Year of Operation	Area of Reservoir KM^2	Volume total/active KM^3		Power in MW	Production of energy mean/year Billions kw hours	Mean natural run-off to hydro-power plant KM^3
VOLGA RIVER BASIN:							
Evan'kovskaya	1937	330	1.1	0.8	30	0.1	10
Uglichskaya	1939	250	1.3	0.8	110	0.2	14
Rybinskaya	1940	4,550	25.4	16.6	330	1.1	36
Gorkovskaya	1955	1,530	8.7	3.9	520	1.4	53
Tscheboksarskaya	1980	2,270	13.9	5.7	1,400	3.5	112
Kuibyshevskaya	1955	6,450	58.0	34.6	2,300	10.1	242
Saratovskaya	1967	1,830	13.4	--	1,290	5.3	247
Volgogradskaya	1958	3,120	31.5	8.2	2,563	11.1	251
KAMA RIVER BASIN:							
Kamskaya	1954	1,920	12.2	9.8	504	1.7	52
Botkinskaya	1961	1,130	9.4	3.7	1,000	2.2	54
Nijne-Kamskaya	1979	2.630	13.0	4.0	1,248	2.6	89

Data compiled from 8-10.

Middle Caspian.

The winter downwelling of the cold North Caspian water along the slope to the deep water of the Middle Caspian tends to produce homogeneous conditions and provides for oxygen enrichment and aeration of these waters. The local or large-scale wind-driven circulation results in the development of upwelling in some areas of the eastern and southwestern coastal zones during summer.

In the winter, the vertical mixing extends down to a depth of 100-200 and 50-150m in the Middle and South Caspian, respectively. In the summer, the mixing depth is narrowed to 20-30m. The well-developed thermo- and haloclines, beneath the low sea boundaries, regulate the concentration of oxygen and many other chemical and biological constituents during late spring, summer and autumn. Internal waves, of 3-7m height and about 100m length, may occur within the thermocline.

The Middle and South Caspian deep water masses are characterized by a relatively uniform distribution of temperature and salinity, maintained by downwelling of winter cold mixed water from the North and Middle shelf zone, as well as by the vertical winter circulation (fig. 4, 6, 7, table 4).

These waters are characterized by the lowest temperature and oxygen content and by the highest salinity concentration. Over 50% of the volume of the deep water masses of the Caspian Sea are confined within the ranges of temperature and salinity of $5.0-6.5^{o}$ and $12.8-12.9^{0}/oo$, respectively.[1]

In sum, the four major water masses of the Caspian Sea are characterized by definite ranges of both temperature and salinity (for the concept of water masses is related to T-S representation of sea water structure), and many other regime characteristics. Their constant movement and water and salt exchange can be accounted for by two types of circulation: thermohaline (gravitational) and wind-driven.

In the North Caspian a strong wind can raise or depress the sea level up to 5m near the Delta, or generate waves up to 11m high in the Middle and South Caspian.

1.3 Water Resources Economic Uses.

In comparison with other regions of the European parts of the USSR, the economic and strategic importance of the Caspian Sea watershed is second to none.

The basin includes almost 100 million hectares of arable lands and produces over one-fifth of agricultural crops and one-third of the total industrial output of the USSR.

Impoundment of rivers in the Caspian Sea basin started in 1941 and reached its climax in 1955-1965.

Eleven large hydropower stations operating within the Volga-Kama basin (Table 4) and a few small ones on the western side of the sea basin provide almost one-third of hydropower production of the USSR.

The three power stations of the Volga basin: Saratovskaya, Kuybishevskaya and Volgagradskaya are considered to be the largest in Europe. The Volga cascade of reservoirs has a total storage capacity of 188 km^3/year while 88 km^3/year is the sustainable capacity (76 and 35% of the Volga River basins mean annual natural runoff), respectively.

Built on the flood plain of the rivers, the Volga basin's 200 small and large reservoirs have inundated an area of about 26,100 km^2, of which 50-69% were highly fertile cropland.[15] Moreover, the accumulation of 200 km^3 water in storage, starting from the late 1960's, has significantly contributed to the reduction of freshwater flow to the lower Volga-Caspian Sea ecosystem and has resulted in a drop in the sea level and a series of negative ecological consequences in the enormous Volga delta (about 21,000 km^2) and the adjacent sea shoal (approximately 28,000 km^2).

The major purposes of these water resource projects on the Volga River have been to provide: 1) an appropriate supply of electrical energy for industries and the growing population, 2) an effective centralized deepwater shipping network to serve interior needs in transportation and trade, 3) maximum available water supply for more than 4 x 10^6 ha. of arable land in the lower Volga region, suffering very often from droughts and, 4) reasonable runoffs to the Volga Delta-North Caspian ecosystem to maintain an optimal hydrological and chemical regime in this area to meet demands for water, to sustain migration, spawning and feeding activities, mainly for semi-anadromous and anadromous fish.

The economic significance of the Caspian Sea is determined by the considerable variety of the fishery and the harvest of seals for skins and oil, as well as by resources of crude oil, gas and salts (especially from the Kara-Bogaz Gol) and the extensive development of transportation and recreational cruises.[6-10, 17]

Shipping in the Caspian Sea basin has ice free navigable access during spring-fall to the Black, Azov, White, and Baltic Seas through the complicated networks of sophisticated canals that were built during the last 40-50 years. The shipping is extensive in the basin: the Volga alone with its tributaries accounts for 75% of inland waterways cargo turnaround of the European part of the territory of the USSR. The Caspian surface transportation connects the Caucasian and Central Asian republics through the shortest route from Azerbaijan to Turkmenia. Ferries run across the Caspian Sea between the cities of Baku and Krasnovodsk.

The Caspian Sea used to account for 25% of the fish catch of all inland water basins of the USSR, totaling about 600,000 tonnes per year of valuable species of fresh, semi-anadromous and anadromous fish.[6, 13, 16-21]

Before water projects implementation the catch of Russian sturgeon alone constitutes 90-95% of the world commercial landings.[9, 14] The current catch of fresh fishes in the Volga-Kama basin's reservoirs account for 50% of the total USSR fish harvest.[8]

2.0 Physical Effects of Water Resource Projects

Having solved to some extent the first three aforementioned problems of water development, the hydroelectric power plants and huge water withdrawals have created numerous interrelated environmental problems in the Delta-North Caspian systems, resulting in an appalling level of degradation of fisheries and other resources in the sea as a whole.[9, 13, 18-20]

The following sections discuss the affects of the transformation of drainage systems of the Caspian Sea (especially the Volga River runoff), the ecological conditions and the fisheries of the North and South Caspian ecosystems and subsequent alternatives of their survival.

2.1 Seasonal Flows

The water withdrawals by the Volga-Kama cascade have resulted in major changes in seasonal distribution of runoffs discharged to the lower Volga-Delta-North Caspian Sea ecosystem during 1961-1979 (Table 5, Figure 8). These changes in water flow to the North Caspian can be summarized as follows:

1. The mean annual reduction of runoff is estimated to be 12%, however, the mean spring value has decreased by as much as 37% which can be ecologically significant during migration and spawning periods.

Under natural conditions (documented since the 19th century), the 5-year mean total spring water supply fluctuations varied within the range ±10 -15% of the "normal", but in recent years the regulated releases of water supply to the lower Volga are characterized by a pronounced increase of absolute values of negative deviations up to 30 - 50% (Figure 9). (It is interesting to note that the same range of natural deviations of annual water supply from the "normal" were documented in many other rivers subjected at present to water regulation, e.g. Danube, Sacramento-San Joaquin, Delaware, Susquehanna, Potomac.[22])

TABLE 5

Natural and Regulated Runoffs Characteristics of the Lower Volga-Caspian Sea Ecosystem (1967-1979)

Characteristics of Runoff				Regulated Runoffs of the "Normal" In percentage
"Normal" Runoff*	KM^3	Regulated Runoff**,	KM^3	
$\bar{Q}$	251.0	$\bar{Q}r$	224.7	89.5
$\bar{Q}sp$	155.8	$\bar{Q}spr$	98.9	63.5
$\bar{Q}sw$	95.2	$\bar{Q}swr$	125.9	132.0
	Percentage		Percentage	
$\bar{Q}sp$ of $\bar{Q}$	62.0	$\bar{Q}spr$ of $\bar{Q}r$	44.0	39.4
$\bar{Q}sw$ of $\bar{Q}$	38.0	$\bar{Q}swr$ of $\bar{Q}r$	56.0	50.2

*$\bar{Q}$, Qsp and $\bar{Q}sw$ - "normal" annual, spring (April, May, June) and summer-winter runoff (1887-1962)

**$\bar{Q}r$, $\bar{Q}spr$ and $\bar{Q}swr$ - mean regulated annual, spring and summer-winter runoffs (1967-1979).

Computation based on from data from 1-5, 8-10, 18.

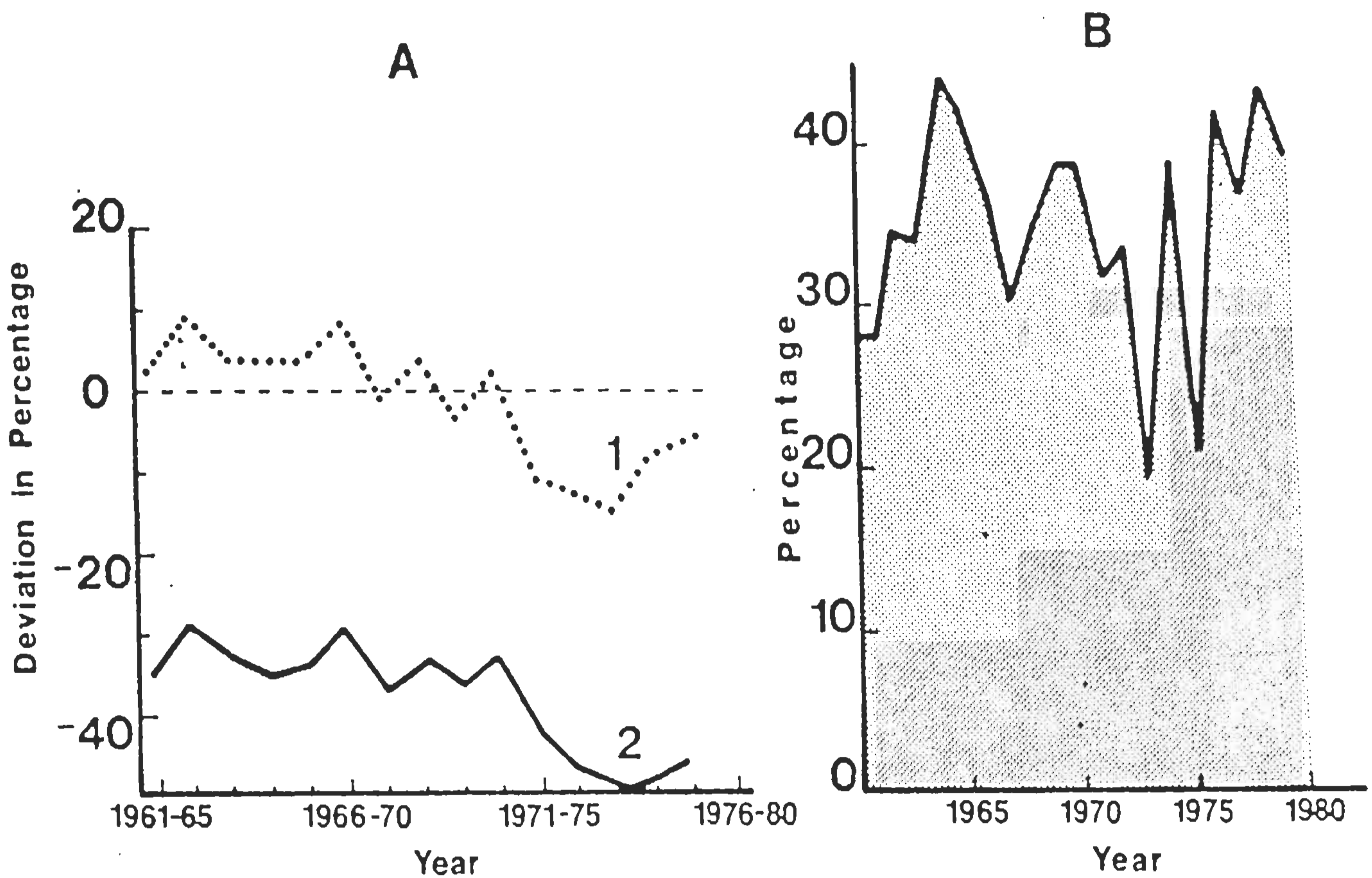


Fig. 9 (A) Deviations of the 5-year running mean natural (1) and (2) regulated (combined Volga-Kama river inflow of the "normal" spring runoff - 155.9 km^3) discharges to the lower Volga River.
(B) Percentage of accumulated water of the mean spring runoff in the Volga-Kama river cascade of reservoirs during the spring (April-May-June). (Data from the Ministry of Energy and Electrification of the USSR.[34])

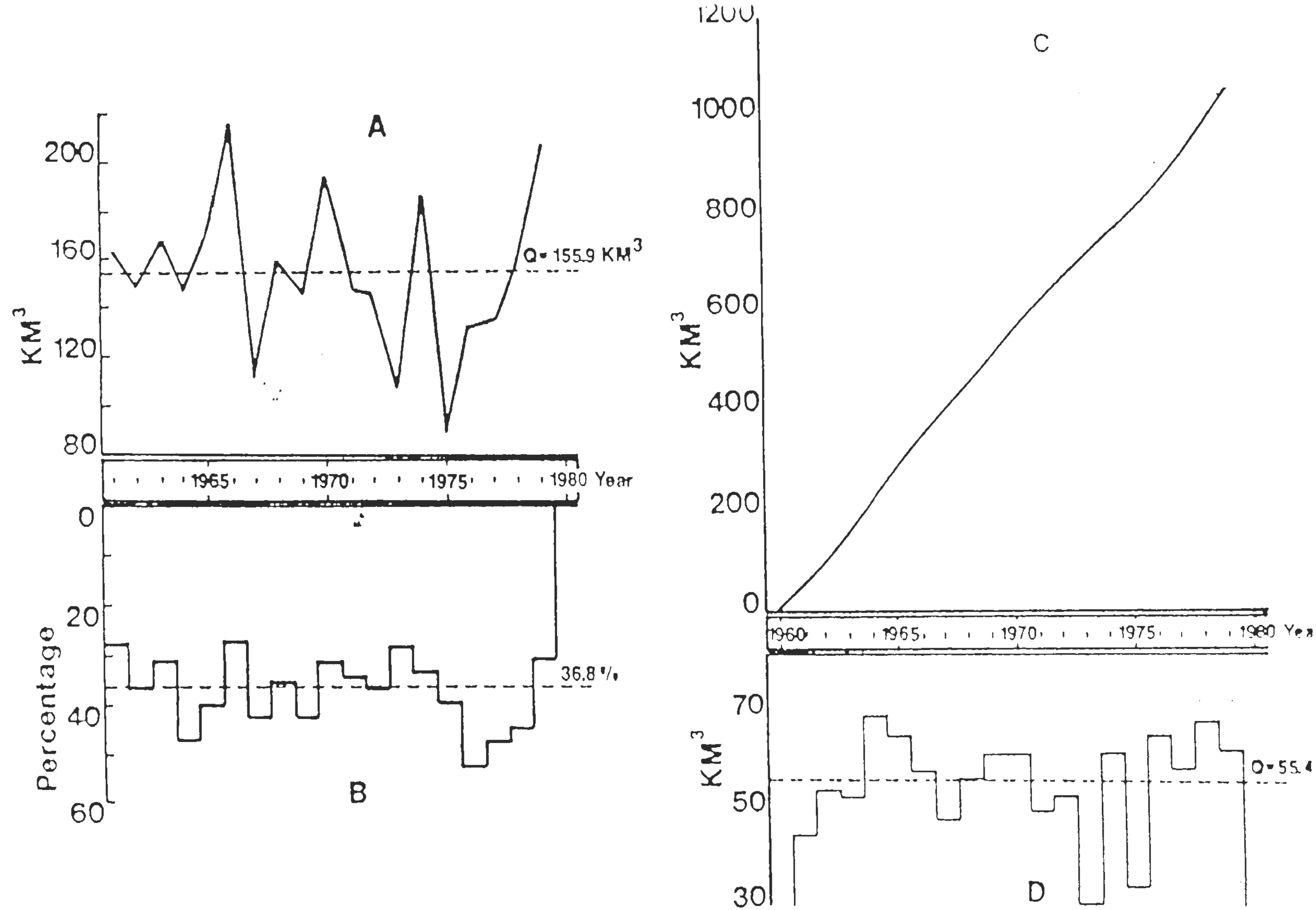


Fig. 8 The Volga-Kama River and Volga delta flow conditions, (A) Natural fluctuations of the spring (April-May-June) Volga-Kama river runoff: (B) Percentage of water diversions 1961-1979; (C) Spring cumulative losses of water supply to the Volga River Delta and Caspian Sea attributed to water withdrawals; (D) Volumes of Volga-Kama river runoff accumulated in upstream reservoirs, 1961-1979, losses and reservoir retentions.

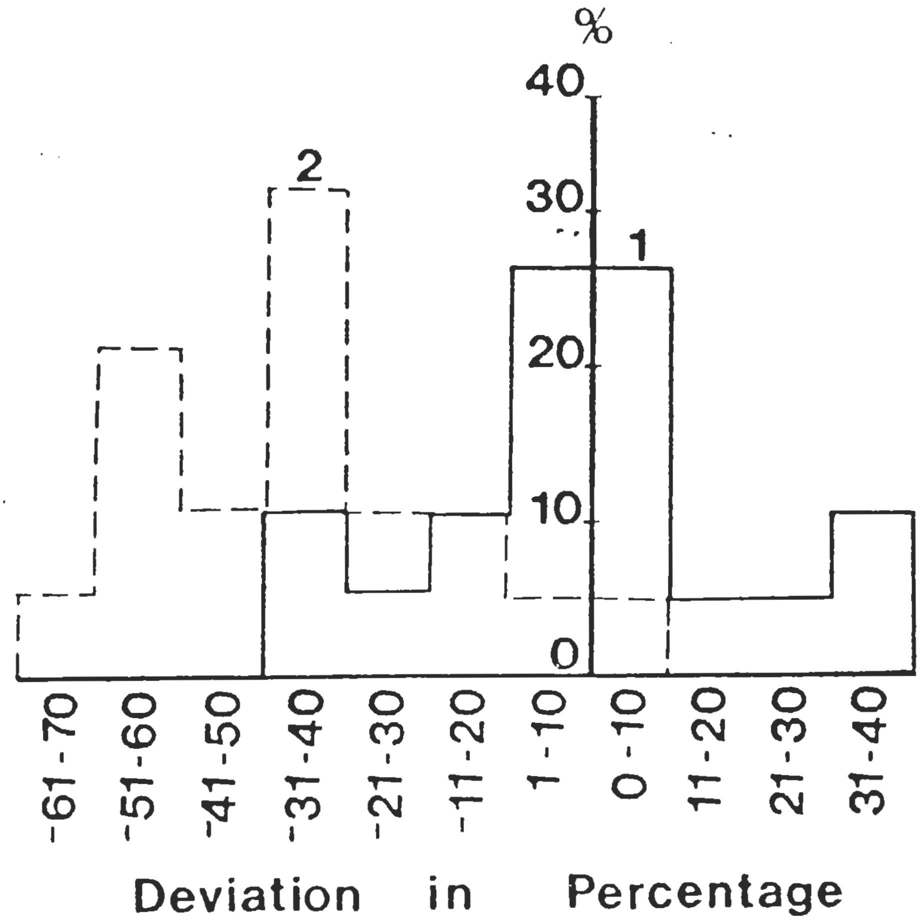


Fig. 10 Deviations of (1) natural spring runoff of the "normal" and (2) regulated spring runoff of the "normal" in the Volga River, 1961-1979.

As a result, the current total regulated mean spring (April, May, June) runoff (98.9 km^3) contributes to only 44% of the mean regulated annual value instead of 62% observed for the natural conditions (Table 5).

More to the point, this spring runoff dropped as much as 1.6 times its "normal" (155.8 km^3). This has led to the dewatering of many delta tributaries, distortion of circulation patterns, decrease in flow velocity, increase in temperature, salinity and detention time. Consequently, it has aggravated the water quality in some sections of the Delta, which were once the most favorable areas for migration and spawning activities of the majority of valuable fish (before the implementation of water projects in the upper and middle Volga basin as well as construction of numerous pumping facilities inside the Delta).

In practice, the current mean regulated total spring discharge to the Delta-North Caspian is almost equal to the mean value of the natural summer-winter runoff, which usually was characterized by the lowest discharges observed for the pre-project period.

As a result of extensive spring water withdrawals (mainly to recharge the storage facilities of power plants) the frequency of occurrence of abnormal range of the negative deviations (31-40%) of regulated spring runoffs from the "normal" value has increased more than 4 times (Figure 10). Practically, this runoff to the lower Volga corresponds to 90-99% of probability of exceedence of the natural spring runoffs (114-92km^3). In other words, the subnormal or critical subnormal types of regulated spring runoffs have occurred much more frequently during several consecutive years (1961-1979) than would be observed for the natural runoffs (only 3 years: 1967, 1973, 1975) when runoffs and their probabilities obtained for a period of more than 60 years equaled 198, 114 and 93.2 km^3 or 90, 94 and 98%, respectively.[10]

In sum, the cumulative losses (Figure 8.C) of spring water supply to the lower Volga Sea ecosystem due to water withdrawals equaled 1,051 km^3 (1961-1979). This volume is as much as 4 times greater than the "normal" annual Volga River runoff and 2.65 times the current volume of the North Caspian (397 km^3).

2. At the same time the regulated winter runoff increased (due to routine seasonal water releases from reservoirs) up to 65.1 km^3 or 2.2 times its "normal" and became almost equal to the summer-autumn "normal" (66 km^3) and slightly higher than current average regulated summer-autumn discharges of 60.8 $km.^3$ Therefore, the average winter, summer-autumn and the total summer-winter regulated discharges constitutes for 26%, 24.2 and 50.0% of the annual "normal" (as opposed to 12, 26.3 and 38.3% for the pre-projects' period).

Hence, while the summer-winter regulated runoff increased 1.3 times its "normal" (95.2 km^3), the spring impaired runoff decrease 1.6 times its "normal". Besides, the spring residual inflow is 1.3 times lower than the current summer-winter runoff (table 5).

According to Baidin and Kosarev,[1] the shift in freshening of the North Caspian water from the historical period of July-August to June (western part) and June-July (eastern part) appeared to play a negative role in the survival and reproduction of the biota. This is explained by the fact that under natural conditions the growth and reproduction of many species were adapted to the period of July-August when the refreshening and warming of the North Caspian water masses used to be higher.

It should be emphasized that this phenomenon, e.g. the inverse intra-annual regulated runoff distribution, has become a new feature of hydrological regime of the Volga River, unobserved in the historical past. One more of the negative ecological consequence of runoffs transformation is the fact that there is an ample surplus of water during the season when there have been no records of migration and spawning activity among the commercially important species of fish.

3. The most severe impact of diversions on water supply to the lower Volga and North Caspian was observed when runoffs of dry and critically dry years (1976 and 1977) characterized by the probability of exceedence of 80% and 98%, respectively, were superimposed on the diversions. In this case, a relatively moderate accumulation of water in reservoirs accounted for 52.5 km^3 had resulted in the decline of volumes of releases to the Delta of as much as 1.9 and 2.5 times in comparison with the average for given years and the "normal" spring runoffs, respectively (Table 6).

The discharges of such small rivers as the Terek, Samur and Sulak (Middle Caspian); Kura and numerous Iranian rivers and streams emptying into the South Caspian (Figure 11) have been so reduced by constant withdrawals of water along their courses by hydroelectric power plants and irrigation systems that adequate runoff rates and water levels in the lower reaches of these

TABLE 6

Some Statistics of Water Diversions in the Volga-Kama Basin

in Critical Water Years*

Years	Natural Inflow km^3	Deviation of Normal %	Accumulated Volume (km^3)	Accumulation %	Releases in Lower Volga km^3	Inflow Deviation in Given Year (%)	Inflow Deviation of "normal" %
1975	93.2	-40	33.8	22	56.8	-39	-64
1976	131.4	-16	65.0	42	63.9	-51	-59
1977	134.0	-14	58.6	38	70.9	-47	-55
Mean	120.9	23.3	52.5	34	63.9	45.7	59.3

*Computation is based on data from ref. 1, 2, 10, 18, 34.

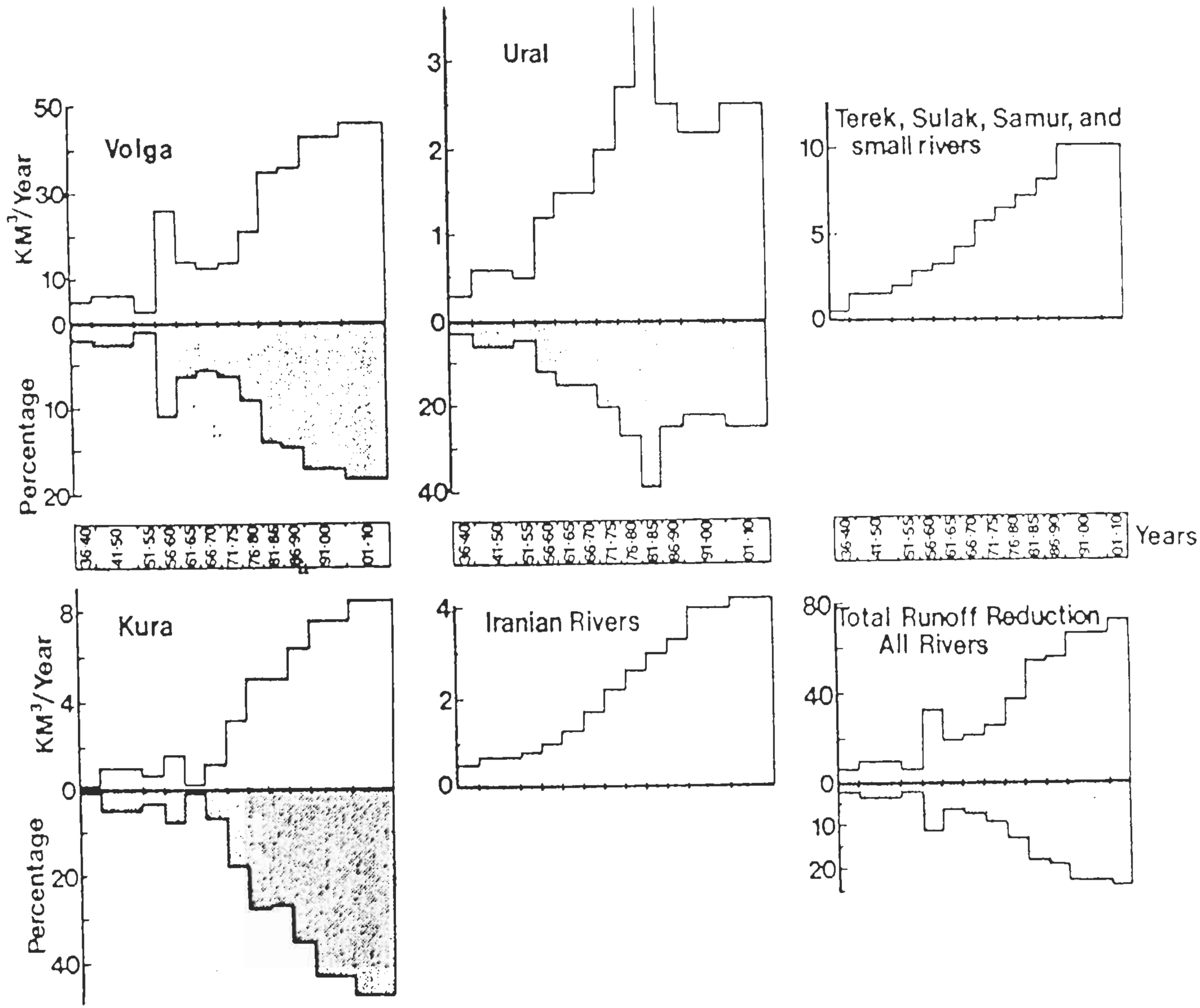


Fig. 11 The mean total annual volumes of water withdrawals by different water users from the rivers of the Caspian Sea basin (km^3/year and the percentage of the "normal" data obtained from Shiklomanov and Georgievsky[2]).

rivers, necessary for natural reproduction of fish, practically no longer occur.[10, 15]

4. In sum, 25-65% of the Volga-Kama discharges during the spring is accumulated above the dams, whose capacity constitutes 35-76% of the "normal" annual runoff of the Volga. (It is interesting to note that the cumulative capacity of major dams of the Northern California (USA) built in the Sacramento-San Joaquin River basin account for 71% of the unimpaired river flow but only 34.6 km^3, e.g. almost 8 times less than Volga runoff. As such, the effect of water withdrawals during late winter-spring (about 60% of the "normal") on runoff variables and the fishery of the San Francisco Bay is nevertheless dramatic).[24, 28]

3.0 Ecological Consequences of Water Withdrawals

Generally, estuarine ecosystems are very resilient to natural disturbances of regimes in their drainages. Their function is to serve as a "buffer" zone between the river and adjacent sea coastal area.[22, 25-29] The major natural events in this zone result in: a) mitigation of the impact of a salt intrusion from the sea through the entraining ability of runoffs to maintain a definite natural range of the river-sea water exchange; b) accumulation, production, and recirculation and processing of the sediment and biogenic yield discharged from the river and sea, and in an estuary itself, through mixing different water masses in the course of their movement within the delta-estuary or delta-sea ecosystem; c) maintenance, within natural scale of seasonal and annual runoff fluctuation of the adequate ecological conditions necessary to the survival of the diversity of brackish water organisms, including, but not limited to the eggs, larvae and juveniles of the semi-anadromous and anadromous fish.[13, 14, 16]

While adult fish are able to survive or remain unaffected by an increase in salinity, disruption of other components within the North Caspian ecosystem on which the young of the year are dependent (i.e., temperature, salinity, oxygen content, alkalinity, pH, biogenic yield, and food resources, circulation patterns, the size of a nursery ground, etc.) contribute to reduction of their survival capability and of adult spawning success.[12, 18, 29, 36]

3.1 Structure and Function

In the process of evolution, the structural and functional peculiarities of the Caspian ecosystem were formed by the supply of freshwater and substances from upstream sources. Biological productivity is determined by the freshwater, ionic and biogenic runoff of the Volga and Ural Rivers and by the highly oxygenated warm waters and shallow depths of the Northern Caspian. The major feeding areas of fish shoals are located here. The concentration of salt and biogenic nutrients in the Northern Caspian depends on the amount of river discharge, which is historically distributed by the more abundant freshwater supply to the western part of the North Caspian and the reduced supply to the eastern side.[1, 5, 11, 13] The biological structure and productivity of the North Caspian, which receives over 80% of the total river discharge of the basin, have fluctuated as a result of the altered freshwater inflow patterns.[32, 33] Water accumulation in reservoirs located in the Upper and Middle Volga basin and seasonal reduction and inverse distribution of releases (low in spring, higher in summer-winter) to the Volga have had a profound effect on the measurable parameters of the lower Volga-North Caspian ecosystem regimes.[31] These ecological effects can be seen in Figure 12 which illustrates the role of different degrees of flow reduction.

The leveling of seasonal runoff fluctuation, with reduction of the amplitude of stage levels into the Delta, reduces adequate conditions (velocity, temperature, oxygen, salinity, nutrients, etc.) for spring migration and spawning success of semi-anadromous and anadromous fish. The monthly regime of controlled river flows below the dams is significantly altered by requirements of the various different water users. Sometimes, the fluctuated quantities of cold or warm surface water gush forth forcefully into the lower part of a river, washing eggs down to the delta where they may be smothered by silt or subjected to desiccation when abrupt recession of high stages take place. The process of dewatering of numerous Volga delta tributaries, especially in its eastern part, has been exacerbated by deepening some major channels to provide sanitary and refreshing circulation in the Eastern Delta, or to improve navigation in the Western Delta.

3.2 Retention Time

The period of recycling (retention time) of the Volga Basin water body increased as much as 8-10 times, i.e., its duration is equal to almost 180 days[9]. This retarded water mixing and ever increasing amounts of fertilizers from the drainage area

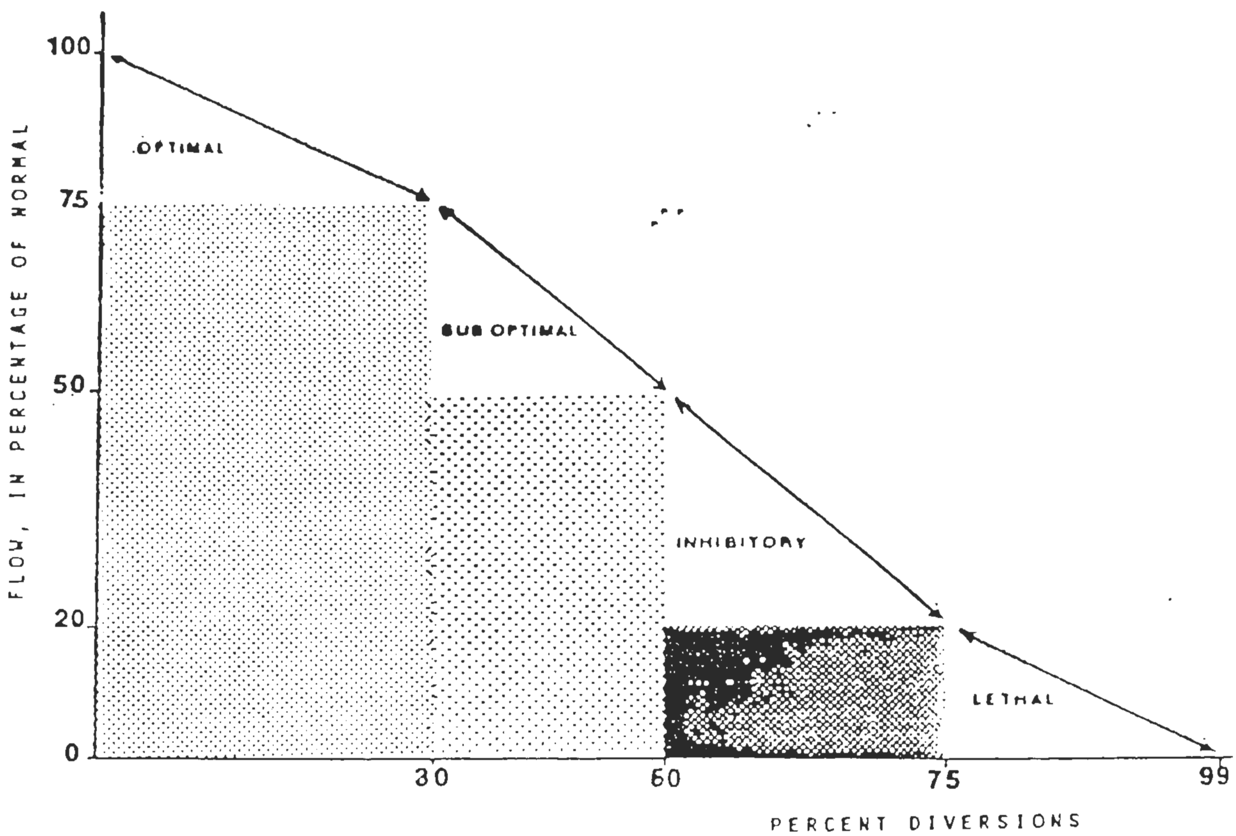


Fig. 12 Conceptual model of the effect of runoff reduction due to diversion on the estuarine environment and living resources.

TABLE 7

The Range of Fluctuations of Mean Annual Salinity ($^{o}/oo$) of the North Caspian Before (1935-1955) and After (1956-1980) the Impoundment of the Volga River

	Salinity of Volga Runoff	Salinity Ranges Regions Western	Eastern	N.Caspian	Mean Salinity $^{o}/oo$ Regions West	East	N.Caspian
*1935-1955	0.2	6.0-11.3	6.3-12.6	6.4-11.7	8.4	7.6	8.0
**1956-1962	0.2	8.2- 9.5	7.1- 8.6	7.8- 9.3	9.1	7.8	8.6
***1973-1977	0.2	9.1-11.0	5.7-10.8	8.8-13.0	10.1	11.3	11.0
****1973-1977	0.2	9.1-11.1	5.7-10.8	8.0-10.4	10.1	8.9	10.1
****1973-1980	0.2	8.6-11.1	5.7-10.8	8.0-11.0	9.7	8.5	9.3
****1977	0.2	_	_	_	10.3	10.8	10.4

Note: Modified data (Salinity concentration is expressed as an average weighted value (g/liter), computed from the mean monthly of April, June, July, August and October at depths: surface, 5m, 10m and bottom)

*April-October, 1935-1955; April-November, 1956-1962, Pahomova & Zatuchnaya[5]

**April-October, 1973-1977, Katunin & Kosarev[35]

***Predicted by Pahomova & Zatuchnaya[5]

****Observed, from Baidin and Kosarev[1] have largely aggravated water quality in the reservoirs and particularly in the lower Volga, the Delta and the eastern shallows of the North Caspian (eutrophication and oxygen depletion in these areas are not rare events).

3.3 Salinity Distribution

The cumulative effect of reduction of annual and especially spring water supply to the North Caspian for the last two decades, accounting on the average to 55.6 km^3 has led inevitably to massive salt intrusion in this region from the Middle Caspian. The mean annual salinity of the North Caspian and its two parts (western and eastern) have increased as much as 1-4^{o}/oo since 1955 (Table 7).[5, 35] Even in the deep water masses the increase in salinity has been documented. In the 1970's the average annual salinity of the North, Upper Middle and South Caspian water masses reached concentrations of 11; 12.1 and 13.1^{o}/oo.[1] Moreover, when excessive diversions were superimposed on the sub-normal spring water supply of 1973-1977, the 50% of the North Caspian area was occupied by brackish water of 6-11^{0}/oo concentration, while the highest known concentration of 13-15^{o}/oo was registered in the south end of the eastern part of the North Caspian. At the same time the Middle Caspian water masses was 12^{o}/oo. The nursery ground of semi-anadromous fish that can tolerate the range in salinity fluctuations of 0.2-5.0^{o}/oo and up to 8^{o}/oo during spawning and feeding, respectively, has shrunk from 25,700 km^2 (1959-1971) to 6,200 km^2 (1977). This contributed to a drastic reduction of phytoplankton and zooplankton, and of the biomass of such benthic organisms as mussels, which are the primary diet of anadromous fish.

In the deep zones of the western part, including the Volga-Caspian shipping canal, the two-layer circulation has become almost a constant feature of altered regime of the areas in question. The strong vertical stratification and anoxia near the bottom are not rare events.[1]

The deficit in water supply, and the subsequent increase of salt accumulation and the vertical stability intensified by evaporation, account for these changes, that had not been observed for pre-project conditions.[35]

The late fall-winter releases of water from the Volgagradskaya power plant resulted in increases of the intra-annual salinity range of as much as 1.5-2.5 times. Moreover, the lack of discharges during June and August substantially reduced the summer amplitudes.

As a result, the vertical salinity (density) gradient decreases in summer, but increases during the late fall-winter period, up to one gram per liter. The immediate consequences of this shift in salinity stratification are the reduction of oxygen concentration and increase of salt content in deep zones which have a detrimental effect on pelagic and demersal fish and benthic organisms inhabiting the North Caspian. (This area decreased after the 1930's by about 28-35 thousand km^2).

3.4 Sediment Transportation and Distribution

Because of dividing the Volga River by dams into eleven sections, the river has developed a unique sediment transport phenomenon: namely, silting in the still water of the reservoir above the dam, intensified erosion down below the dam, especially during releases (a low water level), and silting in the downstream reservoir and so on.[36]

In general, the mean annual sediment load (Table 8) to the Delta-North Caspian Ecosystem dropped to more than 49% of the total yield, and about 64% from that of the Volga basin alone.[8, 36] Besides, only 25-32% of the residual suspended load of the Volga River is carried over to the North Caspian. A near significant drop in the suspended sediment flux took place in the Middle and South Caspian (Table 8). In sum, the total mean sediment load of 45.4 x 10^6 of the major rivers of the Caspian Sea for the period of 1966-1981 was 1.5 times less than it would, had the natural conditions prevailed.[1] This influenced the stability of the river banks, levees in the delta and its entire morphological structure.[4, 8, 9]

3.5 Biogenic Yield

The Volga cascade of reservoirs has therefore become a trap not only for huge amounts of the sediment load but has also significantly decreased and redistributed the nutrient load.

In general, the amount of inorganic and organic phosphorus decreased on the average as much as 1.5 and 2.0 times, respectively.[1, 5, 18, 32]

Inorganic nitrogen constitutes only 70% in comparison with the pre-project conditions in the lower Volga delta.[1, 14, 15, 35]

This reduction in biogenic (especially phosphorous) yield (90-93% account for organic phosphorous) has a negative effect on the primary production of an organic matter in the North Caspian. The latter accounts for only 50% of its value before water projects operational (8 x 10^6 tonnes).[1]

TABLE 8

Mean Annual Suspended Particulates Discharge

to the Caspian Sea Before and After the Impoundment

of the Major Rivers of the Caspian Sea

River	Period	Mean Natural Runoff KM^3	Natural Suspended Load MLNF tonnes	Period Years	Mean Regulated Runoff KM^3	Regulated Suspended Load MLNF tonnes	Reduction regulated of the natural mean in %
Volga	1887-1962	251.0	25.7	1966-1981	232.0	9.2	64.2
Ural	1935-1954	10.0	4.1	?	7.5	2.7	34.2
Terek			25.8	1966-1981	4.0	7.0	83.0
Sulak	1925-1953	5.6	?	?	0.9	?	?
Samur	1925-1953	2.0	?	?	0.6	?	?
Kura	1930-1954	18.0	37.0	1966-1980	13.1	11.2	69.7
Iranian Rivers				1980-1986	8.0	?	
	?	10.?	?	1966-1981	0.5	?	?

NOTE: Compiled from 1, 4, 5, 9, 34. (Other examples of the drastic sediment load reduction because of diversions are: the Nile, Colorado, Don, etc. 85, 96 and 75% respectively).

TABLE 9

Fluctuation of Seasonal Phytoplankton Biomass

Under Different Freshwater Supply to the North Caspian*

Seasonal Total Phytoplankton Biomass Range In the North Caspian, 1956-1962		Biomass of Phytoplankton Mg/M^3 in the Northern Caspian Areas, 1968-1974			
		Western	Eastern	Northern	
Spring**	664 - 2,400	345-4, 794	41-352	245-3,331	41-4,79
April	293 - 1,496	305 - 500***	40-189	218-377	40-500
Summer	1,478 - 6,896	?			
August	3,205 - 6,896 3,132 - 3,286	?			
Autumn	1,666 - 6,697	?			
October	1,666 - 9,697	?			
	1,428 - 9,660	?			

* Data obtained from Levshakova[31]

** Spring: April; Summer: June-August; Autumn: September-October

*** Biomass without Spirogyra

At the same time, the organic nitrogen yield in the low Volga-Delta ecosystem increase as much as 2.5 times in comparison with pre-project conditions.[15, 35] This shift is explained partially by the increase of industrial and municipal waste discharges to the considered area.

Since completion of the project the optimal regulated spring discharge has had a duration of not more than 15-30 days; the total volume of spring releases from the Volgagradskaya power plant decreased by a factor of 2, and the phytoplankton and benthos biomass of the Northern Caspian dropped as much as 2.0 to 2.6 times (Table 9).

3.6 Fisheries

In the shaping of biological productivity of the Caspian Sea, the prevailing factor has been and is now the river discharges, still abundant biogenous elements which have served as the basis of plentiful food resources for the numerous variety of fish species.

The fresh and brackish water relict fish fauna is formed in the Northern Caspian. This originally included fresh water, semi-anadromous (bream-Abramis brama; perch - Lucioperca; Caspian roach, carp - Cyprinus Carpio) and the anadromous fish (Russian Sturgeon, Acipenser guldenstadti Brandt; sevruga-A. stellatus Pallas; beluga - Huso huso L.). Migration and spawning of these and some other indigenous fishes occur in the fresh water of flood plains of the deltas and rivers but most of all in the lower reaches of the Volga-Ural River during the spring (where in the recent past over 2×10^6 ha were covered by the flood waters). The feeding and fattening of the young-of-the-year takes place in water with predominant salt concentration of 1-8^{o}/oo.[7, 13, 16, 18, 39, 41]

During the pre-project period (up to 1940), the migration routes of anadromous and semi-anadromous fish extended 1,000-2,500 km up from the Volga delta toward numerous nursery grounds in the Volga and its tributaries.[15, 18, 42]

In the far past, the Volga-North Caspian ecosystem was producing the biogenic yield (three times higher than current) necessary to maintain 90% of all catches of Acipenseridae the world over.

Before 1930, the catch in the Caspian Sea exceeded 600,000 tonnes and 90% of it were represented by valuable fish belonging to the brackish water varieties. From them, commercial catch of Acipenseridae accounted for 18,000-36,000 tonnes.

Semi-anadromous fish, whose catch in 1930-1955 varied between 120-370 thousand tonnes, and including freshwater fishes, exceeded 200-400 thousand tonnes. However, as mentioned above, the biological productivity of the Caspian Sea in the last two decades has been suppressed by intensive water engineering diversions and altered annual and intra-annual reduction redistribution of river discharge to the lower Volga reaches and overall reduction.

The average annual fisheries catch in the lower Volga in 1966 was 470,000 tonnes of which not more than 2% were valuable commercial anadromous and semi-anadromous species. This was many times less than had been caught before the Volga-Kama reservoirs significantly curtailed the water supply to the lower Volga reaches and extirpated an average of about 80% of nursery grounds of Acipenseridae and other valuable fish. These modifications of the river network compounded by consecutive successions of subnormal and lower than subnormal years of wetness (Section 2.1) have destabilized the delicate environment and fishery of the Volga Delta-North Caspian to the almost irrevocable level if the future of biological resources is of concern.[9, 11, 18-20] It should be noted that the uncontrolled Volga runoff of the "normal" or wet years provided 400,000-550,000 tonnes per year of commercial valuable fish instead of about 45,000-55,000 tonnes in the late 1960's.

The north-eastern part of the Caspian Sea, where the Ural River discharges its waters, is the second important area of migration, spawning and commercial catch of anadromous and semi-anadromous fish. The commercial role of this area was significantly increased since the Volgagradskaya power station curtailed spawning ground of the sevruga. Beginning in the middle 1970's the Ural Delta-North Caspian Sea ecosystem provided almost one-third of a world-wide catch of the Russian sturgeon, from which 90-95% are presented by a spring run of sevruga[40] (since 1965 Acipensiridae have been caught in the river only). Maximum biological productivity in this coastal system was observed when the highest runoffs from the Volga and Ural Rivers coincided, otherwise, dry years cause the lowest productivity in the North Caspian.

The third area of importance - the Kura river-south western Caspian ecosystem was teeming with diversive species of the

Russian sturgeon and other valuable fish before the impoundment of the river by power plants' dams took place in the 1950's. Since that time and despite multimillion releases of fry, the stock and the catch of any known species of anadromous and semi-anadromous fish have plummeted to the catastrophic low level.

In 1931-1940, the catch of Acipenseridae (Russian sturgeon) equaled 4,700 tonnes on the average (or 25% of a total average of Caspian basin catch). While in the late 1960-1970's the catch constituted for less than 1% (160-180 tonnes).[18]

Salmonidae and some other fishes ceased to migrate to spawn since several hydropower plants and irrigation networks have started to divert over 60% of spring runoff (1953) (moreover, the migration routes almost dried up). The sea perch (Lucioperca marina) almost disappeared.

The fourth area of importance - the Atrek river - in the south-eastern part of the Sea, provided the commercial yield of Acipenseridae and other valuable fish equaled almost 14,400 tonnes (1.9% of a total was typified by a very low value of pelagic fish, Clupeonella delicatula delicatula, whose several types commonly referred to as the Caspian "Kilka" by fishermen).[16, 17]

However, in 1968-1972, the catch of the aforementioned valuable fish declined to 1.5%, whereas the Caspian "Kilka" increased up to 57,300 tonnes (98.3% of a total).

Meanwhile, the Acipenseridae (Russian sturgeon) almost vanished.

The causes of these precipitous declines in fish stock are said to be: a) depletion of the Atrek river runoff; b) agricultural pollution, c) overfishing (in the sea) and d) drop in the sea level.[18]

Since that time there has not been any indication that the significant recovery of undermined valuable fisheries in the discussed areas has taken place.

In the southern end of the Caspian Sea (the Iranian Coast) the rivers and streams are subjected to such extensive diversions that there are almost no freshwater discharges during June-September. Razivi and others[43-45] stated that over 90% of the Iranian coastal streams were dry in July due to high demands for water by rice growing irrigation networks. The implication of this is that the averaged commercial catch of valuable fish has declined from 9,500 tonnes to 821 tonnes, e.g. more than ten times.[44,45]

The impoundment of the Sefid Rud river by the dam eliminated runoff to such a level, that migration and spawning of Iranian sturgeon is not only difficult but almost impossible.

The commercial catch of sturgeon in the above coastal area dropped from 6,700 tonnes (1933-1934) to as low as 0.3 tonnes in 1961-1962.[45]

<u>Caspian Herrings</u>

There are six major species and 11 sub-species of the Caspian herrings.

Their commercial catch varied significantly during pre-project periods.[17, 19, 21] However, since the implementation of projects, by the 1970's, the catch dropped to the economically unacceptable level and ceased to exist (table 10).

TABLE 10

Dynamics of Commercial Catch of the Caspian Herring (1885-1973)*

Period	Catch x1,000 tonnes	Period	Catch x1,000 tonnes	Period	Catch x1,000 tonnes
1885-1899	29-124	1945-1953	56-62	1967-1972	0.6-2.1
1900-1917	82-307	1954-1962	34-54		
1918-1932	82-102	1963-1964	12-19		
1933-1944	65-156	1965-1966	3.5-1.4		

*Note: Compiled from Kazancheyv.[10] Since the last period the commercial catch has been banned.

The most severe decline was documented for A. Kessleri volgensis (the Volga-Caspian endemic), namely, from 130,000-160,000 tonnes in 1913-1916 to 5,000-6,000 and 10 tonnes in 1960's and 1969-1972, respectively.

The factors which contributed to the collapse of the herring fishery are: a) impoundment of the river by the Volgagradskaya power plants; b) reduction of the river runoffs; c) unfavorable changes in temperature and many other regime characteristics; d) the siphoning off over 6 km^3 of water from the Upper Delta (billions of larvae and fry killed); e) drying up almost 30,000 km^2 of the North Caspian shallows (nursery area for the Caspian herrings.[19, 21]

Meantime the catch of Clupeidae (the Caspian "Kilka") equaled 418,000 tonnes or 107 times of those in 1930.[18] It should be noted that the 80% of a total catch to date attributed to this low value fish.

Therefore, the Caspian Sea has been transformed (during the exceptionally short period of 1956-1972) from the worldwide known basin of the highest stock of valuable fishes to the "Kilka" type of the sea.

4.0 Environmental Protection and Resource Management Strategies.

There have been several attempts to mitigate the impact of water development on the North Caspian anadromous and semi-anadromous fisheries. Among them, modification of water release schedules and implementation of numerous hatcheries. The controversial results of these programs may serve as well-documented examples of human inability to replace nature.

4.1 The Divider System

By the late 1960's it was obvious that the massive diversions of water from the Volga were adversely affecting the fish populations of the delta. It was estimated that the situation could be improved for spawning and growth of semi-anadromous fishes of the delta by providing for a flow of 12,000 m^3/sec. at the head of the delta. River discharge was to be stabilized at a steady rate without reference to annual differences in river flow. This flow was to be achieved by a "water divider" system (fig. 13).

The construction of the Volga Divider started in the late 1960's and continued through 1976[10,34]. This sophisticated hydrotechnical complex (at a total cost of about 2.5-3.0 billion dollars) consists of: the Volga divider (40 km above the delta); a solid dam 80 km long across the river bed and Delta with a controlling gate to the eastern (left side) of the delta, 33 sectional dams with gates, two structures to guide fish, and a dike dividing the delta into eastern and western parts. There is also a system of 16 canals across the outer shoals of the delta (fig. 14), the total length of which is about 661 km. Two ship locks and navigable sections with vertical lift gates are necessary to bypass the divider system. This divider narrowed the main river bed to almost 50% of the total width and was able to split the residual spring runoff (especially when the dry spring runoff equals 12,000-15,000 m^3/sec) through the "Peripheral Canal" between the western (20-40%) and the eastern delta (60-80%) to ensure a guaranteed flow of 8-9 thousand m^3/sec

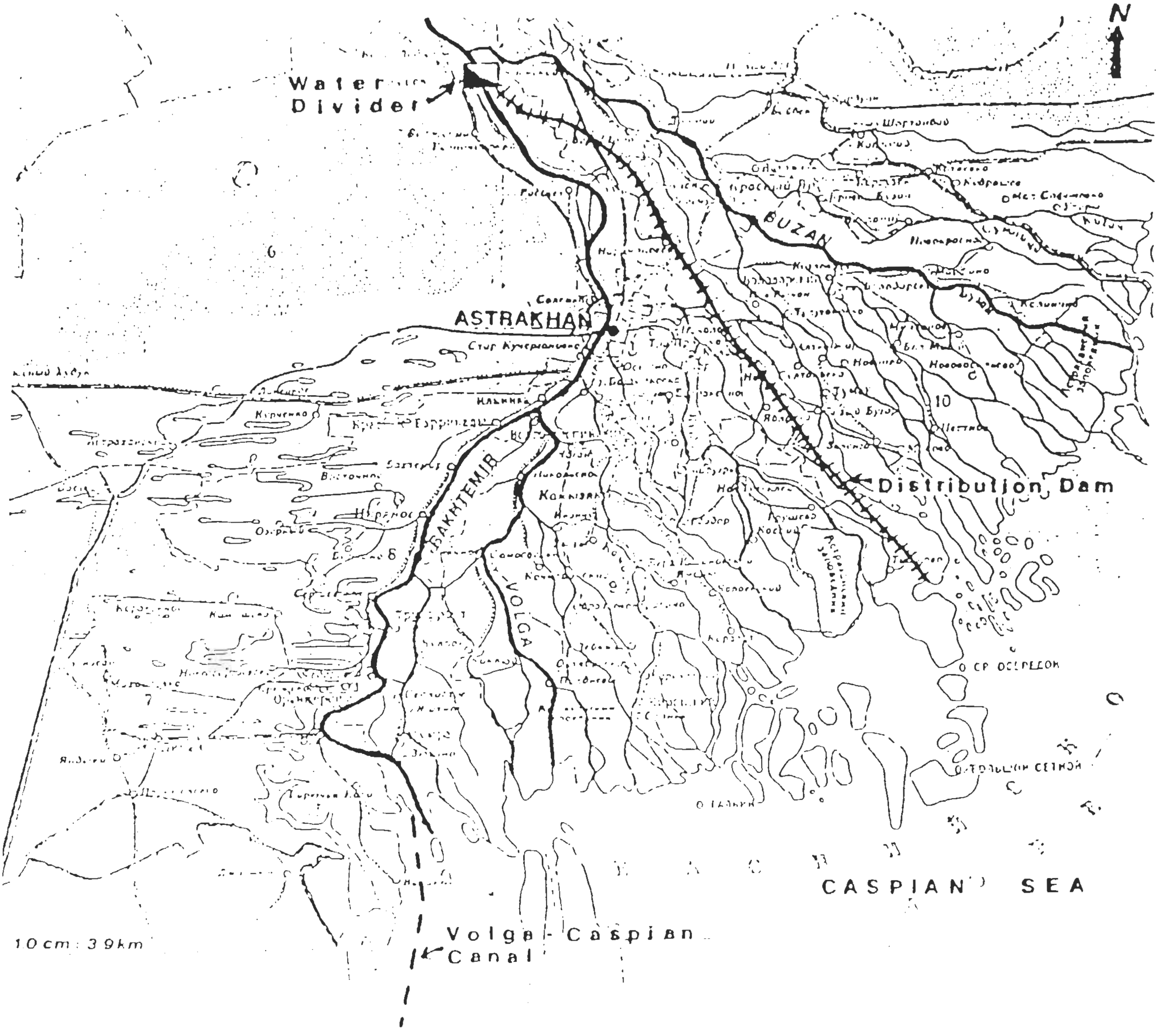


Fig. 13 The lower Volga delta water distribution network.

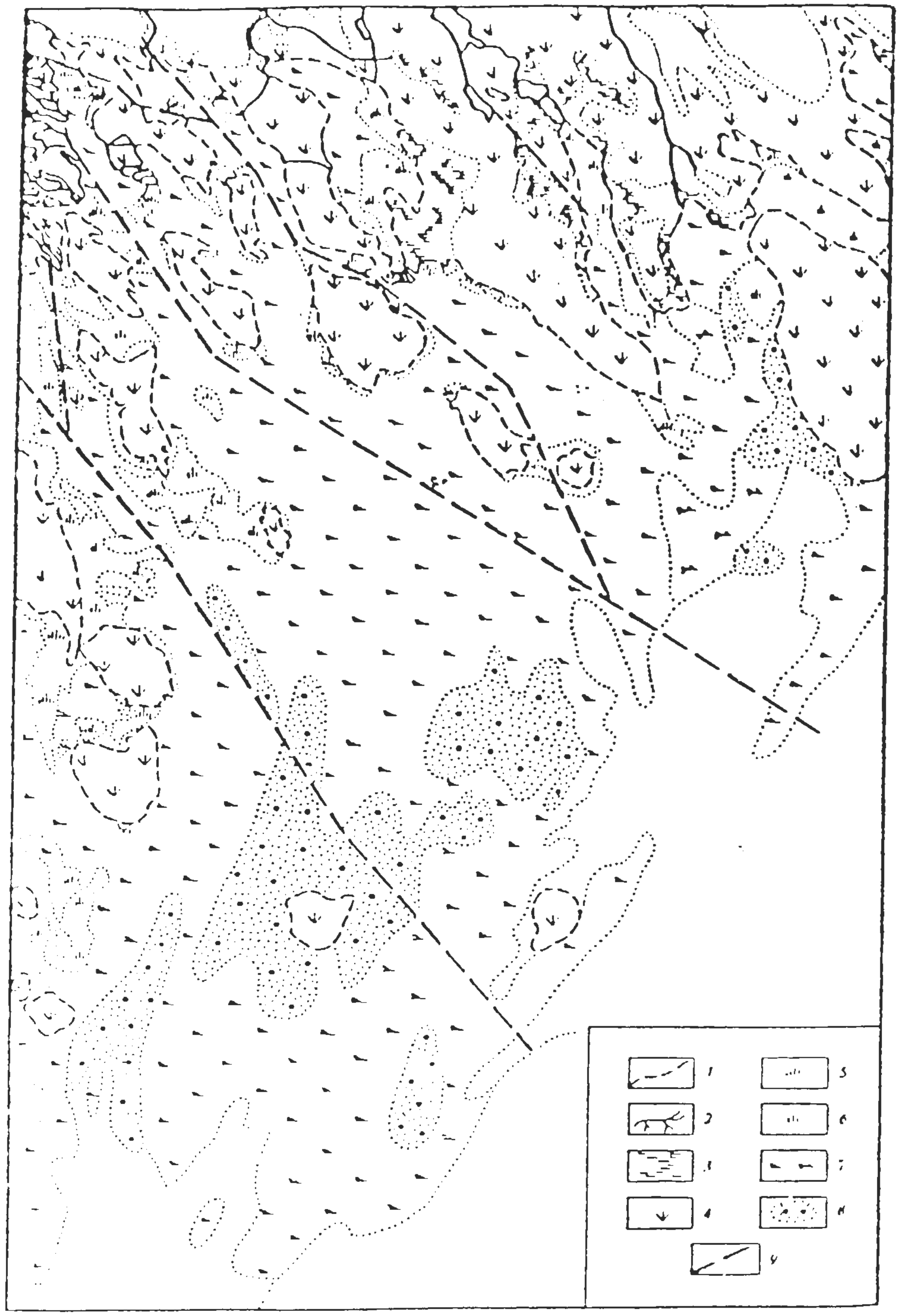


Fig. 14 The central and Eastern area of the Volga Delta hydrographic network composed from satellite observations. Delta: 1. Sea-Delta boundary; 2. Delta tributary network; 3. Swamp; 4. Brushwood reed; Outer Delta: 5. Dense reed; 6. Sparse reed; 7. Submerged vegetation; 8. Sand bar; 9. Fish channels (after Krasnozhon and Sokolov[46]).

to the Buzan, the eastern major tributary of the Volga. It was assumed that this water redistribution would enhance conditions for fish spawning and growth in the eastern delta and adjacent shallows of the North Caspian. When discharge exceeds 24-25 thousand m^3/sec, the sectional dams in the right branch of the Volga are open, as the discharge of 9,000 m^3/sec, the normal flow for the eastern part of the delta, would reach the river naturally. It was believed that during low water flows the artificial flooding regime provided to the delta would correspond to the natural seasonal processes in the lower Volga ecosystem.[42] At the same time it would be expected to divert the fish that might be lost in the predominantly agricultural western side of the delta to the eastern side where conditions favorable for spawning and growth would be maintained. The divider was to begin operation in early April, and continue for 30-35 days to induce spawning migrations into the eastern part of the delta, followed by a diversion of 23,000 m^3/sec for 10-12 days to the western side for agricultural requirements. In order to prevent loss of fish during this agricultural release, reproductively mature fish would be diverted to the eastern delta by releasing 3,000 to 3,500 m^3/sec for a period of 30-35 days beginning in mid-September. It was believed that this artificial flooding regime would correspond to the natural seasonal cycles in the lower Volga ecosystem, and stabilize conditions on a long term basis for the eastern part of the delta. During every third year there was to be a "piscicultural" discharge of at least 120 km^3 (77% of the "normal" spring runoff) to provide for freshening of the northern part of the Caspian Sea. This complicated system of fishways, pumping stations, canals, channels, etc., cost hundreds of millions of dollars by 1976 at the time of completion. Had this system emphasized the elimination of agriculture and development of the western delta as a reseration for living resources, especially fish, and concentrating irrigation for an agricultural complex in the eastern delta, it might have had a better chance for success. As designed and operated, however, it did not work.

During repeated tests, one very classical hydraulics phenomenon was observed, namely, the deeper major distributing canal, in comparison to surrounding shallow delta streams, conveyed more water down to the sea, leaving the natural shallow canals of the delta, indispensable for migration and spawning success, out of water. In addition, it was found that Russian sturgeon prefer to use the historical western delta routes for migration, although the eastern delta had much greater artificial water supply, fresher for spawning and with better phytoplankton and zoobenthos biomass. "The fish lacked the education to cooperate."

The modernization and improvement of the Volga divider during 1977-1982 has not only resulted in preventing gradual destruction of the natural complex of the delta, but instead has transformed it into a plumbing system suitable more or less for two water users out of the aforementioned four, i.e., agriculture and fishery in the lower reaches of the Volga in particular are the major losers.[29, 30, 34, 42]

There are similarities between this elaborate system of waterworks with the modifications suggested for the delta of the Sacramento-San Joaquin river of California, including a bypass, the Peripheral Canal and various alternatives (some of which like inner-delta water conveyance facilities and the six pumping stations were implemented) for handling the diversion of water for irrigation and domestic use at the expense of the fisheries stocks involved.

The losses sustained by the anadromous fisheries of the San Francisco Bay estuarine system for the last two decades account for $2.6 billion, although it may be only one fourth or even less of the capitalized losses of the Caspian commercial fishery.[20,21]

The divider operation has proven that no computerized plumbing system disregarding the natural limitations of runoff can alleviate water shortages and restore historical conditions or even maintain an optimal level of survival of living and non-living resources of the Volga-Delta-North Caspian ecosystem.

5.0 Summary and Conclusions

The ecological conditions and commercial fishery of the Caspian Sea, in particular, its most productive shallow area - the North Caspian - are intimately related to the fresh water supply from the Volga River watershed, especially, the spring runoff. During the last two decades 11 hydroelectric power plants and their storage facilities, having a capacity of about 190 km^3 (75.7% of the annual "normal Volga-Kama river discharges of 251 km^3 for the period of 1887-1962), and the numerous pumping irrigation systems in the lower Volga have transformed the intra-annual runoff pattern to such a formidable scale that the entire ecological future and fishery of the Caspian Sea is in question.

The reduction of spring runoff up to 45-60% has attributed to the decrease of a flood duration 2-3 times and shifted its truncated peak from June to May. As a result, a significant part of the Delta's nursery ground is suffering from a chronic deficit in water supply, salt intrusion, lack of oxygen and sharp temperature fluctuations. These and other changes have a negative effect on food reproduction, spawning and feeding activities of the valuable species of fish of the Delta-North Caspian ecosystem.

The current Volga River spring runoffs are dominated by volumes which correspond to subnormal, lower than subnormal wetness or dry conditions (75-99% probability of exceedence if the frequency curve of the historical spring discharges is used for comparison).

During the period of the most active water development and unfavorable climatological conditions of 1961-1979, the North Caspian did not receive about 1,050 km^3 of spring runoff (4.2 and 2.6 times the Volga annual discharges or the North Caspian volume). The runoff of the majority of small rivers of the Middle and Southern Caspian almost ceased to exist.

The inverse phenomenon in water supply to the North Caspian (summer-winter runoff several times higher than spring) has not brought about positive development (if fish stock is of concern), for the spawning and migration of juveniles takes place in the spring.

The extensive water withdrawal and impoundment of the river basin resulted in: a) negative transformation of morphometric, hydraulics, physical and chemical properties of the Volga and other rivers and deltas; b) an increase of the concentration of waste and recycled waters polluted by agricultural, industrial and domestic discharges; c) a déleterious effect on the biological resources; d) and a sharp increase of detention time as much as 8-10 fold that aggravates water quality conditions in the ecosystem, especially during the dry years.

A substantial part of the Volga flood plains that served as a nursery ground for many valuable fishes have been transformed to dying swamps or progressively-increasing deserts.[1]

In general, the current seasonal vertical and horizontal stratification and displacement of many regime characteristics of the Sea including, but not limited to temperature, salinity, oxygen, phosphorous, nitrogen, etc., differ significantly from those of 1930's or late 1950's.[5, 6, 33, 37]

In our opinion, the North Caspian ecosystem will not recover as long as the cumulative losses in spring water supply (and related losses in chemical elements or negative transformation of the hydrological structure) prevail over the natural deviations. Similar developments in other rather different estuarine systems (Dnieper and Dniester; Don and Kuban; Amur Darya and Sur-Darya; USSR; San Francisco and Delaware Bays, Columbia River; USA; the Nile River, Egypt) give strong support to this statement.

Therefore, these losses are the major cause of the progressive deterioration and significant decline in natural recruitment in stock and commercial catch of anadromous fishes (Acipenseridae) as much as 3-5 times (Russian sturgeon -

Acipenser guldenstadti Brandt; Beluga-Huso Huso Linnaeus and Sevruga, Acipenser stellatus pallas).

While the decline of the major semi-anadromous species: (bream-Abramis brama; perch-Lucioperca, Caspian roach; and carp - Cyprinus carpio) is measured by hundreds of times. Even severe losses were sustained by the Iranian fishery (though its relatively small catch is not comparable with the rest of the Sea) due to impoundment of coastal rivers and streams compounded by pronounced pollution.

The magnitude of these changes, in our opinion from reviewing the data, has exceeded the natural ability of the delta-sea environment to make a "quick" adjustment to the unprecedented decreases in the spring runoff. Therefore, the ecological impacts occurred.

Channelization, deepening and dewatering of the drainage network compounded by overall decrease of the flood peak and its duration have resulted in salinization and desertification of major areas of the delta tidal flats.[1] The progressive development of these processes has altered and practically undermined the migration routes, spawning and feeding grounds of semi-anadromous and anadromous fish and severely affected the agricultural value of the Delta lands and freshwater intakes.

This costly development had been foreseen by some environmental specialists (but it was overwhelmingly ignored by many other single-minded resource planners) who recognized the fact that artificial redistribution of the river flow by Volga divider through its sophisticated network of channels built-in the Delta cannot and will not substitute the historical routes of migration of anadromous and semi-anadromous fish or compensate for losses sustained by fishery due to chronic deficit in water supply during the spring and related to it many other cumulative negative regime changes.

Suffice it to say that unprecendented rehabilitation efforts and multimillion dollar expenditures launched by government institutions to preserve from extinction the unique population of Acipenseridae and other valuable fishes became almost equal to the capitalized gains obtained from the residual Caspian fisheries (4.0-8.0 x 10^8 dollars per year).[20]

The ecological conditions of the Volga delta (as many other deltas of the Caspian Sea) are in a precarious state because no amount of sophisticated hydraulic construction, only optimal water supply from the Volga River to the delta, regardless of the year of wetness, will prevent the destruction of the Delta-North Caspian ecosystem.

The problem is that Soviet engineers and ecologists at early planning stages of these water resource projects did not pay attention to the operating environmental processes and ecological requirements (spatial and temporal) to budget correctly the water requirements needed by all of the users from fishing to agriculture, let alone being in a position to correctly evaluate the impact of these water resource projects. Therefore, the economic benefits in one use area (hydroelectric power or irrigation water) dominate planning, construction and operation without concern for long-term environmental impacts. When these are combined with notions of cost-benefit analysis and trade-offs that justify the demands for water beyond the river limit, the transformation of the delta into the distribution plumbing system or the agricultural wastes' conveying network, the synergetic action may accelerate the destruction of estuarine systems.[47] This universal development has been demonstrated in several places in the US (e.g., San Francisco Bay; the Colorado and Columbia River, the Texas bays), however, not on the scale as seen in the Caspian estuaries or the Sea of Azov.[48-56] The monitoring of these universal failures will be very important in the next 100 years as high quality freshwater supplies become critical to developing and developed nations and high quality fresh water sources become critically necessary for mankind.

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