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TITLE: THE IMPACT OF ALTERED RIVER FLOW ON THE ECOSYSTEM OF THE CASPIAN SEA

AUTHOR: Michael A. Rozengurt
Joel W. Hedgpeth

CONTRACTOR: San Francisco State University

PRINCIPAL INVESTIGATOR: Michael A. Rozengurt

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The Impact of Altered River Flow on the Ecosystem of the Caspian Sea

Michael A. Rozengurt and Joel W. Hedgpeth

I. INTRODUCTION

A. Physical Characteristics

The Caspian Sea lies in the world's largest inland basin, extending from 47° 43′ to 54° 51′ E (Figure 1). The shortest distance between the Caspian Sea and the Black Sea basin, the nearest basin having an open connection with the Mediterranean and through it with the Atlantic Ocean, is across the Caucasus. The northern and southern boundaries of the Caspian watershed are located between 62° N and 35° N (i.e., north of Leningrad and south of Teheran), and its area of 3.5×10^6 km² is equal to about 25% of the continental landmass of the U.S. This enormous basin extends from subarctic to subtropical regions. The climatological, morphometrical, and geophysical features of this area are responsible for the formation of the environment of the Caspian Sea and surrounding lands extending hundreds of kilometers from its shoreline.

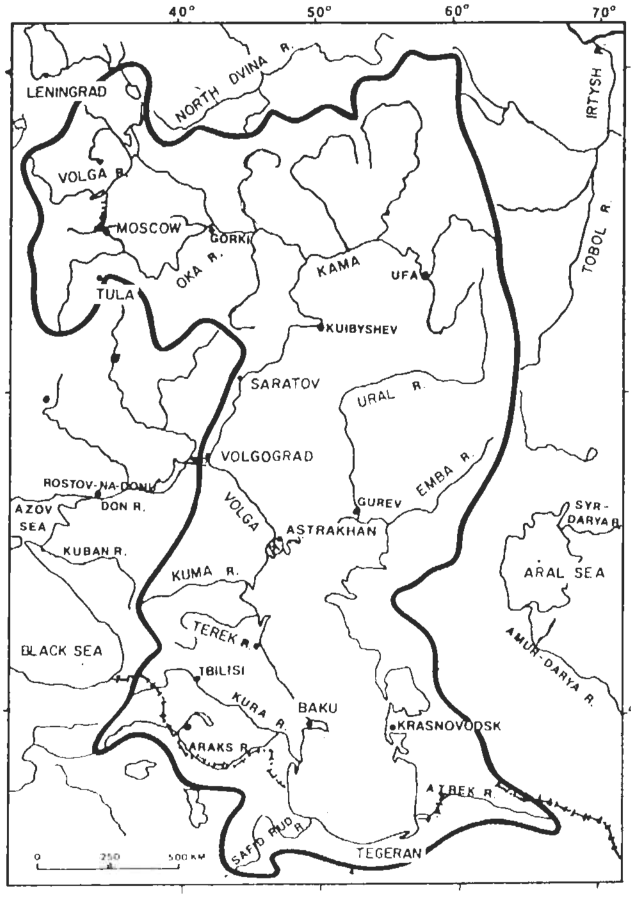

FIGURE 1. The Caspian Sea watershed. (Modified after Reference 6.)

The average surface area of the Caspian Sea (3.784×10^5 km²) constitutes 18% of the total area of all lakes of the world,[1] about five times the surface area of Lake Superior and about 2.7 and 10 times the surface area of the Adriatic Sea and Sea of Azov, respectively. It is roughly equal to the size of Great Britain (Figure 2). The volume of the Caspian Sea (78.1×10^3 km³) 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 (U.S.S.R.) and the Baltic Sea, respectively. Over 130 rivers and numerous streams discharge an average of almost 300 km³/year into the Caspian Sea (or 6% of the total natural runoff in the U.S.S.R.), from which about 85% originates in the Volga-Kama and Ural River basins and about 15% in the southern river drainages of the Caucasus region, the Terek, Sulak, Samur, and Kura rivers and Iranian rivers and streams along the southern part of the Caspian Sea (Table 1).

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

The major water users in the river basins are agriculture (60%), hydroelectric power plants, industry, municipal government, shipping, and commercial fisheries.[2-10] The extensive water developments of the last decades in significant parts of six republics of the U.S.S.R. located in the Caspian watershed (i.e., U.S.F.S.R., Azerbaijian, Armenia, Georgia, Kazakhstan, and Turkmenistan) and in the Iranian coastal zone (Figure 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, and its fisheries.[11-14]

B. Location/Geography

The Caspian Sea is located at the far southeastern margin of the European part of the U.S.S.R., along the boundary of Europe and Asia. This relict sea occupies the largest continental depression, with a surface level about −28 m below mean ocean level.

The Caspian Sea is a landlocked remnant of the Tethyan Sea, which was divided into several basins in the Miocene

Dr. Rozengurt received his M.S. from the Hydrometeorological Institute, Department of Oceanography, Moscow University, Odessa, U.S.S.R. and his Ph.D. from the Federal Oceanographic Institute, Moscow, U.S.S.R. He is currently a Senior Research Scientist at the Paul F. Romberg Tiburon Center for Environmental Studies, San Francisco State University, Tiburon, California. **Dr. Hedgpeth** earned his B.A., M.A., and Ph.D. from the University of California at Berkeley. He is Professor of Oceanography Emeritus at Oregon State University and resides in Santa Rosa, California.

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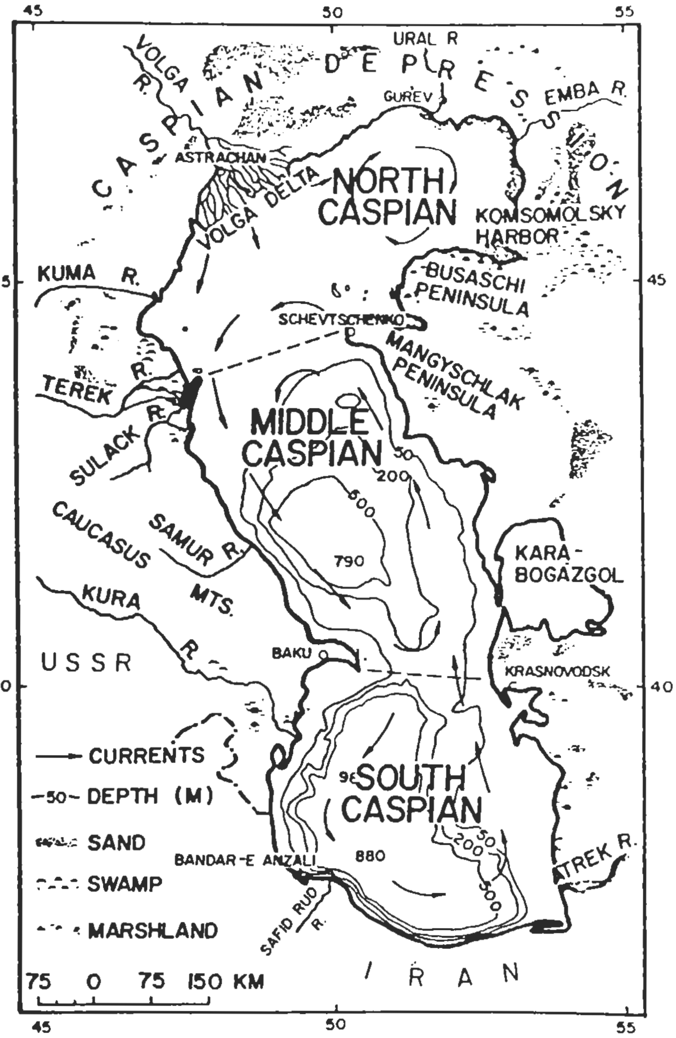


FIGURE 2. The regions of the Caspian Sea. (Modified after Reference 6.)

Epoch. One of these was the Ponto-Caspian basin. About 1 million years ago, this basin was partially divided into the two major water bodies named in the historic past as the Black and Caspian Sea. Recently, the Caspian Sea has undergone many geological and geophysical transformations that gradually led to its full isolation from the Black Sea and, therefore, the world ocean. For the last several thousand years, its climatological, hydrological, and biological characteristics have undergone substantial changes.

The Caspian Sea is usually divided into three sections: north, middle (central), and south (Figure 2). This division is based on morphological, physical, chemical, and biological peculiarities in the regions considered.[5-7] In turn, the North Caspian is divided into two parts — western and eastern — which differ in terms of morphometric characteristics and natural regimes. The western part is deeper than the eastern, although their surface areas are almost equal. Their average and maximum depths are: 5.6 and 25 m and 3.3 and 9 m, respectively.[1] Correspondingly, the western region comprises 63% of the total volume of the North Caspian; it is used for shipping (through the deep Volga-Caspian canal) and serves as a major historical route for migration of anadromous fish (Bakhtemir branch). The North and Middle Caspian are separated by a submerged part of the Mangyschlak Peninsula, and the Middle and South Caspian are separated by the shoal of the Apsheron Peninsula (near the city of Baku).

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

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

The ratio between the volume of the "normal" Volga basin annual runoff (251 km^3) to the mean volumes of the western (249 km^3) and eastern (148 km^3) parts of the North Caspian equals 1:1 and 1.7:1, respectively. These ratios demonstrate the significance of the Volga discharges to the North Caspian. They provide 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] Some 200 years of studies on the Caspian Sea have produced conclusive evidence that the runoff from the Volga watershed, which covers 1.38×10^6 km^2 or almost 40% of a total area of the sea basin,[1] has been and will continue to be a major factor (among climatological, geophysical, and other factors) controlling the hydrological and biochemical structure of the Sea and regulating its biological productivity.

C. Sea Level

The varying intensity of the stochastic fluvial stages has resulted in changes in sea level and volume. In the present geological period, the sea level has fluctuated at an amplitude of 8 m. During the Quaternary Period, sea level fluctuations were approximately 15 m, and during the Holocene Era, the sea level fluctuated up to 50 m due to the different intensities of precipitation and evaporation and the general moistening of Eurasia.

Under natural conditions, the value of the amplitude is determined by the residual value of an algebraic sum, namely, runoff (Q) + precipitation (P) − evaporation (E) over the sea surface and the duration of years of different wetness. For the period of 1900 to 1982, these elements of the freshwater balance of the Caspian Sea were equal to:[1] Q = 278.3 km^3, P = 73.7 km^3, and E = 375.5 km^3, and their residual was equal to −3.5 km^3. Therefore, a drop in the sea level was inevitable.

Table 1
Some Morphometric Characteristics of the Caspian Sea

Basin	Watershed ($\times 10^3$ km^2)	Length (km)	Width Max (km)	Width Mean (km)	Width Min (km)	Area ($\times 10^3$ km^2)	Volume ($\times 10^3$ km^3)	Depth Mean (m)	Depth Max (m)	Natural total runoff (km^3)
Caspian Sea	3600	1030	435	300	196	361—424	75—78.1	180—208	980—1025	200—460
Volga River	1380	3700	?			—	?	?	?	207—375
Entire Volga Delta	1380	70—120	200—180			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[a]	?	?	?			8—12	0.2—?	7—?	10—?	12—22
South Caspian	?	?	?			51—148	49.0—77.5	325—334	980—1025	8—18

Note: 298 km^3 — Mean total modified runoff to the Caspian Sea from 1887 to 1977. 251 km^3 — Volga-Kama River basin mean natural runoff from 1887 to 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 freshwater balance on a rise or fall of sea level for the period from 1929 to 1978.) The Caspian Sea includes many islands of different sizes of which the total area equals 2049 km^2 (North, Middle, and South Caspian — 1813, 71, and 165 km^2, respectively).

[a] 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 and, therefore, to accumulate more water for the Caspian basin (about 8 to 9 km^3/year). The latest increase of abnormal wetness made this dam an unnecessary, expensive experiment. At present, the Kara Bogaz-Gol is drying up, its area decreased nearly four times. As a result, the chemical industry sustained a great financial loss. The salinity concentration of its water ranges between 200 to 300 g/ℓ.

Compiled from References 1, 2, 4, 6, 9, and 10.

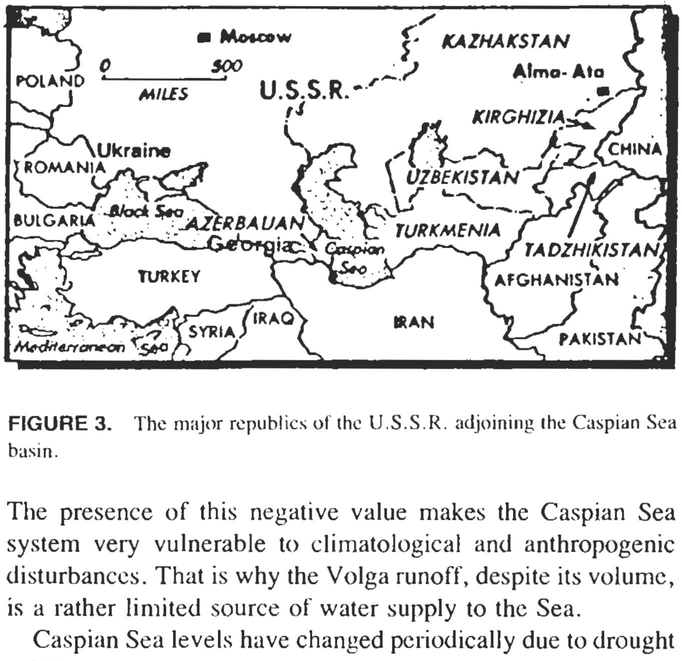


FIGURE 3. The major republics of the U.S.S.R. adjoining the Caspian Sea basin.

The presence of this negative value makes the Caspian Sea system very vulnerable to climatological and anthropogenic disturbances. That is why the Volga runoff, despite its volume, is a rather limited source of water supply to the Sea.

Caspian Sea levels have changed periodically due to drought (1930 to 1941) or increased volumes of irretrievable water withdrawals to meet agricultural needs and to fill the storage facilities of hydropower plants (1950 to 1977, Table 2). The effect of extensive water development, compounded by a frequent recurrence of years of subnormal or even lower than subnormal precipitation (Section II) was devastating for the delta-sea ecosystem. The drop in the level of the Caspian Sea from its "normal" −26 m (1837 to 1929) exceeded 3 m (1.3 to 1.7 m due to anthropogenic effects), and the sea surface reached its lowest mark of −29 m in comparison with the mean global level for the last 150 years of field observations. As a result, the topography, hydraulics, and hydrology of the deltas and adjacent shelf zones have been changed beyond recognition. For example, the size of the deltas increased due to sediment accumulation by several to many square kilometers, and many old inner waterways in the delta ceased to exist.

The transformation of the deltas has had an impact on fish populations. If the trend in runoff reduction of the 1970s were to continue through the end of the century, the consequent separation of the deltas from the Caspian Sea could result in the demise of its semi-anadromous and anadromous fisheries. Economic losses have amounted to \$110 to \$150 × 10^6 per year. Fortunately, there are indications that for the last decade sea level is now rising (the increment equals 1 m). This rise is explained by the significant natural increase of the Volga runoff and precipitation over the sea surface.[1] Ironically, this type of development may devastate the economic balance of the lower Volga-North Caspian system, after more than 40 years of gradual adjustment of the regional industry to prevailing low sea levels.

D. Water Masses

There are four major water masses whose displacement

Table 2
Historical Fluctuations of Sea Level in the Caspian Sea (1809 to 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-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	?	−1

Note: The mean natural Volga River runoffs were 259 km^3 (1881 to 1929) and 208 km^3 (1930 to 1941). The average regulated runoffs to the Caspian Sea basin were 240 km^3 (1970 to 1977) and 311 km^3 (1979 to 1982).

Table compiled from References 1 to 3 and 12.

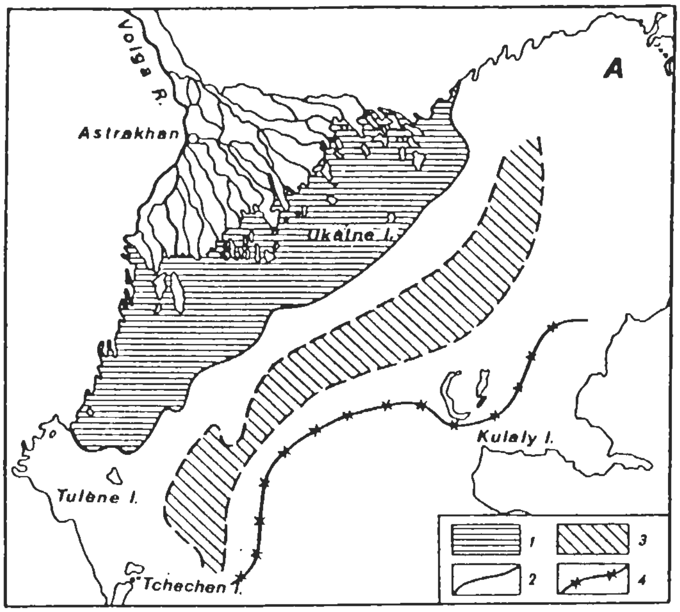


FIGURE 4A. Salinity zoning of the North Caspian Sea water masses adjacent to the Volga Delta: (1) river freshwater transition; (2) boundary between transition and mixing of freshwater and sea water; (3) hydrological front within the mixed water zone; and (4) sea boundary of river water. (After Reference 1.)

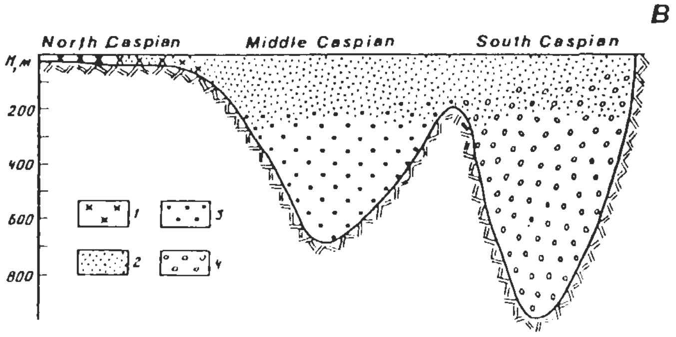


FIGURE 4B. Water masses of the Caspian Sea along the 51°E meridian: (1) North Caspian; (2) Upper Caspian; (3) Deep Middle Caspian; and (4) Deep South Caspian. (After Reference 1.)

corresponds approximately to the geophysical division of the Sea, namely, North Caspian, Upper Caspian, Deep Middle Caspian, and Deep South Caspian (Figure 4).[1,5] The North Caspian water masses, in turn, are divided into four zones: fresh, intermediate, brackish, and sea (Figure 4A; Table 3). The Volga runoff, influenced by wind-induced circulation, determines the seasonal and average location and displacement, as well as the intra-annual regime of these water masses. In general, the North Caspian water masses (Figures 5 to 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.

The highest seaward horizontal temperature and salinity gradients are observed in April; the highest vertical gradients occur in May and June during the start and peak of spring flooding. The vertical difference in temperature and salinity may reach 12°C and 9‰, respectively, especially in the deep

Table 3
Fluctuations of the Mean Seasonal Hydrological and Chemical Parameters of the Caspian Sea Water Masses (1964—1981)[1]

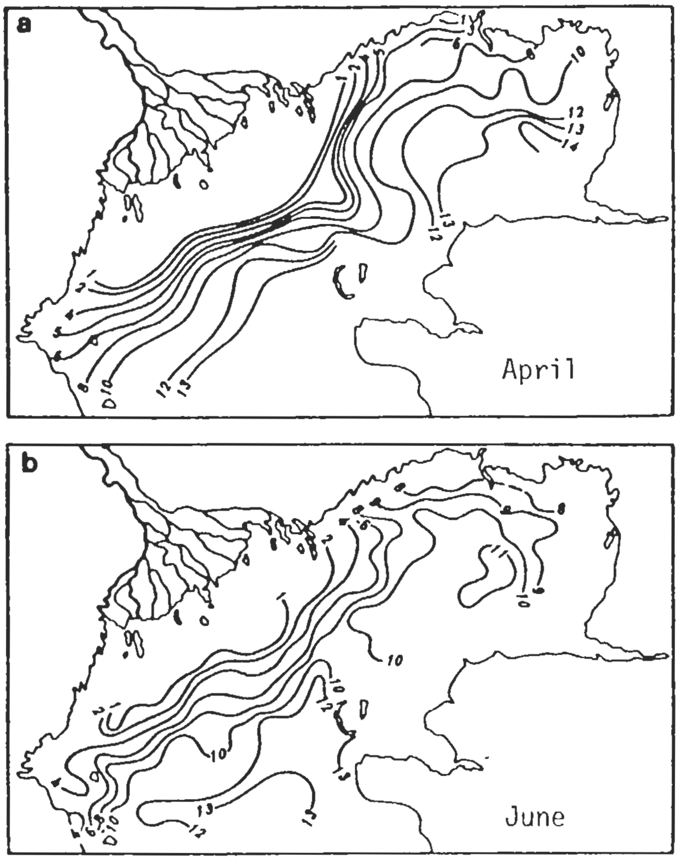
	Parameters						
Season	t°C	‰ (g/l)	O_2 (ml/l)	pH	NH_4 (mg-at/l)	P (mg-at/l)	Si (mg-at/l)
North Caspian (Western Part, Surface)							
Winter	−0.6—4.0	?	?	?	?	?	?
Spring	6.0—22.0	0.2—12.0	6.2—7.5	8.3—8.4	97.2—136.8	5.0—5.9	1324—1574
Summer	21.0—26.0	1.0—13.0	4.9—6.9	8.5—8.7	64.8—100.8	5.0—5.3	1855—1883
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 Part, 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 Part, 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
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—?	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 (200 m)							
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—600 m)							
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)
Fluctuations of the Mean Seasonal Hydrological and Chemical Parameters of the Caspian Sea Water Masses (1964—1981)[1]

	Parameters						
Season	t°C	‰ (g/l)	O_2 (ml/l)	pH	NH_4 (mg-at/l)	P (mg-at/l)	Si (mg-at/l)
			South Caspian (600—800 m)				
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

Note: North Caspian: surface (0—4 m); bottom (deep waters). t°C, ‰, and O_2 — mean monthly values for winter (February), spring (April to June), summer (August), and fall (October); 1960—1980. NH_4, P, and Si — mean monthly inorganic values for spring (April to June), summer (July and August), and fall (September and October); 1955—1979, pH — for the same period. 60, 25, and 15% of the North Caspian water masses have average weighted salinity concentrations of 2 to 8, <2, and >10‰, respectively. Upper, Middle, and South Caspian: t°C and ‰ (1968—1978); O_2 and pH (1964—1980) — mean monthly values. NH_4 — summer and winter (1979—1981); P and Si — inorganic mean monthly values; winter (February), spring (April), summer (August), and fall (November); 1964—1981.

Compiled from Reference 1.



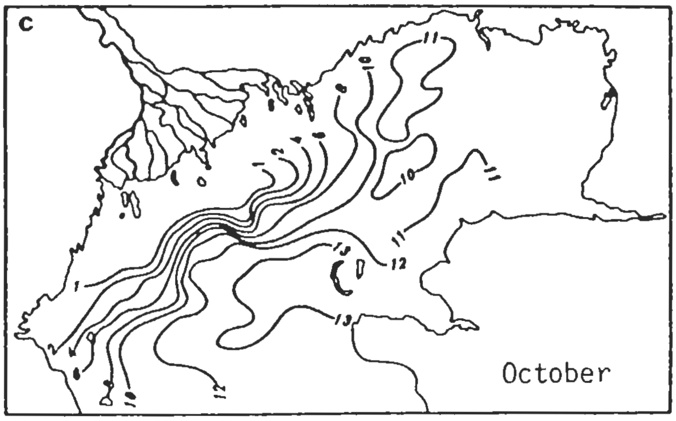


FIGURE 5. Salinity distribution on the surface of the Caspian Sea in 1976. (After Reference 1.)

water of the western area when the preceding year is typified by subnormal wetness or when stormy wind surges occur. Such conditions cause the development of a strong thermocline and halocline, whose location coincides in space and time, resulting in pronounced vertical stability. In this case, the less-dense surface freshwater underlain by denser brackish seawater flows down from the delta as far as 60 to 80 km seaward. This freshwater discharge is the basis of the highest biological productivity of the North Caspian and of the Sea as a whole. It transports and recirculates over 60% of the annual volume of inorganic and organic matter, repels salt intrusion, reduces salt concentration in the nursery grounds of fishes to appropriate levels for egg, larval, and juvenile survival (especially for semi-anadromous fish), and purifies the area of natural and man-induced wastes. In addition, the freshwater flow entrains and warms (through gradual increase of vertical mixing) the deep cold waters of the adjacent Middle Caspian. The mixing of the

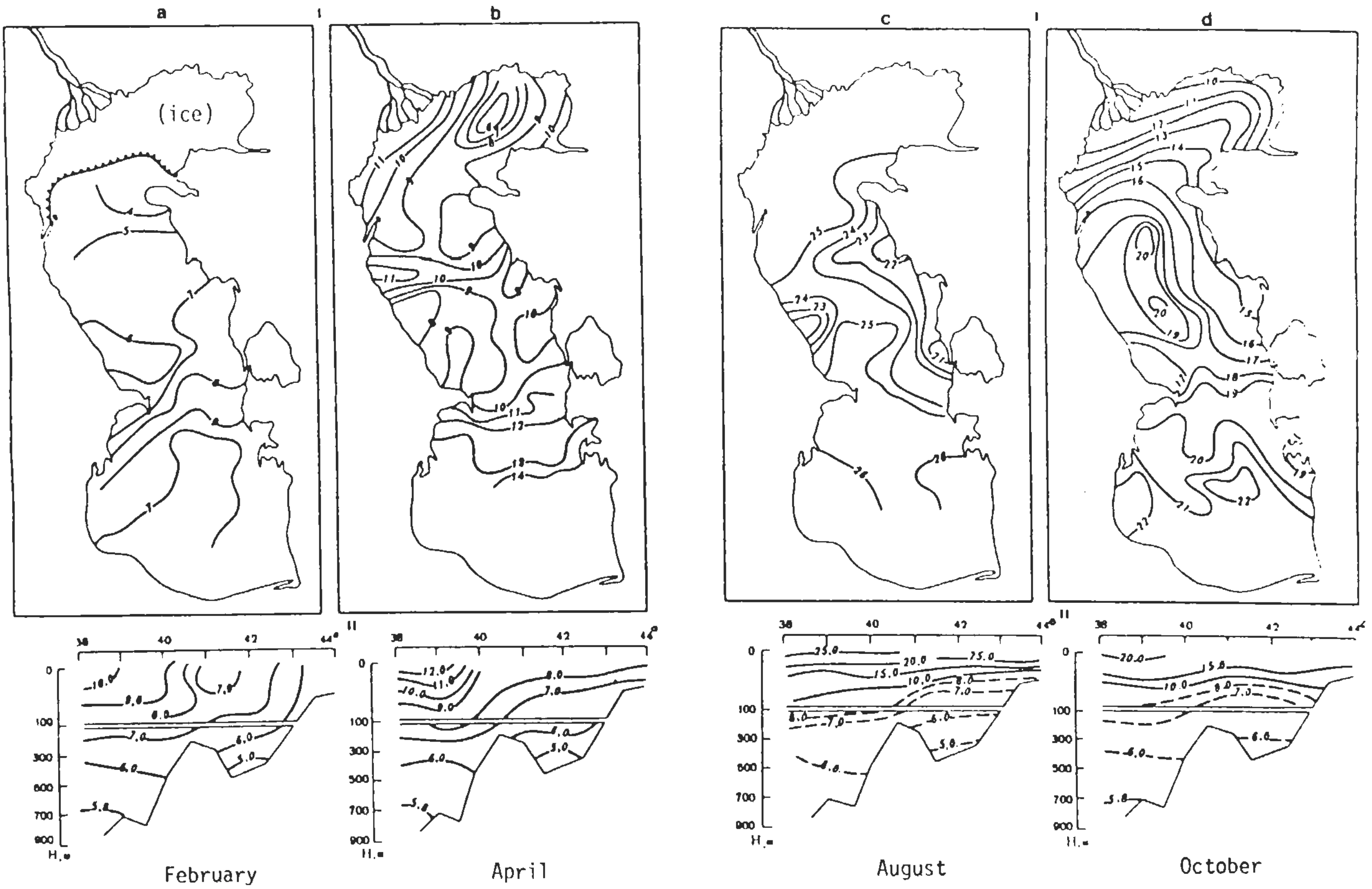


FIGURE 6. Water temperature distribution on the surface of the Caspian Sea (I) and along the 51° meridian transection (II): (a) February, (b) April, (c) August, (d) October. (After Reference 1.)

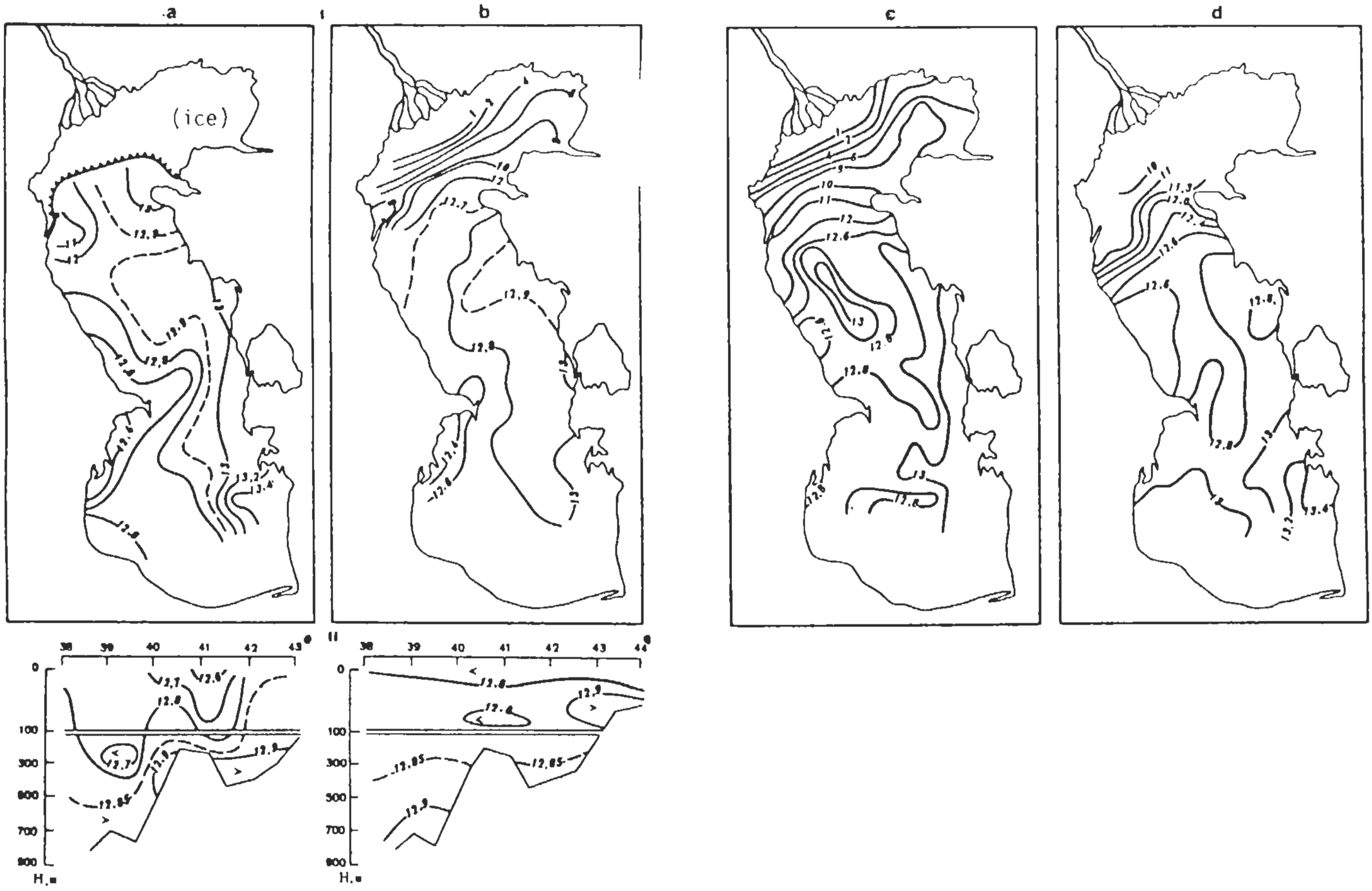
water bodies provides additional biogenic enrichment for the North Caspian.

During the summer, a season characterized by stable, warm weather, the surface temperature gradient is insignificant, while the vertical stratification in salinity and temperature can be traced near the boundary with the Middle Caspian. During the fall, when the cooling effect of low air temperature on the surface water is pronounced, sharp landward horizontal and inverse vertical stratification in water temperature occurs. It produces an increase in vertical mixing and leveling of surface-bottom differences in temperature and salinity (and in many other characteristics). By the end of fall and during winter, most of the North Caspian is homogeneous and covered with ice, although weak horizontal and vertical gradients in salinity may be observed in proximity to the deep delta channels.

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 stress; 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 (e.g., wind currents and waves, downwelling and upwelling, internal waves, turbulence, etc.) that affect and amplify water and salt transport between the North and 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 the summer. Here, as elsewhere, the organic enrichment of surface water is conspicuous.

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



February April August October

FIGURE 7. Salinity distribution on the surface of the Caspian Sea (I) and along the 51° meridian transection (II). (After Reference 1.)

in height and about 100 m in length, may occur within the thermoclines.

The deep water masses of the Middle and South Caspian have relatively uniform distributions of temperature and salinity (Figures 4, 6, and 7; Table 4). Their older, more stable structure is said to be maintained by downwelling of winter, cold, mixed water from the North and Middle shelf zone, as well as by the vertical winter circulation. These waters have the lowest temperature and oxygen content and the highest salinity concentration. More than 50% of the volume of the deep water masses of the Caspian Sea has temperature and salinity ranges of 5 to 6.5°C and 12.8 to 12.9‰, respectively.[1]

In sum, the constant movement as well as the water and salt exchange of the four major water masses are caused by two types of circulation: thermohaline (gravitational) and wind-driven. The thermohaline circulation reaches its maximum development during winter. Wind-driven circulation largely determines the local depth of the thermocline and halocline, or mixing zone, and a compensatory rising of cold, deep water (upwelling) in the Middle and South Caspian during summer. In the North Caspian, a strong wind can raise or depress the sea level up to 5 m near the delta or generate waves up to 11 m in height in the Middle and South Caspian.

For the following discussion, it is important to emphasize that the North Caspian absorbs and recirculates over 80% of inorganic and organic matter and sediment load discharged from the Volga River. In addition, the annual Volga runoff carries more than several million tonnes of dissolved oxygen and other chemical constituents to the North Caspian. For example, the mean regulated runoff in winter alone delivers nearly 0.7×10^6 t of oxygen, at an average concentration of 10 ml/l O_2. The aforementioned fluxes, through intrinsic and extrinsic hydrophysical and biochemical processes of different seasonal and spatial scales, are the bases of biological productivity of the Caspian Sea.

II. WATER RESOURCES AND ECONOMIC USES

A. General

In comparison with other regions of the European section

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 (MW)	Production of energy mean/year (billions kw hours)	Mean natural runoff to hydropower 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	4550	25.4	16.6	330	1.1	36
Gorkovskaya	1955	1530	8.7	3.9	520	1.4	53
Tscheboksarskaya	1980	2270	13.9	5.7	1400	3.5	112
Kuibyshevskaya	1955	6450	58.0	34.6	2300	10.1	242
Saratovskaya	1967	1830	13.4	—	1290	5.3	247
Volgogradskaya	1958	3120	31.5	8.2	2563	11.1	251
KAMA RIVER BASIN							
Kamskaya	1954	1920	12.2	9.8	504	1.7	52
Botkinskaya	1961	1130	9.4	3.7	1000	2.2	54
Nijne-Kamskaya	1979	2.630	13.0	4.0	1248	2.6	89

Data compiled from References 8 to 10.

of the U.S.S.R., the economic and strategic importance of the Caspian Sea watershed is second to none. The basin includes 1×10^8 ha of arable land and produces more than one fifth of the agricultural crops and one third of the total industrial output of the U.S.S.R. Impoundment of rivers in the Caspian Sea basin started in 1941 and reached its climax between 1955 and 1965.

Eleven large hydropower stations operating in the Volga-Kama basin (Table 4) and a few small ones on the western side of the Sea basin provide almost one third of the hydropower production of the U.S.S.R. 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 mean annual natural runoff of the Volga River basin, respectively).

Built on the flood plain of the rivers, 200 small and large reservoirs have inundated an area of about 26,000 km^2 of the Volga basin, of which 50 to 69% was highly fertile cropland.[15] Moreover, the accumulation of 190 to 200 km^3 of water in storage, starting from the late 1960s, has significantly contributed to the reduction of freshwater flow to the lower Volga-Caspian Sea ecosystem. It also 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 objectives 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 4×10^6 ha of arable land in the lower Volga region, which often suffers 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, and to sustain migration, spawning and feeding activities, mainly for semi-anadromous and anadromous fish.

The economic significance of the Caspian Sea is coupled to its fisheries, the harvest of seals for skins and oil, 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 from spring through fall to the Black, Azov, White, and Baltic areas through the complicated networks of sophisticated canals built during the last 40 to 50 years. Shipping is extensive in the basin; the Volga and tributaries alone account for 75% of the cargo in the inland waterways of the European territory of the U.S.S.R. 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 once accounted for 25% of the total finfish catch of the inland water basins of the U.S.S.R., amounting to about 6×10^5 t/year of valuable species of semi-anadromous and anadromous fish.[6,13,16-21] Before the implementation of the water projects, the catch of Russian sturgeon alone constituted 90 to 95% of the world commercial landings.[9,14] The current freshwater fish catch in the Volga-Kama basin reservoirs constitutes 50% of the total U.S.S.R. finfish harvest.[8] The same utilization of freshwater resources used to be typical for the majority of valuable species migrating and spawning in numerous small rivers of the Soviet and Iranian coastal zones before alteration of runoff by irrigation networks and impoundment.[17]

B. 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 to their survival.

1. Seasonal Flows

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

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 of fish. Under natural conditions (documented since the 19th century), the 5-year mean total annual water supply fluctuations varied within the range ± 10 to 15% of the "normal". It is interesting to note that the same range of natural deviations of annual water supply from the "normal" have been documented in many other rivers subjected to water regulation (e.g., the Danube, Sacramento-San Joaquin, Delaware, Susquehanna, and Potomac Rivers[22]). However, in recent years, the regulated releases of water supply to the lower Volga have been characterized by a pronounced increase in absolute values of negative deviations up to 30 to 50% (Figure 9). As a result, the current total regulated mean spring (April, May, and June) runoff of 98.9 km^3 contributes only 44% of the mean regulated annual value instead of 62% observed for the natural conditions (Table 5). Therefore, this spring runoff dropped as much as 1.6 times from its "normal" (155.8 km^3).

Table 5
Characteristics of Natural and Regulated Runoffs of the Lower Volga-Caspian Sea Ecosystem (1967—1979)

Characteristics of runoff				Regulated runoffs of the "normal" (%)
"Normal" runoff[a]	km^3	Regulated runoff[b]	km^3	
$\overline{Q}$	251.0	$\overline{Q}$r	224.7	89.5
$\overline{Q}$sp	155.8	$\overline{Q}$spr	98.9	63.5
$\overline{Q}$sw	95.2	$\overline{Q}$swr	125.9	132.0
	(%)		(%)	
$\overline{Q}$sp of $\overline{Q}$	62.0	$\overline{Q}$spr of $\overline{Q}$r	44.0	39.4
$\overline{Q}$sw of $\overline{Q}$	38.0	$\overline{Q}$swr of $\overline{Q}$r	56.0	50.2

[a] $\overline{Q}$, $\overline{Q}$sp, and Qsw — "normal" annual, spring (April, May, and June) and summer-winter runoffs (1887—1962).

[b] $\overline{Q}$r, $\overline{Q}$spr, and $\overline{Q}$swr — mean regulated annual, spring, and summer-winter runoffs (1967—1979).

Computation based on data from References 1 to 5, 8 to 10, and 18.

In practice, the current mean regulated total spring discharge to the Delta-North Caspian is nearly 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 the abnormal range of the negative deviations (31 to 40%) of regulated spring runoffs from the "normal" value has increased more than four times (Figure 10). This runoff to the lower Volga corresponds to 90 to 99% of the probability of exceedence of the natural spring runoffs (114 to 92 km^3). In other words, the subnormal or critical subnormal types of regulated spring runoffs have occurred much more frequently during several consecutive years (1961 to 1979) than would be observed for the natural runoffs (only 3 years: 1967, 1973, and 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 8C) of the spring water supply to the lower Volga Sea ecosystem due to water withdrawals equaled 1051 km^3 (1961 to 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]

During the same period, 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 nearly to the summer-fall "normal" (66 km^3) and slightly greater than the current average regulated summer-fall; the total summer-winter regulated discharges constitute 26, 24.2, and 50% of the annual "normal", respectively (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 from its "normal" (95.2 km^3), the spring impaired runoff decreased 1.6 times from its "normal". In addition, the spring residual inflow was 1.3 times lower than the current summer-winter runoff (Table 5).

According to Baydin and Kosarev,[1] the shift in freshening of the North Caspian water from the 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

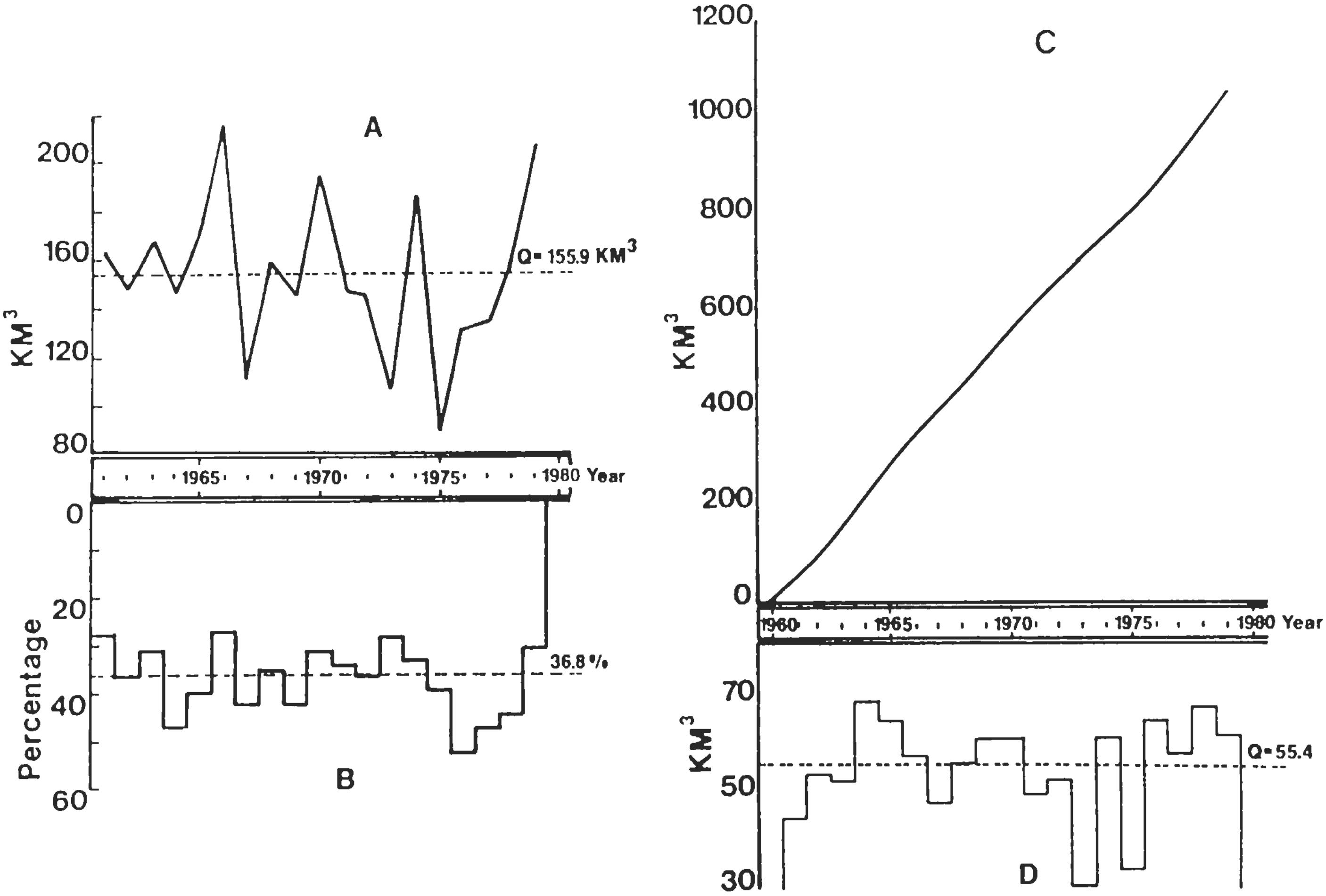


FIGURE 8. The Volga-Kama River and Volga Delta flow conditions. (A) Natural fluctuations of the spring (April-May-June) Volga-Kama river runoff; (B) percentage of water diversions 1961—1979; (C) spring cumulative losses of water supply to the Volga River Delta and Caspian Sea attributed to water withdrawals;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

biota. The growth and reproduction of many species were probably adapted to the period of July-August when the refreshening and warming of the North Caspian water masses were greater. It should be emphasized that this phenomenon of inverse intra-annual regulated runoff distribution has become a new feature of the hydrological regime of the Volga River, unobserved in the historical past. An additional negative ecological consequence of the transformation of runoff relates to the ample surplus of water during the season when there have been no records of migration and spawning activity among the commerically important species of fish.

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 amounting to 52.5 km^3 resulted in declining volumes of releases to the Delta by as much as 1.9 and 2.5 times in comparison with the average for the years 1976 and 1977 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 greatly reduced by the constant withdrawals of water along their courses by hydroelectric power plants and irrigation systems. Consequently, adequate runoff rates and water levels in the lower reaches of these rivers, necessary for natural reproduction of fish, have been severely reduced.[10,15]

In sum, 25 to 65% of the Volga-Kama discharges during the spring accumulates above the dams, whose capacity constitutes 35 to 76% of the "normal" annual runoff of the Volga River. In comparison, the cumulative capacity of major dams of northern California (U.S.) built in the Sacramento-San Joaquin River basin account for 71% of their combined unimpaired normal, which is only 34.6 km^3 (i.e., almost 8 times less than the Volga runoff). Nevertheless, the effect of water withdrawals during late winter-spring of 60% of the

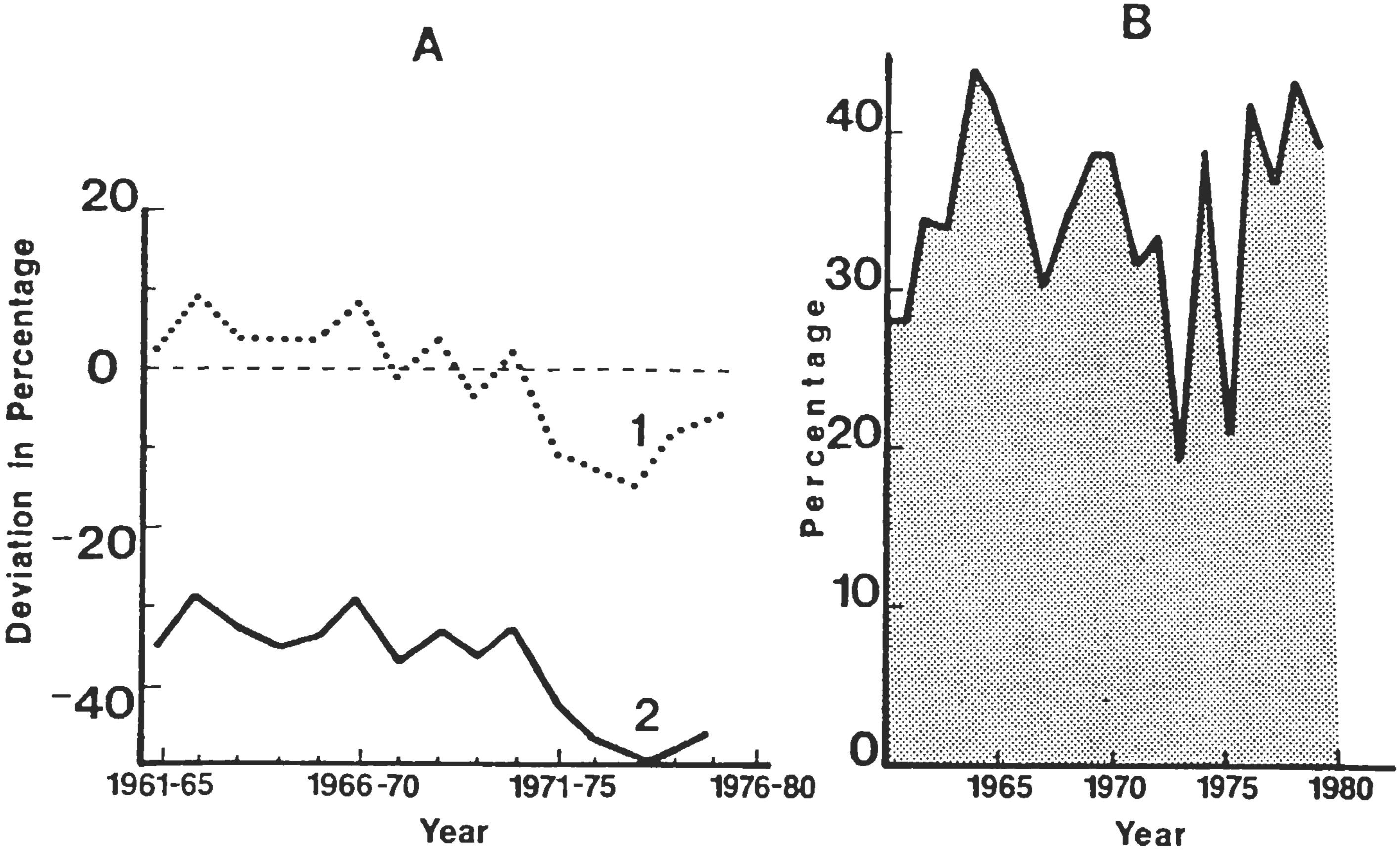


FIGURE 9. (A) Deviations of the 5-year running mean (1) natural and (2) regulated (combined Volga-Kama river inflow of the "normal" spring runoff — 155.9 km^3) discharges to the lower Volga River. (B) Percentage of accumulated water of the mean spring runoff in the Volga-Kama river cascade of reservoirs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

"normal" on runoff variables and the fishery of the San Francisco Bay is dramatic.[24,28]

2. *Ecological Consequences of Water Withdrawals*

Generally, estuarine ecosystems are very resilient to natural disturbances of regimes in their drainages. They function as a "buffer" zone between the river and adjacent coastal sea area.[22,25-29] The major natural events in this zone result in: (1) 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; (2) accumulation and processing of the sediment, as well as biogenic yield discharged from the river and sea, generated in the estuary itself, through the mixing of different water masses in the course of their movement within the delta-estuary or delta-sea ecosystem; (3) maintenance within the natural scale of seasonal and annual runoff fluctuations of the adequate ecological conditions necessary for the survival of many brackish water organisms, including, but not limited to the eggs, larvae, and juveniles of the semi-anadromous and anadromous fish.[13,14,16] However, the current transformation of runoff has led to the dewatering of many delta branches, a distortion of circulation patterns, a decrease in a flow velocity, and an increase in temperature, salinity, and retention time. Consequently, water quality in the Delta, once the most favorable area for migration and spawning activities of the majority of valuable fish, has deteriorated. While adult fishes are able to survive or remain unaffected by an increase in salinity, the disruption of the other components of the North Caspian ecosystem on which the young-of-the-year are dependent (e.g., temperature, salinity, oxygen content, alkalinity, pH, biogenic yield, food resources, circulation patterns, and the size of a nursery ground) has contributed to reduction of juvenile survival capability and adult spawning success.[12,18,29,36]

III. ECOSYSTEM ALTERATIONS

A. Structure and Function

In the process of evolution, the structural and functional characteristics of the Caspian ecosystem were formed by the supply of freshwater and chemical elements from upsteam sources. Biological productivity is determined by the freshwater supply and nutrients in the runoff of the Volga and Ural Rivers

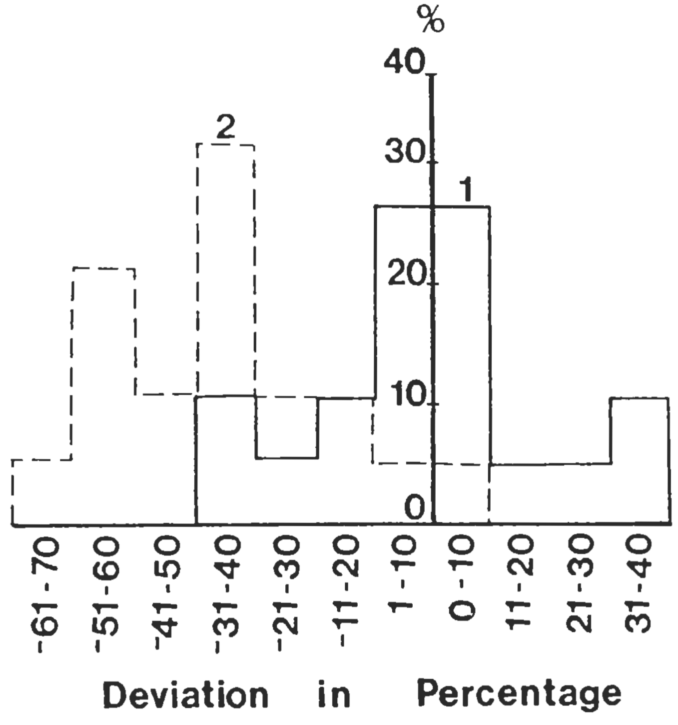


FIGURE 10. Deviations of (1) natural spring runoff of the "normal" and (2) regulated spring runoff of the "normal" in the Volga River, 1961—1979.

and by the highly oxygenated warm waters and shallow depths of the North Caspian. The major feeding areas of fish are located here. The concentration of salt and biogenic nutrients in the North Caspian depends on the amount of river discharges, which historically has been greater to the western part of the North Caspian than 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 lower Volga have had a profound effect on the measurable parameters of the Volga Delta-North Caspian ecosystem regimes.[31] The relation between flow reduction and ecological effects can be seen in Figure 12.

The leveling of seasonal runoff fluctuation, with reduction of the amplitude of stage levels into the Delta, affects environmental conditions (e.g., velocity, temperature, oxygen, salinity, and nutrients) that can modulate the spring migration and spawning success of semi-anadromous and anadromous fish. The monthly regime of controlled river flows below the dams and by the Delta water-pumping facilities is significantly altered by requirements of the various water users. Sometimes, the cold or warm water gushes forth down to the Delta, carrying eggs and larvae, where they may be smothered by silt, subjected to desiccation, or dried out during an abrupt recession of high stages. The process of dewatering of numerous Volga Delta branches, particularly in their eastern part, has been exacerbated by the deepening of some major channels to provide sanitary and refreshing circulation in the eastern Delta and to improve navigation in the western Delta.

B. Retention Time

The retention time of water in the Volga Basin increased the period of recycling by eight to ten times after completion of the projects in 1979, a duration equal to almost 180 days.[9] This retarded mixing of water, as well as the ever-increasing concentration of fertilizers entering from the drainage area, has adversely affected water quality in the reservoirs, particularly in the lower Volga and Delta, and the eastern shallows of the North Caspian. Eutrophication and oxygen depletion in these areas now occur frequently.

C. Salinity Distribution

The cumulative effect of the reduction of annual and (especially) spring water supply to the North Caspian for the last 2 decades, amounting to an average of 55.6 km^3, has led inevitably to massive salt intrusion in this region from the Middle Caspian. The mean annual salinities of the North Caspian and its two parts (western and eastern) have increased as much as 1 to 4‰ since 1955 (Table 7).[5,35] Even in the deep water

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 References 1, 2, 10, 18, 34.

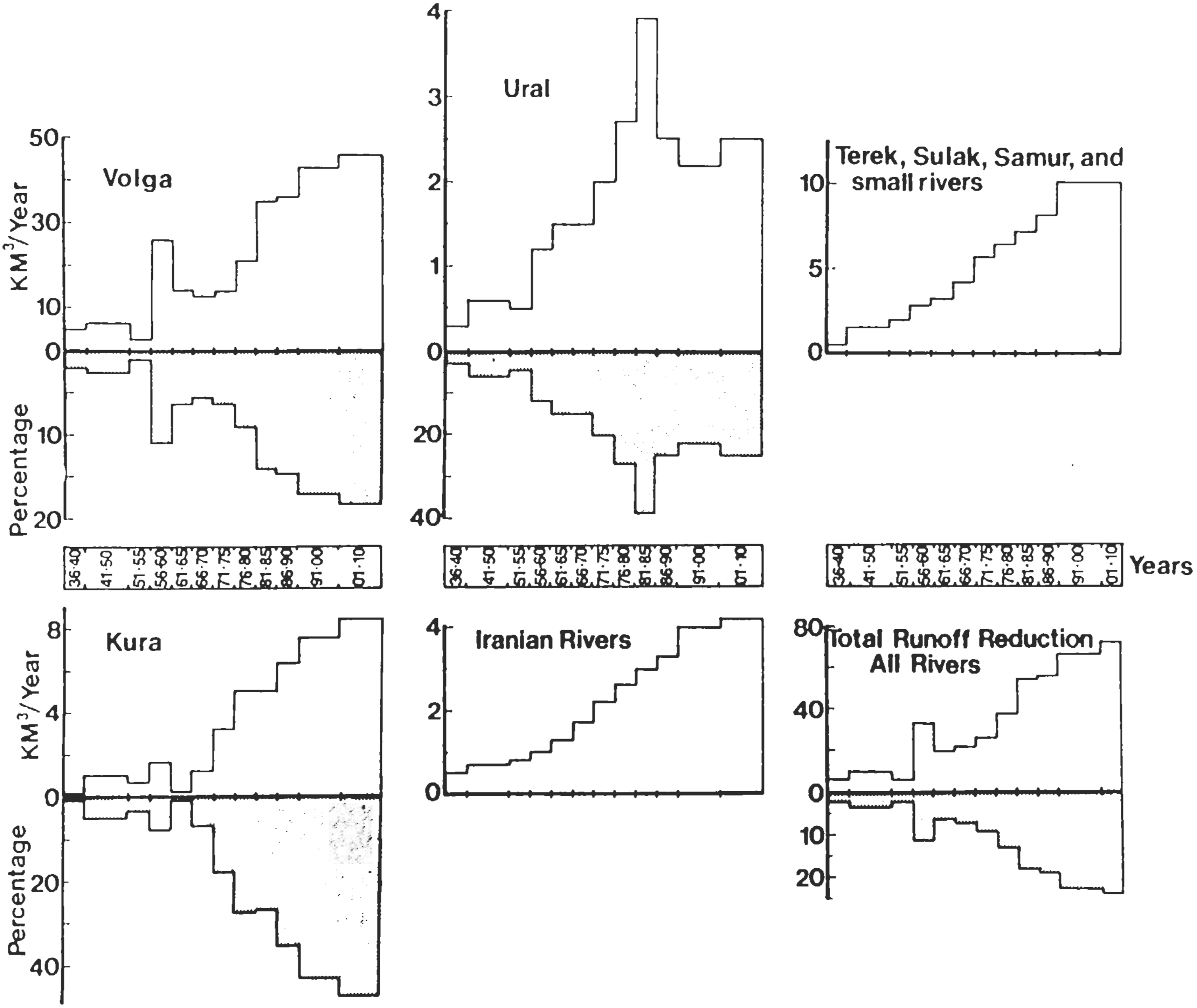


FIGURE 11. The mean total annual volumes of water withdrawals by different water users from the rivers of the Caspian Sea basin (km³/year and the percentage of the "normal" data obtained from Shiklomanov and Georgievsky[2]).

masses, the increase in salinity has been documented. In the 1970s, the average annual salinity of the North, upper Middle, and South Caspian water masses reached concentrations of 11, 12.1, and 13.1‰, respectively (Table 3).[1] Moreover, when excessive diversions were superimposed on the subnormal spring water supply of 1973 to 1977, 50% of the North Caspian area was occupied by brackish water, with a salinity range of 6 to 11‰, while the highest known salinity of 13 to 15‰ was registered in the south end of the eastern part of the North Caspian. At the same time, the salinity of the Middle Caspian water masses was 12‰. The nursery ground of semi-anadromous fish, that can tolerate a range of salinity fluctuations of 0.2 to 5‰ and up to 8‰ during spawning and feeding, respectively, has decreased from 25,700 km^2 (1959 to 1971) to 6200 km^2 (1977). The reduction of nursery grounds and salinity have both contributed to a drastic decline of phytoplankton and zooplankton, as well as benthic organisms such as mussels, which are the primary diet of anadromous fish. The optimum salinity of 2‰ for mussels was observed only within 30% of their historic habitat area in that part of the North Caspian.

The maximum increase of the mean salinity in the western and eastern part of North Caspian reached about 0.8 to 1.6 and 1 to 1.3‰ during June and August, respectively. In the deep zones of the western part, including the Volga-Caspian shipping

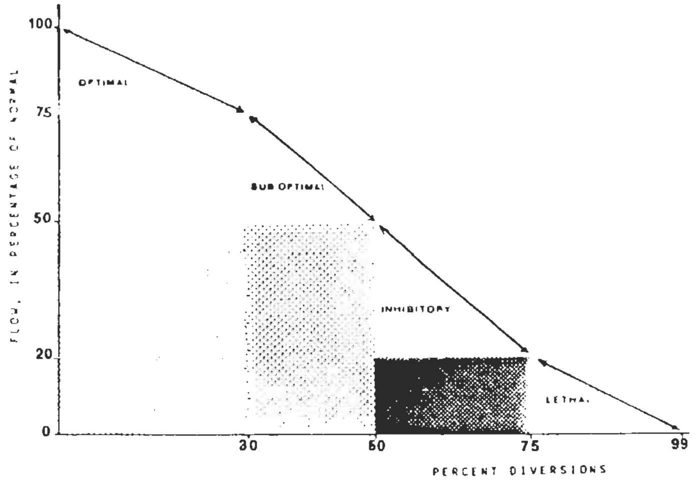


FIGURE 12. Conceptual model of the effect of runoff reduction due to diversion on the estuarine environment and living resources.

canal, a two-layer circulation has persisted. Strong vertical stratification and anoxia near the bottom are common.[1]

The deficit in water supply and subsequent increase in salt accumulation and vertical stability, intensified by evaporation, account for these changes. They were not evident under pre-project conditions.[35] It is interesting to note that the Volga salt flux alone equals an average of 64 × 10^6 t (1951 to 1980).

Releases of water from the Volgagradskaya power plant in late fall and winter have resulted in increases in the intra-annual salinity range by as much as 1.5 to 2.5 times. Moreover, the lack of discharges during June and August has substantially reduced the summer amplitudes. Consequently, the vertical salinity (density) gradient decreases in summer and increases during the late fall-winter period by as much as 1 g/l. The immediate effect of this shift in salinity stratification is (1) a depletion of oxygen during the late fall-winter with the concentration dropping to 1 to 2 mg/l, and (2) an increase in oxygen concentration in deep layers during the summer due to the nearly complete absence of vertical salinity stratification.

The reduction of oxygen concentration in deep zones has a detrimental effect on pelagic and demersal fish and benthic organisms inhabiting the North Caspian. Their area decreased after the 1930s by about 2800 to 3500 km^2, including 1500 to 1800 km^2 of productive habitats. The area, having a salt content above 10 to 12‰ (Table 3) which is unsuitable for the life of the brackish-water fauna of the North Caspian, covers more than 10% of the former nursery area (4 × 10^4 km^2).

D. Sediment Transportation and Distribution

The Volga River has been divided by dams into 11 sections; consequently, a unique pattern of sediment transport has developed, namely, silting in the slack water of the reservoir above the dam, intensified erosion below the dam (especially during releases), and silting in the downstream reservoir.[36] These peculiarities have brought about substantial changes in the seasonal distribution of the sediment load. For example, the mean sediment load has declined by 30% or more in the spring, with an appreciable decrease occurring in the summer and a considerable increase during the winter. The winter increase is explained by the fact that the average winter releases are two or more times greater than the natural runoffs encountered during the pre-project conditions. The winter water releases have intensified the erosion of the river bed by increasing stages of fluctuations much higher than those of the pre-project periods.[8,36] In general, the mean annual sediment load (Table 8) to the Delta-North Caspian ecosystem dropped to less than 49% of the total yield, and about 64% of that of the Volga basin alone. Only 25 to 32% of the residual suspended load

Table 7
The Range of Fluctuations of Mean Annual Salinity (‰) of the North Caspian Sea Before (1935—1955) and After (1956—1980) the Impoundment of the Volga River

	Salinity of Volga runoff	Salinity ranges (‰) & regions			Mean salinity (‰) & regions		
		Western	Eastern	N. Caspian	West	East	N. Caspian
1935—1955[a]	0.2	6.0—11.3	6.3—12.6	6.4—11.7	8.4	7.6	8.0
1956—1962[b]	0.2	8.2—9.5	7.1—8.6	7.8—9.3	9.1	7.8	8.6
1973—1977[c]	0.2	9.1—11.0	5.7—10.8	8.8—13.0	10.1	11.3	11.0
1973—1977[d]	0.2	9.1—11.1	5.7—10.8	8.0—10.4	10.1	8.9	10.1
1973—1980[d]	0.2	8.6—11.1	5.7—10.8	8.0—11.0	9.7	8.5	9.3
1977[d]	0.2	—	—	—	10.3	10.8	10.4

Note: Modified data (salinity concentration is expressed as an average weighted value [grams/liter], computed from the mean monthly salinities of April, June, July, August, and October at the surface, 5 m, 10 m, and the bottom).

[a] April to October, 1935 to 1955; April to November, 1956 to 1962; Pahomova and Zatuchnaya.[5]

[b] April to October, 1973 to 1977; Katunin and Kosarev.[36]

[c] Predicted by Pahomova and Zatuchnaya.[5]

[d] Observed from Baidin and Kosarev.[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 (10^6 t)	Period (years)	Mean regulated runoff (km^3)	Regulated suspended load (10^6 t)	Percentage of reduction of regulated suspended load from its natural mean
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	?	10.?	?	1980—1986	8.0	?	
				1966—1981	0.5	?	?

Note: Other examples of the drastic sediment load reduction because of diversions are the Nile, Colorado, and Don Rivers, amounting to 85, 96, and 75%, respectively.

Compiled from References 1, 4, 5, 9, and 34.

of the Volga River is carried to the North Caspian. A drop in the suspended sediment flux also occurred in the Middle and South Caspian (Table 8). In sum, the total mean sediment load of the major rivers of the Caspian Sea for the period of 1966 to 1981 was 45.4 × 10^6 t or 2 to 4 times less than it would have been had the natural conditions prevailed.[1] The reduced sediment load has influenced the stability of the river banks, the levees in the deltas, and their entire morphological structure.[4,8,9]

E. Biogenic Yield

The Volga reservoirs have not only become a trap for huge amounts of the sediment, but also have significantly decreased and redistributed the nutrient load. In the winter, the biogenic flux increased 10 to 35%; in the spring it decreased, accounting for 25 to 40% of the "normal". This alteration nearly coincides with the regulated seasonal runoff distribution. In general, the amount of inorganic and organic phosphorus decreased on the average as much as 1.5 and 2 times, respectively.[1,5,18,32] The enormous biomass of phytoplankton in reservoirs consumes a significant amount of inorganic phosphorus. About 70 to 80% of the residual phosphorus empties into the sea during late spring-summer. The amount of inorganic nitrogen also has declined. It now constitutes only 70% of the concentration observed during the pre-project conditions in the lower Volga Delta.[1,14,15,35]

The reduction in nutrient yield (especially phosphorus, 90 to 93% for organic phosphorus) has a negative effect on primary production in the North Caspian, accounting for only 50% of the value before water projects became operational (8 × 10^6 t).[1] At the same time, the organic nitrogen yield in the lower Volga-Delta ecosystem increased as much as 2.5 times over that of pre-project conditions.[15,35] This shift is explained partially by the increase of industrial and municipal waste discharges to the area. The highest concentrations of phosphorus, nitrogen, and silica were observed in areas where the salinity range varied between 0.2 and 2‰. The lowest concentrations were observed in waters where salinity ranged from 10 to 13‰.

The Volga runoff has resulted in three kinds of spatiotemporal distribution of silica: (1) a maximum concentration up to 2 × 10^3 mg/l that corresponds to the highest runoff, and a minimum concentration of 1 × 10^2 mg/l that coincides with the lowest runoff; (2) typically, the western part of the North Caspian has a greater silica concentration during the flood over its deep areas than the eastern part because of substantial differences in freshwater supply; (3) since the 1970s, a persistent trend in the increase of silica concentration has been observed in the late summer, primarily attributable to a reduction of diatom biomass.

In general, the annual average regulated biogenic flux from the Volga River to the North Caspian for the period of 1976 to 1980 (including dry and wet years) equaled 398,000, 47,200, and 440,000 tonnes (t) of nitrogen, phosphorus, and silica, respectively.[1]

F. Phytoplankton

Before the massive water projects development had been undertaken, the dynamics of the seasonal composition of phytoplankton (during 1956 to 1962) were characterized by: (1) a spring (April to June) peak of diatoms (60% of a total diversity of 37 to 127 species: *Diatoma elongatum, Ag.* var *elongatum, Rhizosolenia calcar-avis* Shultze, *Chaetoceros Wighamii* Bright, *Skeletonema costatum* and green algae (*Spirogyra* sp. and *Pediastrum boryanum*), etc.; (2) a summer

(July to August) peak of blue-green algae (*Merismopedia punctata* Meyen, *M. tenuissima*, *Aph. flos-aquae*, *Anabaenopsis elenkinii V.* Mill, *G. lacustris f. lacustris*, *Exuviaella cordata*), with species richness ranging from 54 to 108 species; and (3) a fall (September to October) peak of *R. calcar-avis*, *Spirogyra* sp., *E. cordata*, and *Scenedesmus quadricauda*.[33] The number of species in the fall ranged from 78 to 119. Phytoplankton species richness was strongly coupled to seasonal runoff fluctuations.[37]

The increase of winter (January to March) releases from the Volgagradskaya dam by as much as 1.8 times on the average over pre-project conditions and the redistribution of residual runoff between the western and eastern Delta by the divider built in the lower Volga in 1974 have substantially altered the spatial distribution, diversity, and concentration of the phytoplankton in the North Caspian during spring (Table 9). The diversity of algae (250 to 345 species) was much higher than documented for natural conditions (150 to 155) or at the onset of massive water diversions (late 1940s to 1960s).[33,37] Before 1970, brackish water diatoms comprised 60% of the total algal biomass. However, with the redistribution of runoff and increased freshening of the major channels of the eastern and central Delta due to the divider operation, fresh-brackish water green algae (e.g., *Spirogyra* sp. and *Binucleatia lauterborni*) and freshwater diatoms (e.g., *Fragilaria capucina*, *Melosira italica*, *Asterionella formosa*, and *A. gracillima*, etc.) became the numerically dominant species of phytoplankton in the spring of 1974. The genus *Spirogyra* accounted for 60% of all species.

Spirogyra constitutes about 90% of the total mean phytoplankton biomass in the North Caspian, which had a maximum biomass of 43 g/m³ in the eastern perimeter. With such a high density, the vast eastern area, characterized by sluggish circulation patterns, was subjected to eutrophication. At the same time, the diatom *R. calcar-avis* experienced a noticeable decline in the western region and the entire North Caspian Sea. Its biomass dropped from 3.4 g/m³ (1960) to 0.02 g/m³ (1974).

Without *Spirogyra*, the total biomass in the western area of the North Caspian was as much as 2.3 to 7.6 times higher than in the eastern part. The western area has stronger circulation, a higher freshwater supply in general, and a shorter distance to the deep water of the Middle Caspian, which may explain this phenomenon. These effects may mitigate the freshening excess through the North-Middle Caspian salt exchange and, therefore, may be able to maintain the dynamic equilibrium in chemistry, nutrient enrichment, and phytoplankton production in the western area.[1,5,32,33]

G. Zoobenthos

The most abundant bottom invertebrates of the northern Caspian are *Dreissena*, *Adacna*, *Monodacna*, chironomids, and *Nereis*. The biomass (grams per square meter) of these organisms in the eastern part of the North Caspian is twice that in the western part. They constitute the most important fraction of the food of the commercially valuable anadromous fish of the Volga. Strong linear correlations (r = 0.75 to 0.90) have been demonstrated for natural annual and spring runoffs of the Volga with benthic biomass (without *Mytilaster* and *Cardium*) during 1935 to 1953, and with the regulated spring and annual discharges for 1956 to 1973 for a given year in regions where the salinity range was 2 to 10‰. During the post-project period, the benthic biomass has decreased by 2 to 2.6-fold, to 60 to 80 g/m² or less. This results from (1) reduced duration of spring flooding (from 75 to 110 down to 15 to 30 d) and (2) a decrease of spring water discharges to half of their natural volumes following operation of the Volgagradskaya hydropower plant. It should be emphasized that these truncated releases

Table 9
Fluctuation of Seasonal Phytoplankton Biomass Under Different Freshwater Supply to the North Caspian[33]

Seasonal total phytoplankton biomass range in the North Caspian, 1956—1962[a]		Biomass of phytoplankton (mg/m³) in the North Caspian, 1968—1974			
		Western	Eastern	Northern	
Spring	664—2400	345—4794	41—352	245—3331	41—4794
April	293—1496	305—500[b]	40—189	218—377	40—500
Summer	1478—6896	?			
August	3205—6896	?			
	3132—3286				
Fall	1666—6697	?			
October	1666—9697	?			
	1428—9660	?			

[a] Spring: April; summer: June to August; fall: September to October.

[b] Biomass without *Spirogyra*.

have become a permanent feature of the hydrographic regime of the North Caspian. According to the prevailing opinion of Soviet specialists, they are the major cause for the deterioration of pelagic and demersal food webs and progressive decline of recruitment, standing stock, and commercial catch of Russian sturgeons and other valuable fishes in this productive part of the Caspian Sea.

H. Fisheries

The principal factor controlling the biological productivity of the Caspian Sea appears to be river discharges. Biogenic elements, in part derived from riverine influxes, have served as the basis of plentiful food resources for many fishes. A fresh- and brackish water relict fish fauna existed in the North Caspian. This fauna originally included the freshwater, semi-anadromous fishes — bream (*Abramis brama*), perch (*Lucioperca*), Caspian roach, and carp *(Cyprinus carpio)*, as well as the anadromous fishes — Russian sturgeon (*Acipenser guldenstadti* Brandt), sevruga (*A. stellatus* Pallas), and beluga (*Huso huso* L.). Migration and spawning of this ichthyofauna, and some other indigenous fishes, occur in the freshwater 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 growth of the young-of-the-year take place primarily in waters having a salinity range of 1 to 8‰.[7,13,16,18,39,41]

The vast areas of highly productive spawning beds in flood plains and deltas, together with broad regions rich in food, supported more than 90% of the reproduction of anadromous and semi-anadromous fish in the historic past. In 1912, the commercial catch of these fishes in the Caspian Sea basin was about 1 million t.[6] During the pre-project period up to 1940, the migration routes of anadromous and semi-anadromous fish extended 1000 to 2500 km inland from the Volga delta to numerous nursery grounds in the Volga and its tributaries.[15,18,42]

The Volga-North Caspian ecosystem once produced three times as much fish as presently and was capable of maintaining 90% of the world catch of sturgeon. The total productivity of fish in the North Caspian under natural conditions was, according to Marti and Ratkovich,[11] over 5 t/km^2 (compared with approximately 6 t/km^2 in the Sea of Azov, which was the most productive basin in the world during the recent past). In 1935, the total yield of fish in the Caspian Sea was about 32 kg/ha, and in the North and Aral Sea it was 17 and 4 to 5 kg/ha, respectively.[17] Before 1930, the catch in the Caspian Sea exceeded 6 × 10^5 t, 90% of which was comprised of valuable brackish water forms. The commercial catch of Acipenseridae accounted for 1.8 × 10^4 to 3.6 × 10^4 t.

Between 1930 and 1955, the catch of semi-anadromous fish ranged from 1.2 × 10^5 to 3.7 × 10^5 t, and including freshwater fishes, it exceeded 2 × 10^5 to 4 × 10^5 t. However, as mentioned earlier, the biological productivity of the Caspian Sea in the last 2 decades has been suppressed by intensive water-engineering diversions and reduced flow to the lower reaches of the Volga.

The average annual fisheries catch in the lower Volga in 1966 was 4.7 × 10^5 t; however, no more than 2% of the catch consisted of valuable commercial anadromous and semi-anadromous species. The magnitude of this catch was substantially less than that before the Volga-Kama reservoirs significantly curtailed the water supply to the lower Volga reaches and extirpated an average of about 80% of the nursery grounds of the Acipenseridae and other valuable fishes. These modifications of the river network, compounded by consecutive successions of subnormal and lower than subnormal years of wetness, have destabilized the delicate environment and fisheries of the Volga Delta-North Caspian to an almost irrevocable level.[9,11,18-20] It should be noted that the uncontrolled Volga runoff of the "normal" or wet years provided 4 × 10^5 to 5.5 × 10^5 t/year of commercially valuable fish compared with about 4.5 × 10^4 to 5.5 × 10^4 t in the late 1960s.

The northeastern part of the Caspian Sea, which receives discharges of the Ural River, is the second important area of migration, spawning, and commercial catch of anadromous and semi-anadromous fish. The commercial significance of this area increased after operation of the Volgagradskaya power station prevented access of the sevruga to their original spawning ground. Beginning in the mid-1970s, the Ural Delta-North Caspian Sea ecosystem provided nearly one third of the worldwide catch of the Russian sturgeon, of which 90 to 95% resulted from spring runs of sevruga.[40] Since 1965, the Acipenseridae has only been caught in the river. Under current ecological conditions, the catch of sevruga (*Acipenser stellatus* Pallas) in the Ural River accounts for 2000 t/km^3, while the Volga runoff provides only 20 t/km^3. This difference is explained by two factors: (1) the lower Ural has nearly four times the natural nursery ground area than the modified lower Volga (480 ha), and (2) the water supply to the Ural Delta nursery area during spring, despite significant fluctuations of runoff in some years, has provided favorable conditions for spawning and growth.[40] Musatov and Podushko[40] state that here, as in the case of the Volga River, there is a very high correlation between runoff and spawning success, recruitment, and commercial catch of anadromous and semi-anadromous fish. They found that when the runoff is less than 5 km^3/year (or about 50% of the "normal") the nursery area is decreased as much as eight times, and the catch drops as much as three to ten times for sevruga and the semi-anadromus bream, perch, and roach. If runoff is more than 9 to 10 km^3/year (wet year) during several successive years, the nursery zones with a salinity of 0.5‰ increase significantly beyond the delta onto the eastern shallow part of the North Caspian. In this case, the spawning success and catch of a spring run of anadromous fish, mainly sevruga, and semi-anadromous fish (bream, perch, and carp) are highest. The 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. They result in an increase in salinity in the mouth of the river up to 10 to 12‰ which has a negative effect on juvenile survival, especially of semi-anadromous fish. During an average spring diversion of 1.7 km^3, amounting to 35% of the normal and 61% of the dry year spring runoff to fill the Iryckliṅsky reservoir (located above the Ural Delta), the delta nursery area is not covered with enough water to provide appropriate conditions for migration or spawning, especially when subnormal and dry periods occur. These conditions are unfavorable for semi-anadromous fish inasmuch as winter temperature fluctuations contribute to an additional severe decline in fish population size and catch.

The third area of importance — the Kura River-southwestern Caspian ecosystem — was teeming with Russian sturgeon and other valuable fish before the river impoundment for power plant operations in the 1950s. Despite multimillion fry releases, the stock and catch of anadromous and semi-anadromous fishes in this area have plummeted to catastrophically low levels. From 1931 to 1940, the catch of Acipenseridae equaled 4700 t on the average (or 25% of the total average Caspian basin catch of Acipenseridae). In the late 1960s and the 1970s, the catch constituted less than 1% (160 to 180 t).[18]

The Salmonidae and some other fishes ceased spawning migrations after several hydropower plants and irrigation networks began to divert more than 60% of the spring runoff (1953). Moreover, the migration routes were nearly eliminated. The sea perch (*Lucioperca marina*) approached local extinction.

The fourth area of importance — the Atrek river in the southeastern part of the Sea — provided the commercial yield of Acipenseridae. The catch of *Rutilus r. caspicus*, *C. carpis* and *L. marina* was nearly 1.44 × 10^4 t. A small portion of this total (1.9%) was comprised of sprat *(Clupeonella delicatula delicatula)*, a pelagic fish of low value commonly referred to as the Caspian "Kilka".[16,17] However, from 1968 to 1972, the catch of the aforementioned valuable species declined to 1.5%, whereas the Caspian "Kilka" catch increased up to 5.73 × 10^4 t (98.3% of a total).

From 1931 to 1935, the catch of the Caspian roach *(R. r. caspicus)* in this region ranged from 7500 to 10,072 t, or slightly more than 50% of a total catch of this fish in the southeastern Caspian. However, from 1960 to 1973, the average catch equaled only 220 t, with maximum and minimum values of 808 and 1.1 t recorded in 1961 and 1965, respectively.[18] Harvest of the Acipenseridae also decreased sharply, although the catch of this group in 1935 equaled 1.8 × 10^3 t (nearly 10% of the total average Caspian catch from 1931 to 1935).

The causes for these precipitous declines in fish stock are considered to be (1) depletion of the Atrek River runoff; (2) agricultural pollution; (3) overfishing (in the sea); and (4) a drop in sea level.[18] Currently, there is no indication of any significant recovery of these valuable fisheries in the aforementioned areas although the sea level has risen.

In the southern end of the Caspian Sea (the Iranian Coast), the rivers and streams are subjected to such extensive diversions that little freshwater discharges occur during June to September. Razivi et al.[43] 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 effects of the changes are (1) larvae of spring spawners are carried out over agricultural fields where they die; (2) migration and late summer spawning of *Barbus brachycephalus* and *Aspius aspius* are obstructed; and (3) depletion of the Caspian salmon *(Salmo trutta caspius)* or Mahi azad and *Rutilus frisii kutum* (Sefid mahi), which cannot spawn in residual shallow, very warm, and weed-choked waters.[44] The average commercial catch of these species (family Cyprinidae) and clupeid species (*Mugil*, *Liza* sp., *Stizostedion*, *Lucioperca*, and *Silurus glanis*) declined from 9500 t (1927/1928 to 1931/1932) to 821 t (1957/1958 to 1961/1962).[45]

The impoundment of the Sefid Rud River by damming reduced runoff to such a level that migration and spawning of the Iranian sturgeon have been nearly obliterated. As a result, delays in migration lead to degeneration of eggs and losses in fecundity. In addition, the residual runoff in this river, as in many other impounded streams, experiences overheating that lowers oxygen concentrations, thereby creating an intolerable environment for aquatic insects and crustaceans that constitute the most desirable food for young-of-the-year sturgeon.[45] Moreover, the pumping stations and irrigation networks decrease the survival of the five species of sturgeon (*Acipenser guldenstadti, A. nudiventris, A. percicus, A. stellatus stellatus natio cyrensis, and Huso huso caspicus)*, resulting in an inexorable decline of their stock, as well as those of other anadromous and semi-anadromous fishes. The commercial catch of sturgeon in the coastal area dropped from 6700 t (1933 to 1934) to as low as 0.3 t in 1961 to 1962.[45]

It should be stressed that the aforementioned piscatorial problems, despite their seriousness, exerted much less influence on the Caspian fishery than the collapse of the herring and semi-anadromous fish populations, whose yield was the highest in the Sea. These fishes probably were the most susceptible to changes in the ecological conditions of the North Caspian during the last 2 decades.

The nursery and propagation area of the semi-anadromous fish (*Abramis ballerus, Abramis sapu, Blicca bjorna, Aspius aspius, Abramis brama* (L.), *Lucioperca lucioperca*, etc.) are restricted by a very low tolerance to salinities greater than 7 to 8‰. The Caspian herrings, in turn, are more sensitive to water temperatures that modulate successful migration and spawning. These characteristics depend on the volumes of the Volga spring discharges to the Delta-North Caspian system.

I. Caspian Herrings

There are 6 major species and 11 subspecies of Caspian herrings. Commercially important species include the anadromous forms, *A. kessleri volgensis* and *A. kessleri kessleri*, which spawn in the Volga and less so in the Ural and Terek Rivers during the spring. Other valuable herrings are *A. caspia caspia*, *A. saposhnikovi*, *A. brashnikovi brashnikovi*, and *A. brashnikovi agrachanica*, which spawn in the brackish water of shallows along the western, eastern, and Iranian coasts during the spring.[17,19,21]

The commercial catch of herrings varied significantly during pre-project periods mainly due to the natural cyclicity of the population sizes. However, since the inception of the projects, the progressive decline of the populations has altered the natural cyclicity. By the 1970s, the catch dropped to an economically unacceptable level and ceased to exist (Table 10). The most severe decline was documented for *A. kessleri volgensis* (the Volga-North Caspian endemic), namely, from 130,000 to 160,000 t from 1913 to 1916, to 5000 to 6000 t in the 1960s and 10 t from 1969 to 1972.[19]

A small amount of another herring species *(A. brashnikovi)* continued to be caught in the Volga Delta during the spring migration (limited by the Volgagradskaya dam), and some pelagic species (e.g., *A. caspica tanaica* and *A. klessleri pontica*) were caught in the Middle and South Caspian. Factors which contributed to the collapse of the herring fishery are (1) impoundment of the river by the Volgagradskaya power plants; (2) diversion of river runoff; (3) unfavorable changes in temperature and other regime characteristics; (4) the siphoning off of more than 6 km^3 of water from the upper Delta (billions of larvae and fry killed); and (5) loss of nearly 3 × 10^4 km^2 of the North Caspian shallows, serving as nursery area for *Alosa caspia caspia* (Eichwald), *A. saposhnikovi* (Grimm), *A. brashnikovi* (Borodin), and other species.[19,21]

It is important to note that in 1972 (the post-project period) the commercial catches of the Caspian herrings (2 × 10^3 t), roach (1.54 × 10^4 t), sea perch (8.5 × 10^3 t), bream (2.74 × 10^4 t), and carp (2.9 × 10^3 t) were 67, 17, 11, 1.4, and 4.8 times, respectively, less than those in 1930 (the pre-project period). The total commercial catch of valuable fish (7.53 × 10^4 t, including sturgeons) was 7.3 times less. At the same time, the catch of sprat (Caspian "Kilka") equaled 4.18 × 10^5 t or 107 times that in 1930.[18] About 80% of the total Caspian catch to date is attributed to this much lower priced fish. The population and catch of other anadromous fish of freshwater origin (i.e., those that spawn in the lower reaches of rivers, streams, and deltas and inhabit adjacent brackish water shallows), such as *Rutilus frisii kutum, Abramis brama, Barlus brachycephalus caspius, and Pelecus cultratus*, have experienced the same level of decline.[17]

Therefore, the Caspian Sea has been transformed during an exceptionally short period of time (1956 to 1972) from a basin having a high stock of valuable fishes to one dominated by the "Kilka" type fishery. The looming sign of the impending piscatorial disaster appeared during 1961 to 1965. During this period, the average commercial catch of the aforementioned species, excluding the "Kilka", dropped twofold in comparison with the catch from 1951 to 1955 (before the operational impact of the Kuibyshevskaya and Volgagradskaya power plants). The catch of valuable fish, including sturgeon, during this latter period amounted to 2.9 × 10^5 t, a figure considered to be near optimal prior to construction of the power plants.[18] The catch during the 1970s, even with the inclusion of the Caspian Kilka, was 245 × 10^3 t or 37 and 40% of those harvested in the Caspian Sea in 1913 (663 × 10^3) and 1930 (606 × 10^3 t), the peak years of valuable commercial catches, respectively.

It is interesting to note that an equally severe drop in the commercial catch of anadromous and semi-anadromous fish has occurred in the Sea of Azov where, before regulation (1952), nearly 1.7 × 10^5 t of valuable fish had been caught in 1936 contrasted with 3.2 × 10^3 t in 1978.[13] Here, the diversions and storage accumulation accounts for 35 to 80% of the spring runoff of the Don and Kuban Rivers, where the migration and spawning activities of these fish take place.

IV. ENVIRONMENTAL PROTECTION AND RESOURCE MANAGEMENT STRATEGIES

A. General

Several attempts have been made to mitigate the impact of

Table 10
Dynamics of Commercial Catch of the Caspian Herring (1885—1973)

Period	Catch (× 1000 t)	Period	Catch (× 1000 t)	Period	Catch (× 1000 t)
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: Since the 1970s, the commercial catch has been banned.

Compiled from Kazancheyv.[19]

water development on anadromous and semi-anadromous fisheries of the North Caspian. Among them are the modification of water release schedules and the installation of numerous hatcheries. The controversial outcome of these programs may serve as well-documented examples of the inability of man to replace nature.

Several proposed projects included a scheme to increase water releases in spring (May) in an amount suitable for different water users (i.e., hydroelectric power plants, shipping, agriculture, and fisheries). The results were anticipated: (1) heavy losses in the energy output; (2) the lack of water to maintain navigable depth during the summer; and (3) inadequate duration of the flooding to provide suitable water levels for migration and spawning. The only benefit was the subsequent (temporary) conversion of a submerged flood plain to haymaking and grazing lands in the Volga delta.[7-9]

To save the Acipenseridae from full extinction, dozens of modern hatcheries encompassing 11,000 ha have been put into operation in the lower reaches of the Volga, as well as in other above-mentioned areas, between 1954 and 1980. These hatcheries were expected to release about 84 million fry of Russian sturgeon per year (primarily sevruga): 0.5 million salmonids and 13.4 million fry of other anadromous and semi-anadromous fish.[10] In addition, to improve migration routes and to mitigate the impact of the deficit of spring water supply on the delta environment, different runoff redistribution schemes between the western and eastern parts of the delta were introduced in the 1970s. However, the natural shift in migration of sevruga to less disturbed nursery grounds of the Ural River has been more successful in preventing the disappearance of the stellate sturgeon than any of the implemented water regulation and fish reproduction schemes. The commercial catch of sturgeon increased from 2×10^3 t in the late 1960s to 1×10^4 to 1.1×10^4 t in the early 1980s.[39]

Slivka et al.[39] note that the major success of the fisheries rehabilitation program lies in the fact that a number of natural breeding sevruga populations were still optimal enough (e.g., 1.45×10^5 to 4.63×10^5 and 6.6×10^4 to 2.34×10^5 in the Ural and Volga Rivers, respectively, between 1964 and 1980). However, according to these authors, this condition may change by 1990 when "poor year classes (1973, 1975, 1977) will enter the fishery"; consequently, the catch could decline to an estimated 8000 t at that time. Therefore, of all artificial attempts to compensate for losses sustained by the anadromous fishery, only the growth of natural populations may revitalize the fishery, if an optimal flow regime can be maintained in the delta-estuarine system to enhance fish propagation.

B. The Lower Volga Divider System

By the late 1960s, it became evident that the massive diversion of water from the Volga River was adversely affecting fish populations of the delta. Speculation was that the situation could be improved for spawning and growth of semi-anadromous fishes of the delta by providing a flow of 1.2×10^4 m^3/s at the head of the delta. A plan was devised in which the river discharge would 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 (Figure 13).

The construction of the Volga divider started in the late 1960s and continued through 1976.[10,34] The completed hydrotechnical complex consisted of: (1) the Volga divider above Astrakhan (40 km above the delta); (2) a solid dam 80 km long across the river bed and delta with a controlling gate to the eastern side of the delta; and (3) 33 sectional dams with gates, 2 structures to guide fish, and a dike dividing the delta into eastern and western parts. There was also a system of 16 canals across the outer shoals of the delta (Figure 14), the total length of which amounted to 661 km.

Two ship locks and navigable sections with vertical lift gates are necessary to bypass the divider system. This divider narrows the main river bed to almost 50% of the total width and causes the residual spring runoff to split (especially when the dry spring runoff equals 1.2×10^4 to 1.5×10^4 m^3/s) through the "Peripheral Canal" between the western (20 to 40%) and the eastern delta (60 to 80%) to ensure a guaranteed flow of 8×10^3 to 9×10^3 m^3/s to the Buzan, the major eastern branch of the Volga Delta. 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 24,000 to 25,000 m^3/s, the sectional dams in the right branch of the Volga are opened.

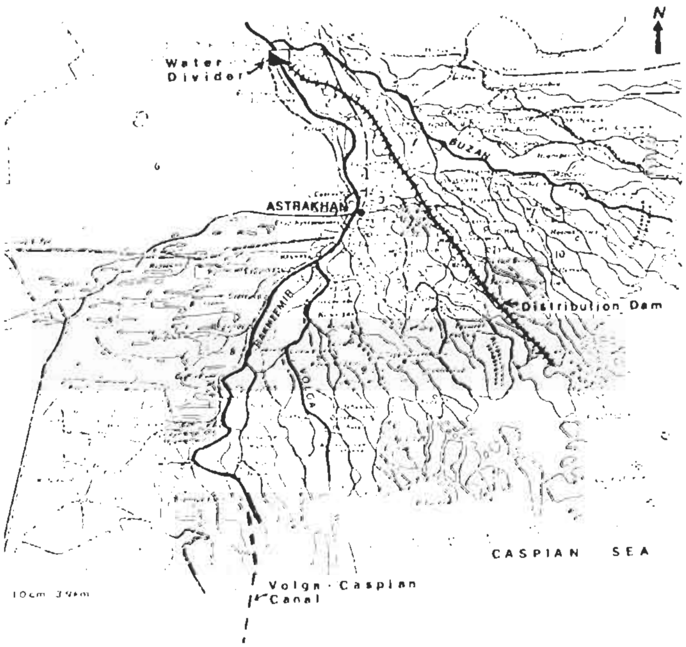


FIGURE 13. The lower Volga Delta water distribution network.

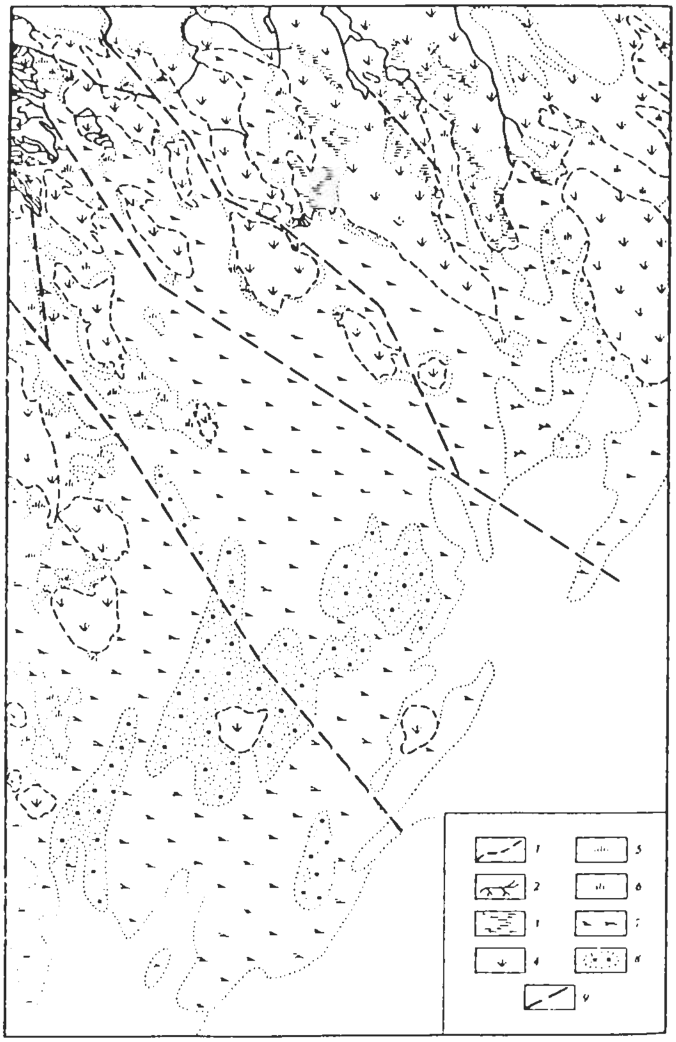


FIGURE 14. The central and eastern area of the Volga Delta hydrographic network produced from satellite observations. Delta: (1) sea-delta boundary, (2) delta tributary network, (3) swamp, and (4) brushwood reed. Outer Delta: (5) dense reed, (6) sparse reed, (7) submerged vegetation, (8) sand bar, and (9) fish channels. (After Reference 46.)

The discharge of 9×10^3 m^3/s, the normal flow for the eastern part of the delta, reaches the river naturally. Concurrently, 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 to 35 d to induce spawning migrations into the eastern part of the delta. This procedure was to be followed by a water diversion of 2.3×10^4 m^3/s for 10 to 12 d to the western side for agricultural requirements. In order to prevent a loss of fish during this agricultural release, reproductively mature fish would be diverted to the eastern delta by releasing 32×10^3 to 35×10^3 m^3/s of water for a period of 30 to 35 d beginning in mid-September. Every third year there was to be a "piscicultural" spring 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. At the time of completion in 1976, this complicated system of fishways, pumping stations, canals, gates, and channels cost the equivalent of hundreds of millions of dollars. Had the system emphasized the elimination of agriculture and the development of the western delta as a reservation for living resources, especially fish, and concentrated irrigation for an agricultural complex in the eastern delta, it might have been successful. As designed and operated, however, it did not work.

During repeated tests, one very classical hydraulics phenomenon was observed, namely, that the deeper distributing canals, in comparison to surrounding shallow delta branches, transported more runoff to the sea, thereby depleting the natural shallow branches of water. These shallows are indispensable for migration and spawning. In addition, it was found that the Russian sturgeon prefers the historical western delta routes for migration, although the eastern delta had a much greater controlled water supply for spawning and greater biomasses of phytoplankton and zoobenthos.

The modernization and improvements of the Volga divider from 1977 to 1982 have not prevented the gradual destruction of the natural delta complex. On the contrary, the divider transformed the delta into a plumbing system suitable more or less for water diversion, power plant operations, and shipping, but severely impacted delta agriculture and fisheries.[29,30,34,42] There are similarities between this elaborate system of water works and the modifications suggested for the delta of the Sacramento-San Joaquin River of California, including a bypass, the "Peripheral Canal", and various alternatives for handling the diversion of water for irrigation and domestic use at the expense of fisheries stocks. The losses sustained by the anadromous fisheries of the San Francisco Bay estuarine system for the last 2 decades amount to $2.6 billion, which may be only one fourth or less of the capitalized losses of the Caspian commercial fishery.[20,24] The Volga divider network of different channels and its "Peripheral Canal", that was designed to mitigate the cluster of problems in the Delta-North Caspian ecosystem created by the Volga-Kama storage facilities, has failed to work ecologically as well as economically. 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 nonliving resources of the Volga-Delta-North Caspian ecosystem.

V. SUMMARY AND CONCLUSIONS

The ecological conditions and commercial fishery of the Caspian Sea, in particular its most productive shallow area the North Caspian, are closely related to the freshwater supply from the Volga River watershed, especially the spring runoff.

During the last 2 decades, 11 hydroelectric power plants and their storage facilities, with a capacity of about 190 km^3 (equaling 75.7% of the annual "normal" Volga-Kama River discharges of 251 km^3 for the period of 1887 to 1962), together with the numerous pumping irrigation systems in the lower Volga have transformed the seasonal runoff pattern so greatly that the entire ecological future and fishery of the Caspian Sea are threatened.

Since the implementation of water projects, the total mean regulated spring runoff for the period of 1967 to 1979 amounts to only 63.5% of its 155.8 km^3, or 39% of the value of the normal annual runoff of 251 km^3 (for the period of 1887 to 1962). Under pre-project conditions, the spring runoff accounted for 62% of the annual "normal". For dry and critical dry years, the total regulated spring Volga discharges amount to only 49% or less of the natural spring runoff. The reduction of spring runoff has been attributed to a two- to threefold decrease in the flood duration as well as a shifting of its truncated peak from June to May. As a result, a significant part of the delta's nursery ground is suffering from a chronic water deficit and acute temperature fluctuations. Both have a negative effect on spawning, food supply, and feeding activities of the valuable fish of the Delta-North Caspian ecosystem.

The negative deviations of regulated spring water supply from the spring normal have increased up to 30 to 50% in comparison with the predominant deviations of the natural spring water supply from the same normal of ± 10 to 15%. At this time, the Volga spring runoffs are dominated by volumes which correspond to subnormal and lower than subnormal wetness, or dry conditions (a 75 to 99% probability of exceedence if the frequency curve of the historical spring discharges is used for comparison).

The inverse phenomenon in water supply to the North Caspian (summer-winter runoff several times higher than spring runoff) has not resulted in improved fish stocks because the spawning and migration of juveniles take place in the spring. During the period of the most active water development and most unfavorable climatological conditions of 1961 to 1979, the North Caspian did not receive about 1050 km^3 of the spring runoff (4.2 and 2.6 times the Volga normal runoff and the North Caspian volume, respectively). The runoff of the majority of small rivers of the Middle and Southern Caspian nearly ceased.

The extensive water withdrawal and impoundment of the river basin caused: (1) negative transformation of morphometry, hydraulics, and physical and chemical properties of the Volga River and Delta as well as neighboring rivers and deltas; (2) an increase in the concentration of waste and recycled waters polluted by agricultural, industrial, and domestic discharges; (3) a deleterious effect on the biological resources; and (4) a sharp increase of detention time as much as eight- to tenfold that adversely affects water quality in the ecosystem, especially during the years of low wetness.

The effect of water withdrawals on the North Caspian might be briefly summarized as follows: (1) the mean salinity increased from 8 to 11‰; (2) the estuarine mixing zone was compressed and moved up to the delta; (3) the nutrient yield, especially phosphorus, and sediment load were reduced as much as 2.5 and 3 times, respectively; (4) biomass of phytoplankton, zooplankton, and benthic organisms were decreased as much as 2.5 times; and (5) a substantial part of the Volga flood plains that served as a nursery ground for many valuable fishes was transformed to drying swamps or prograding deserts.

The most noticeable changes in hydrological and chemical structure of the Middle and South Caspian water masses attributable to modification of the Volga runoff, as observed from 1964 to 1981, were the following[1] (1) salinity increase from the surface to the bottom of about 0.2 to 0.3‰; (2) an increase in the aeration of deep layers and in their oxygen content as high as 2 to 3 ml/l down to depths of 600 to 800 m (in comparison with conditions in the 1930s) due to activation of convection and thermal winter mixing; (3) an increase in the depth of the euphotic zone and total photosynthetic layers down to depths of 50 and 100 m, respectively; (4) an increase in pH of surface layers and in deep water masses during the winter; (5) a decrease in inorganic matter and its vertical gradient; and (6) an increase in the role of wind-driven circulation on horizontal and vertical displacement of temperature, salinity, and the picnocline, especially in the North Caspian, as well as in the shallows of the Middle and South Caspian. In general, the current seasonal vertical and horizontal stratification and displacement of many regime characteristics of the Caspian Sea, including but not limited to temperature, salinity, oxygen, phosphorus, nitrogen, and other elements, differ significantly from those of the 1930s or the late 1950s.[1,5,6,33,37]

The North Caspian estuarine system has been responsible for the success or failure of the reproduction of anadromous and semi-anadromous fishes throughout the Caspian Sea. We contend that the North Caspian ecosystem will not recover as long as the cumulative reduction of spring discharges (and related losses in chemical yields or transformation of the hydrological regime) prevail over the natural deviations. Similar developments in other different estuarine systems, the Dnieper and Dniester, Don and Kuban, and Amur Darya and Sur-Darya, (U.S.S.R.); San Francisco and Delaware Bays, and Columbia River, (U.S.); and the Nile River (Egypt) give strong support to this contention.

The above-mentioned modification of the river-delta-sea ecosystem is the major cause of the progressive deterioration and significant decline in natural recruitment, stock, and commercial catches of anadromous fishes by as much as three to five times (Acipenseridae: Russian sturgeon — *Acipenser guldenstadti* Brandt, beluga — *Huso huso* Linnaeus; and sevruga — *Acipenser stellatus* Pallas). The sevruga has been partially saved from extinction by releases of millions of fry from dozens of hatcheries for the last 2 decades. However, the decline of the major semi-anadromous species — bream (*Abramis brama*), perch (*Lucioperca*), Caspian roach, and carp (*Cyprinus carpio*) — has been more than tenfold. The most severe losses were sustained by the Soviet commercial fishery of Caspian herrings (nearly 100 times less than before water projects implementation in the late 1960s to 1970s). Impoundment of Iranian coastal rivers and streams, compounded by acute pollution, resulted in a dramatic decline of Iranian commercial catch of anadromous and semi-anadromous fish.

It should be emphasized that in the hisorical past a natural reduction of runoff combined with a drop in sea level did not effect such formidable disturbances on the estuarine systems and their fisheries. The impact of the natural alteration of years of different wetness and the corresponding values of river discharges on the estuarine environment are not comparable in both scale and duration with the impact of the ascending runoff deficit caused by continuous water withdrawals for commercial and domestic purposes.

The natural amplitudes of stochastic fluctuations of the Volga runoff to the Delta-Caspian ecosystem has been overridden by the artificially regulated deterministic fluctuations of runoff discharges. As a result, the natural water supply with limited amplitudes from its normal has been replaced by progressively high negative amplitudes of regulated discharges, from the same normal runoff, less favorable for the ecosystem, particularly in spring. For example, the predominant values of the current spring regulated runoff would correspond to a natural frequency of occurrence of one or several times per 20 to 50 years. In other words, the frequency of subnormal spring runoff values has significantly increased. Thus, we contend that the magnitude of these changes has exceeded the natural ability of the delta-sea environment to adjust to the unprecedented decreases in the spring runoff, resulting in ecological impacts.

Channeling and deepening of some branches in the western and central part of the Volga Delta have led to excess storage of residual runoff in these waterways and, at the same time, left the numerous shallow branches without an adequate water supply. This dewatering of the drainage network, compounded with an overall decrease of the flood peak and its duration, has resulted in salinization and desertification of major areas of the delta flood plain, ultimately causing the contamination of agricultural water intakes. Furthermore, the inexorable increase of water diversions up to 30 to 65% of natural spring runoff has altered and effectively undermined the migration routes and spawning and feeding grounds of semi-anadromous and anadromous fish, as well as severely affecting the agricultural value of the delta lands.

The river flow diverted by the Volga divider through its network of peripheral and inner channels in the delta cannot substitute for the historical routes of migration of anadromous and semi-anadromous fish, nor compensate for losses sustained by the fishery due to the chronic deficit in water supply during the spring. It is not surprising that these fisheries have not benefited from man's intervention. The Volga divider network and its numerous hatcheries in the river basin has not resolved the fisheries problems.

This costly development had been foreseen by some environmental specialists. However, such predictions were overwhelmingly ignored by many shortsighted resource planners who could not understand that such artificial redistribution of runoff would not work. Suffice it to say that unprecedented rehabilitation efforts and multimillion ruble expenditures launched by government institutions to preserve the unique population of Russian sturgeons and other valuable fishes from extinction nearly equaled the capitalized gains obtained from the residual Caspian fisheries ($4 to $8 × 10^8 per year).[20]

According to Baydin and Kosarev,[1] Vendrov and Avakyan,[8] Vendrov,[9] and Berdichevsky,[18] the ecological conditions of the Volga Delta, as well as many of the other deltas of the Caspian Sea, are in a precarious state because of anthropogenic reduction of runoff to their ecosystems. Inasmuch as the period of 1978 to 1986 has been abnormally wet, this assertion is given added strength by the recent slight recovery of previously depressed fish populations, including the most productive Caspian herrings *Alosa caspia caspia* Eichwald, *A. brashnikovi* (Borodin), and *A. saposhnikovi* (Grimm).[21]

During the early planning stages of the water resource projects, engineers and ecologists did not have adequate knowledge of the spatial and temporal environmental process and ecological requirements of the biota to correctly budget the water supply among all of the users to avert environmental impacts. The economic benefits in one use area (i.e., hydroelectric power or irrigation) dominated the planning, construction, and operation without concern for long-term environmental degradation. When these failures in understanding ecological effects are combined with notions of cost-benefit analysis and tradeoffs that justify the demands for water beyond the river limit, the synergistic result may accelerate the destruction of the estuarine systems involved.[47] This universal development scenario has been demonstrated in several places in the U.S. (e.g., San Francisco Bay, the Colorado and Columbia Rivers, and the Texas bays), but not on the scale of the Caspian and Azov Seas.[48-58] The monitoring of these universal failures will be very important in the next century as high-quality freshwater supplies become critical to developing and industrial nations and to the ecology of the delta-estuary-sea coastal ecosystems.[59,60]

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