

Perspective

Challenges for Sustainable Use of the Fish Resources from Lake Balkhash, a Fragile Lake in an Arid Ecosystem

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Abstract: Lake Balkhash is the largest water body in Central Asia. More than three-quarters of its inflow comes from the Ili River, which is under increasing strain due to the diversion of water for energy and food production. Commercial fishing in Lake Balkhash began in 1929 and is currently in a state of crisis. The construction of the Balkhash dam and reservoir in the late 1960s reduced Ili River flows into the lake and upset the natural cycle of spring floods, which greatly reduced spawning and feeding areas for carp (*Cyprinus carpio*). Carp populations were consequently reduced by more than 90% during the filling of the reservoir and have not recovered, even though the lake's level subsequently rose. Catches of carp and freshwater bream (*Abramis brama orientalis*) have shown an inverse relationship since the 1960s, and the age structure of freshwater bream is changing. Historically, most captured fish of this species were 4- to 7-years-old, but smaller, 3- to 5-year-old fish have dominated recent catches. The total fish harvest from Lake Balkhash is currently at near historical lows, not just because of environmental factors, but also because of structural changes triggered by the collapse of the Soviet Union. Poaching, government disinterest, lack of enforcement of fishing regulations, and the economic challenges faced by today's small fishing enterprises all contribute to the problem.

Keywords: arid river basins; Lake Balkhash; Ili River delta; hydrological regimes; fisheries; overfishing; poaching

1. Introduction

Lake Balkhash is the largest water body wholly within the borders of Kazakhstan (Figure 1). Five permanent rivers flow into it: the Ili, Karatal, Aksu, Lepsa, and Ayaguz [1]. These rivers originate in the mountainous regions of the Tien Shan range, and to a lesser extent, the Tarbagatai and Chingiz-Tau ranges. The Ili River is by far the most important, nourishing the largest delta in

Central Asia. The Ili enters the western part of the lake, supplying nearly 80% of the total annual inflow, whereas the four smaller rivers flow into the more brackish eastern arm of the lake. Lake Balkhash and its delta are characterized by a unique biodiversity that includes vertebrate fauna of great environmental, aesthetic, and practical importance [2,3].

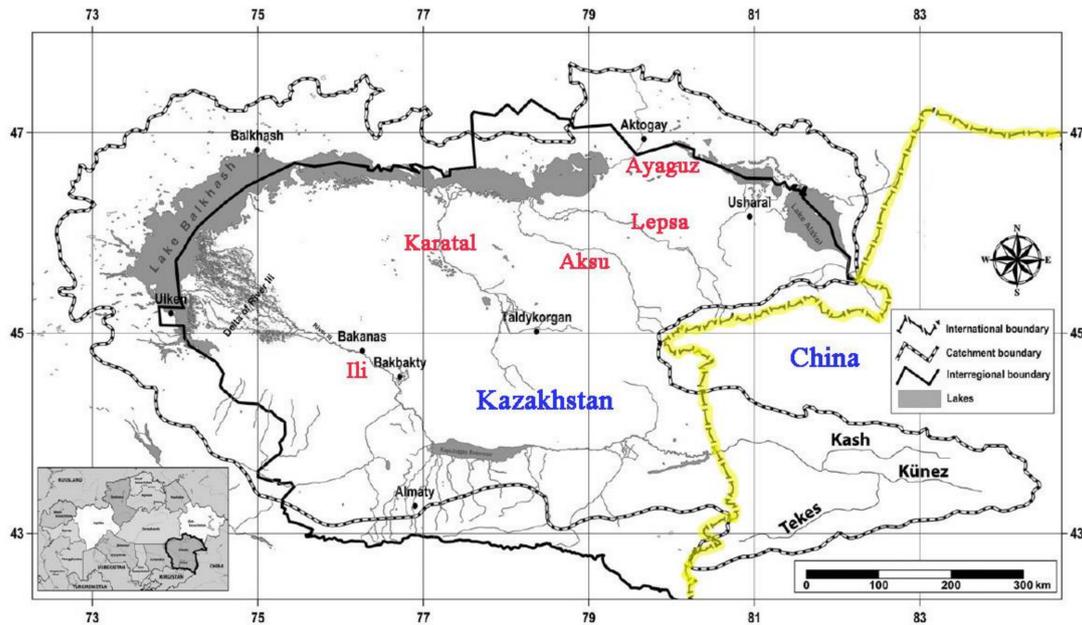


Figure 1. Map of the Ili River basin and Lake Balkhash showing the five feeder rivers in red and the international border in yellow; modified after [3].

The lake is a valuable source of fish for local consumption and export, accounting for roughly 25% of the total commercial fish catch of Kazakhstan in some years [4,5]. Commercial fisheries have operated on it since the late 1920s, providing significant economic activity and employment for the local population [6]. Lake Balkhash is currently the republic's second most important fishing ground after the Caspian Sea, a much larger body of water that is shared with bordering countries. Commercial fishing in Lake Balkhash, and indeed in Kazakhstan as a whole, is nevertheless in a severe crisis [7,8]. Some contributing factors are directly attributable to human activities. These include water pollution; overfishing; poaching; mismanagement of the fishing industry; and the lack of storage, processing, and other infrastructure required to market fish and fish products [9].

Lake Balkhash fisheries are also vulnerable by virtue of the lake's location in an extremely arid and hydrologically fragile ecosystem that is vulnerable to the effects of climate change [10]. Central Eurasia has a markedly continental climate with great variation in daytime and nighttime temperatures and significant summer and winter temperature differentials [11]. Annual precipitation, as measured at Balkhash on the lake's northern shore (Figure 1), varied between 53 and 221 mm during the period from 1935 to 2005 (an average of 125 mm). The relative humidity averaged only about 50% [12]. These factors cause high evaporation from the delta and from the shallow lake, which has an average depth of only 5.8 m and a nominal coastline of 2835 km. The lake's surface elevation varied between 340.7 and nearly 344 m above sea level during the period from 1880 to 1990 [1]. Although natural variability in water flow makes it difficult to precisely measure the lake's surface area [13], a drop of just 160 cm is estimated to reduce the surface area from 19,000 to 15,800 km² [14]. Surface area losses of this magnitude disproportionately affect shallow areas of the lake, which are places for fish spawning and feeding.

In short, the ongoing, colossal damage to Lake Balkhash fish resources is attributable to the lack of adequate reproduction of fish stocks against the background of weakening state control over their use,

as well as the ill-conceived organization of fishing under market economic conditions. The objective of this report is to integrate historical information about the ichthyofauna of Lake Balkhash with recent data to provide an analysis of the most urgent problems of the conservation and sustainable use of the lake's fish resources. We take into account a variety of associated risks that will likely determine the future of the lake.

2. Changes in the Hydrological Regime of Lake Balkhash

The level of Lake Balkhash is a principal indicator of the status of the surrounding ecosystem. Historically, the area and volume of the lake have expanded and contracted in response to long- and short-term environmental factors [15,16]. Thus, at the beginning of the 20th century, and during the period from 1958 to 1969, the area of the lake increased to a range of 18,000 to 19,000 km², but it was as low as 15,500 to 16,300 km² at the end of the 19th century and in the 1930s and 1940s. Over the past few centuries, the amplitude of water level fluctuations has been about three meters [1].

These natural cycles in the lake's level persisted until 1970, when water was first diverted from the river to fill Kapchagai Reservoir. Thereafter, the inflow from the Ili River, and thus the level of the lake, has been regulated by dams and other upstream hydraulic structures in both countries that share the ecosystem [17,18]. Between 1950 and 1969, the annual Ili River runoff averaged 16.2 km³ (516 m³/s), as measured at Kapchagai. The maximum runoff occurred in July, during the most intensive melting of snowfields and glaciers in the mountains, leading to a pronounced seasonal cycle of river flow (Figure 2). During this period, spring runoff (April–May) averaged 455 m³/s, summer runoff (June–August) averaged 950 m³/s, and autumn–winter runoff (October–March) averaged 321 m³/s.

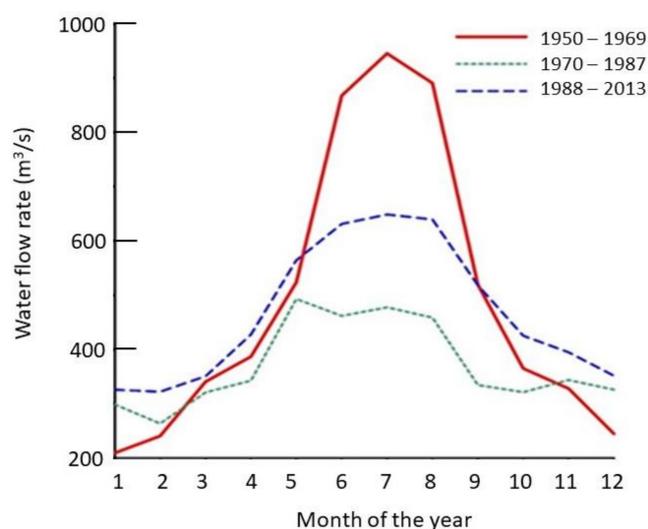


Figure 2. Average monthly water flows as measured at the Kapchagai hydropost during three periods of time: immediately prior to closure of the dam (1950–1969), while the reservoir was being filled (1970–1987), and after filling of the reservoir ceased (1988–2013). Raw data are from Kazhydromet.

The annual runoff decreased by more than one-quarter, to an average of 370 m³/s during 1970–1987, as the reservoir was being filled to approximately half of its envisioned capacity of 28.1 km³. Additional filling was halted at this time in order to avoid further ecosystem damage, which had been conditioned by a combination of factors that included net loss of water due to evaporation from the reservoir's surface (estimated to be as much as 2.3 km³ per year) [19], seepage into the ground, dissipation of water abstracted for irrigation, and accumulation of salts and other pollutants in the lake [1,20]. The seasonality of water release from the dam became an issue. High water flows were impounded in the reservoir during late spring and summer and then released through the turbines during the winter months, when the demand for electrical power was greatest. This led to an average

reduction of 48% in summer flows and increase of 28% in winter flows (Figure 2). Winter floods were common during this period as waves in the upper delta reached 0.5 m, causing ice drift, congestion, and numerous spills with damaging effects on biota.

The annual flow of the Ili River increased during the period 1988–2013, averaging 466 m³/s. Although this is near the flow level experienced prior to the construction of the dam, efficient operation of the turbines means that disruptions to the normal cycle of natural flows into the lake persist. The seasonal amplitude has been partially restored, but in comparison to historical levels, much less water now flows past the Kapchagai hydropost in the summer, compared to more in the other seasons (Figure 2). Upstream effects are also becoming more evident, as large dams in China divert water for consumptive use in irrigation and alter the cyclic flows of the Ili River before it enters Kazakhstan [17,18,21]. The level of Lake Balkhash has nevertheless recovered, such that over the past 15 years, it has fluctuated between 342 and 343 m above sea level. This is partly because of enhanced melting of glaciers in the surrounding mountains [19,22,23]. The area of glaciation in just the Kazakh part of the Ili River basin decreased by 38.5% from 1955 to 2004 [22], a consequence of atmospheric trends that are affecting the entire basin [10,24,25]. The benefits of glacier retreat will nevertheless be short-lived, because the glaciers will eventually disappear and deprive the ecosystem of its most significant source of water [10,26].

3. Commercial Fishing on Lake Balkhash

The primary ichthyofauna of Lake Balkhash arose in the relatively recent geological past and was formed by species that entered from the rivers of the Tien Shan mountains and waterways that then flowed into the lake from the north. Subsequent isolation of the basin resulted in the formation of a stable fish population composed of a small number of species, five or six of which are considered to be endemic [1,13,27]. Historically, fishing has always been essential for feeding the local population. Until the twentieth century, however, there were few professional fishermen on the lake. During the first decade of the 20th century, catches were a negligible 68 to 106 tons per year [28]. Organized commercial fishing began in 1929 with the formation of the first collective fishing brigades. These were later reorganized into the Balkhash State Fishing Cooperative. Only 2500 tons of fish, including several indigenous species, were caught in 1930, but fisheries developed rapidly thereafter (Figure 3). Just two years later, 14,650 tons of fish were caught. The following decade was characterized by high sustained captures, which reached 18,650 tons by 1941. Early fisheries on the lake depended on common carp (a species that had been introduced in 1910; see [1]), which made up 58–86% of the catch, and perch (*Perca schrenki*) and marinka (*Schizothorax* spp.), which made up 4–30%, depending on the year.

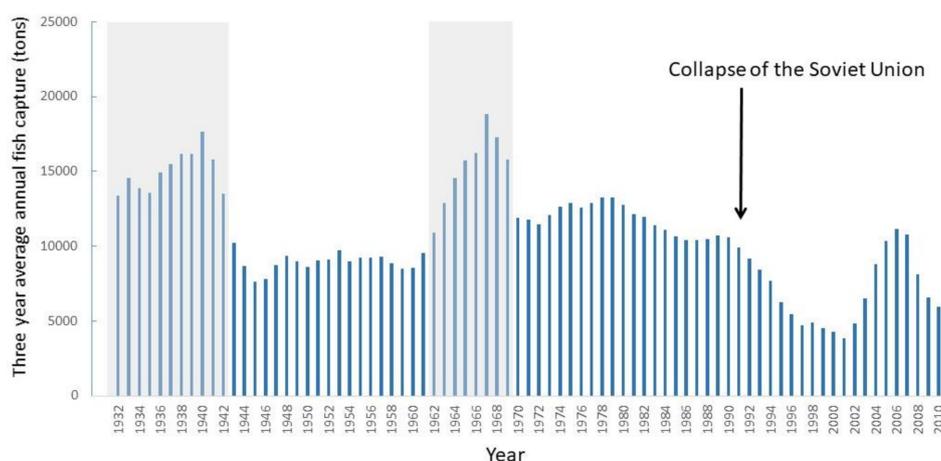


Figure 3. Commercial harvest of fish from Lake Balkhash expressed as 3-year running averages during the interval from 1932 to 2010. The shaded areas indicate early periods of relatively high catch. The raw data are from [4].

The limited productivity of the lake and the prevalence of low commercial value native species encouraged the Soviets to introduce species that were perceived to be more valuable [1]. In addition to common carp (*Cyprinus carpio*), particularly widespread alien species included Prussian carp (*Carassius gibelio*), roach (*Rutilus rutilus*), freshwater bream (*Abramis brama orientalis*), asp (*Aspius aspius*), wels catfish (*Silurus glanis*), and pike-perch (*Sander lucioperca*). The Soviets took pains to provide a feeding base for these new fish species. The following species were introduced for this purpose: freshwater shrimp (*Dikerogammarus aralensis*), the amphipod *Chelicorophium curvispinum*, several species of mysids (*Paramysis intermedia*, *P. lacustris*, *P. ullskyi*, *P. baeri*, and *Diamysis pengoi*), and two species of polychaetes (*Hypania invalida* and *Hypaniola kowalewskii*) [29–31].

Despite favorable environmental conditions that allowed the water level of the lake to enter a period of long-term rise of 2 m [1], catches remained low and fairly constant throughout most of the 1940s until the early 1960s. The average annual capture during this period was approximately 9000 tons. Carp catches during this interval varied between 4000 and 7800 tons annually (an average of 6300 tons), while perch and marinka catches varied between 1540 and 3590 tons (an average of 2630 tons) [4].

As a result of stocking efforts, more than 20 types of alien fish settled into new ecological niches in the lake, quickly displacing the native species [32]. The introduced carp, freshwater bream, pike-perch, and fringebarbel sturgeon (*Acipenser nudiiventris*) represented 83.5% of the catches in 1962, with native species, such as perch and marinka, accounting for the remainder [33]. The average annual commercial catch of fish from Lake Balkhash was about 16,600 tons per year between 1965 and 1969 (Figure 3), with the introduced species accounting for 90% of the total catch during that period [34]. The yield of several alien species increased significantly after they were introduced. The annual harvest of pike-perch, for example, reached 4870 tons in 1964, stabilized at 2500 to 4000 tons, and then, since 1979, has declined to levels not exceeding 2000 tons per year. On average, native fish species represented just 0.2 to 5% of the total. The commercially relevant ichthyofauna of Lake Balkhash is now dominated by nine species that have been introduced over the years: common carp, freshwater bream, asp, roach, wels catfish, Prussian carp, pike-perch, Volga pike-perch (*Sander volgensis*), and snakehead (*Channa argus*).

With a few exceptions, the past 40 years have witnessed a period of relatively stable harvests, followed by a progressive decline that began coincidentally with the dissolution of the Soviet Union (Figure 3). Yearly catches exceeded 10,000 tons through 1991, but then plunged to less than half this amount—in part because of inaccurate reporting. Although fish production from the lake rebounded for a brief, economically favorable period early in this century, it has plunged again to a state of near collapse [8,9]. The current situation was conditioned in part by the privatization of Kazakhstan's fishing industry, which created small- and medium-sized businesses that could not operate profitably during the economic crisis that followed independence, even though investments in fish processing are now occurring and fish exports are rising [35]. Fluctuations in water levels and depleted fish stocks due to overfishing are often cited as threats to the health of fisheries in developing countries [36–39]. Both issues are relevant to the future status of the lake, as is the fact that the levels of several heavy metals and organic pollutants in the lake appear to exceed the minimum standards of safety for the fishing industry [9,40]. Lake Balkhash thus remains vulnerable to the twin threats of unsustainable levels of fish removal and a disturbed and unstable hydrological regime.

4. Influence of the Hydrological Regime on the Ichthyofauna of Lake Balkhash

In the 1970s, A. P. Ilyasov and L. S. Tsoi of KazSRIF, the Kazakh Scientific Research Institute of Fisheries, noticed a positive correlation between catches of small carp in Lake Balkhash and water levels during the month of May [41]. At approximately the same time, employees of the Gidryrybproekt Institute in Moscow found a similar association between commercial carp catches from the lake and runoff volumes from the Ili River during the previous 5-year period [42]. These relationships can be explained in terms of the sensitivity of natural floodplain ecosystems to seemingly insignificant

fluctuations in water levels [43], and the requirement for adequate water to maintain the spawning and feeding sites necessary for successful carp reproduction [44].

As shown in Figure 4, yields of carp from Lake Balkhash declined precipitously in the decades following the construction of Kapchagai reservoir. Carp harvests tracked the level of the lake's water rather closely in the years prior to the closure of the dam, when the river was still flowing naturally [42]. This changed between 1970 and 1987, when the reservoir was being filled and the lake's level was constantly falling. Carp harvests plummeted during this period, to the extent that commercial harvests had nearly vanished within 10 years of completion of the dam. Although diversion of water to raise the level of the reservoir was halted, carp fisheries did not recover in the period after 1987, even though the lake's level returned to that experienced prior to construction of the dam (Figure 4).

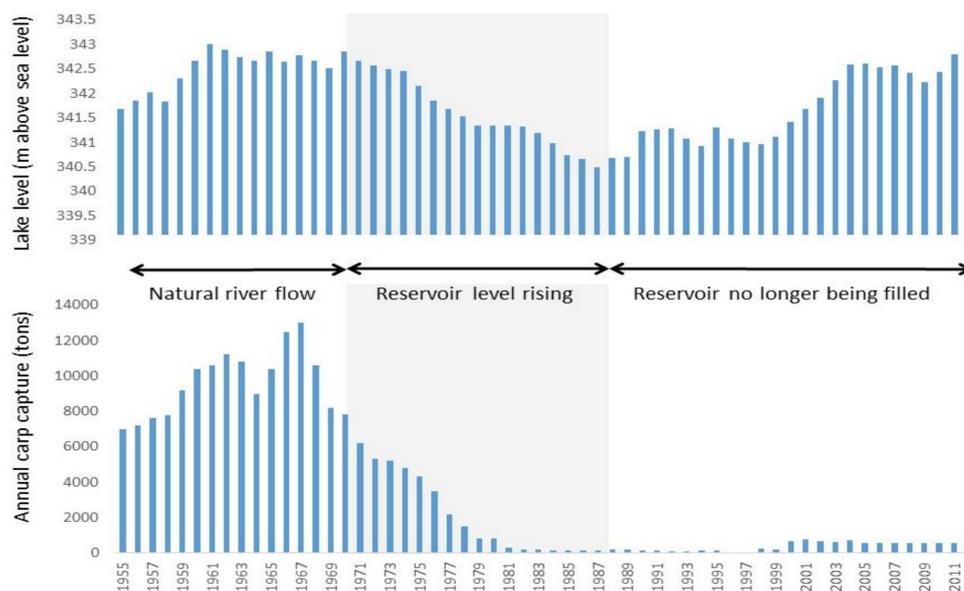


Figure 4. Relationship between the level of Lake Balkhash (as measured by Kazhydromet) and the reported annual commercial capture of carp from the lake before construction of Kapchagai dam, during the filling of Kapchagai reservoir, and after the filling was complete.

Construction of the dam had a different effect on freshwater bream, a less desirable cyprinid species introduced into Lake Balkhash in 1949. Prior to dam construction, its population, as measured by commercial capture, was less than 1000 tons annually (Figure 5a). Harvest of this species increased rapidly as Kapchagai reservoir was being filled, surpassing 8000 tons per year by 1978 and remaining above this level until 1991, when populations began a decline that was nearly as rapid as the earlier increase. There is a strong negative correlation ($r = -0.79$) between populations of freshwater bream and carp in the lake during the period 1960 to 2010 (Figure 5b), a fact that can be explained by the ecological adaptability of the species, which allowed it to outcompete carp and other more desirable species [45]. Freshwater bream populations have nevertheless declined substantially in the delta region in recent years [8], with fluctuations (Figure 5a) that mirror those in total fish harvest (Figure 3). This species currently comprises from 50 to more than 70% of the total Lake Balkhash capture, depending on the year [8,46].

The collapse of carp fisheries in Lake Balkhash following construction of the dam can be explained in part by environmental factors. Changes in the hydrological regime of the Ili River caused about 40% of the delta to desiccate [47,48], which led to a sharp reduction of spawning and feeding areas and a corresponding decline in carp capture in the delta [8,49]. Spawning and feeding were also affected as the lake's surface area contracted and its shoreline receded [50]. Other factors were also at play, including uncontrolled water abstraction and noncompliance with the discharge schedule from

Kapchagai Reservoir during the early 1990s [39,51]. Fishermen also began to conceal their catches, which contributed to the decline in reported carp capture.

Water was artificially released from the dam in the spring, but this did not compensate for the absence of natural floods. Although still of concern [52], water quality nevertheless has improved as the lake's level has risen over the past 15 years; mineralization has declined, fish feeding areas have expanded, spawning areas have doubled, and the incidence of dermatofibrosarcoma in pike-perch has decreased significantly [53]. This has been accompanied by a slight but consistent increase in reported annual capture of carp from the lake (Figure 4). The lower reaches of the Ili River, which include numerous lakes, stream systems, and spills, play a significant role in the reproduction of this species. A decrease in the water level of just 0.2 m would likely remove 500 to 600 km² of the lake's surface area, which corresponds to about 400 km² of carp spawning grounds. If river flows decline in the future because of additional construction of hydrological facilities and the resulting loss of water due to evaporation and seepage, the level of the lake will again fall; carp feeding and spawning grounds will again disappear with corresponding detrimental impacts on fisheries [54].

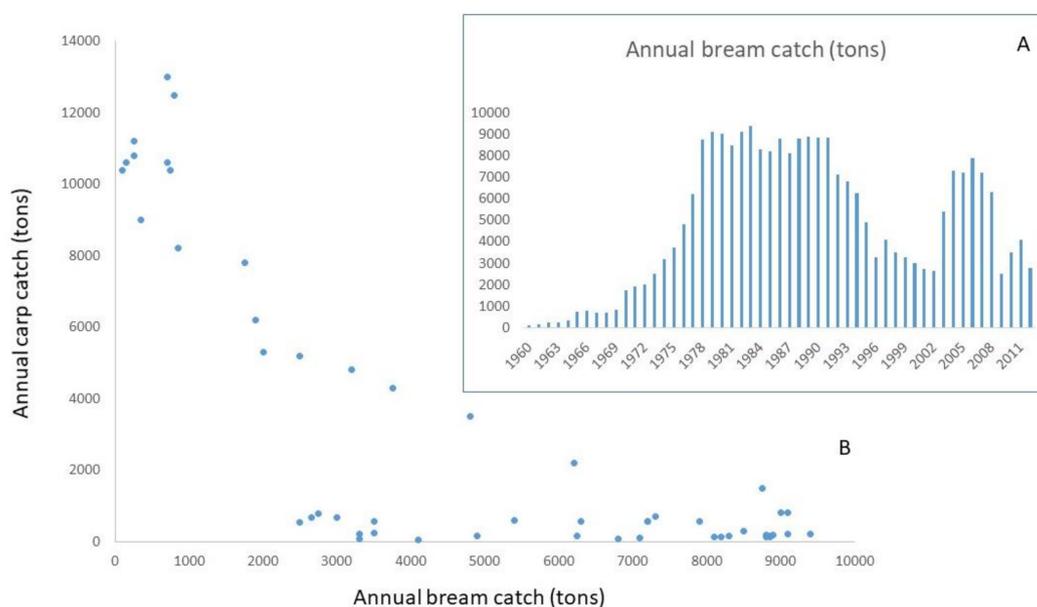


Figure 5. (A) Reported annual catch of freshwater bream from Lake Balkhash between 1960 and 2012. (B) Relationship between the reported annual catch of carp and that of freshwater bream from Lake Balkhash between 1960 and 2012 ($r = -0.79$).

5. Influence of Economic and Social Factors on Fisheries in Lake Balkhash

Recent changes in economic models have profoundly affected the Lake Balkhash fishing industry, influencing both its effectiveness and its sustainability. During the Soviet period, capture fisheries and aquaculture were supported by the state. From 1960 to 1966, for example, the waters of Lake Balkhash and the lower Ili River delta were subdivided into 11 fishing areas on the basis of characteristic abiotic and biotic properties. Fishing was carried out by five collectives that employed more than 700 fishermen on average, each nominally responsible for the capture of between 13.4 and 21.3 tons of fish per year (Table 1). All captured fish were immediately surrendered to receiving and transport vessels of the Balkhash fish factory. Prices were low and stable, amounting to slightly more than 24 cents U.S. per kg during the period 1970 to 1980. Catch limits were not generally established, but the authorities conducted inspections to ensure that undersized fish were not harvested. As a rule, fishermen did not conceal even a few fish for personal consumption. Official statistics on fish stocks and industrial catches were accurate, and although violations occasionally occurred [55], poaching was virtually nonexistent.

Table 1. Fishermen and fish capture on Lake Balkhash during the period 1960 to 1966. Sources: Kazakh Research Institute of Fishery and [8].

Year	Fishermen	Total Catch (tons)	Average Catch Per Fisherman (tons)
1960	664	8870	13.4
1961	574	8850	15.4
1962	641	11,810	18.4
1963	724	13,450	18.6
1964	781	15,040	19.3
1965	787	16,170	20.6
1966	775	16,500	21.3
Mean	707	15,115	18.1

The situation changed dramatically with the introduction of a capitalist economic model. Fishing organizations obtained the right to independently sell their catch at market prices, and the self-serving interests of private entities began to predominate. These entities were motivated by the potential for rapid profits, and in the absence of strict accounting and control of fish catches by inspectors, they ignored previously mandated quotas. The five collective fishing operations, or *kolkhoz*, that had been operating on Lake Balkhash at the onset of the hasty and ill-conceived reform of the industry were subdivided into smaller private enterprises. Depending on the year, their number fluctuated between 28 and 45, with 4 to 19 fishermen per enterprise. The owners privatized the main assets of the former collectives, including fishing fleets, vehicles, and storage facilities, and on a competitive basis, they negotiated long-term leases for 119 fishing areas and sub-areas of Lake Balkhash and the lower Ili River delta. These leases could be extended every 10 years. Lake Balkhash is currently divided into 70 fishing zones that are used by 45 fishing organizations under various forms of ownership. This is triple the number of organizations operating at the beginning of this century [9].

Fishermen and owners of fishing organizations have informed us that by 1992, the share of the total fish catch that was unaccounted for soon equaled the share that was officially registered. As a rule, fishing entities tried to include the more valuable species as part of the unregistered share. These practices distorted the statistics on the extent of fish capture from the lake (Figure 2), which indicated a precipitous fall in harvests, beginning with the dissolution of the Soviet Union and extending until 2005, when the government of Kazakhstan adopted policies to prevent the concealment of catches [56].

The twin advantages of sharply weakened control over fishing and the right of private enterprises to independently sell fish at market prices allowed the Lake Balkhash-based fish industry to become very profitable. This in turn made possible the purchase of new fishing vessels and gear, including small boats with outboard engines. Owners also created shoreline infrastructure, including fish receiving stations that were equipped with refrigeration, repair, and other facilities. Beginning in 1992, the number of fishermen also increased in comparison to the 1960s, when average numbers were about 700 per year (Table 1); by 2005, the lake provided employment for 1543 fishermen. In short, the period beginning with independence and leading up to 2005 was characterized by poaching [57] and intense, almost uncontrolled commercial overfishing, even though quotas were in place and fishing was nominally restricted to just 7 months of the year.

The consequences of the resulting rapid reduction in fish stocks were predictable. The number of fishermen declined from 1543 in 2005 to just 1109 in 2009—a 28% reduction in just four years. Yearly catch per fisherman, which had been as much as 21.3 tons in the 1960s, fell to 7.8 tons in 2005–2007. The decline has continued in subsequent years, as measured by the number of fishing firms in operation, active fishermen on the lake, and seines and fishnets in use; the total commercial catch in 2017 is estimated to be almost 20% less than the 9070 tons that were harvested in 2010 [8]. Poaching has also taken its toll, as local residents use small, high-speed boats with powerful engines to harvest fish year-round, including during spawning season. Uncontrolled recreational and trophy fishing,

including spearfishing—a practice that is widely prohibited elsewhere—have also caused enormous damage, especially in the Ili delta.

6. Age Structure of Fish in Lake Balkhash

Given the above environmental and socioeconomic challenges to the ichthyofauna of the lake, we thought it of interest to examine recent changes in age structure and linear-weight growth of freshwater bream, one of the main commercial species in the lake. Samples from commercial catches during the main summer fishing season of the years 2012 to 2016 were collected by the Department of Ichthyology and Hydrobiology at Al-Farabi Kazakh National University and by KazSRIF. Freshwater bream currently dominates the Lake Balkhash fishery, and most individuals reach puberty between the ages of 4 and 6 years. They approach the spawning grounds when the water warms to 13–16 °C, but spawning occurs at temperatures of 16–18 °C and higher, which commonly occur from mid-April to early July. The annual catch of this species is 5000 to 5500 tons per year, which accounts for 65.4% of the total. Pike-perch and carp account for an additional 8.8% and 7.4% of the total, respectively.

The studies of Lake Balkhash freshwater bream by Tsyba [58] in the 1970s provide a historical baseline for our analysis (Figure 6). Across 10 recorded age categories from 1+ to 10+ years, more than three-quarters of the freshwater bream population in 1972 consisted of 4- to 6-year-old fish (the mean was 5.2 years). The average body length was 20.9 cm, and the average weight was 270 g. By 1985, and across nine recorded age categories from 2+ to 10+ years, about 55% of the population was 4 to 6 years old (the mean was 5.79 years). Average length was 21.6 cm, and the average weight was 206 g.

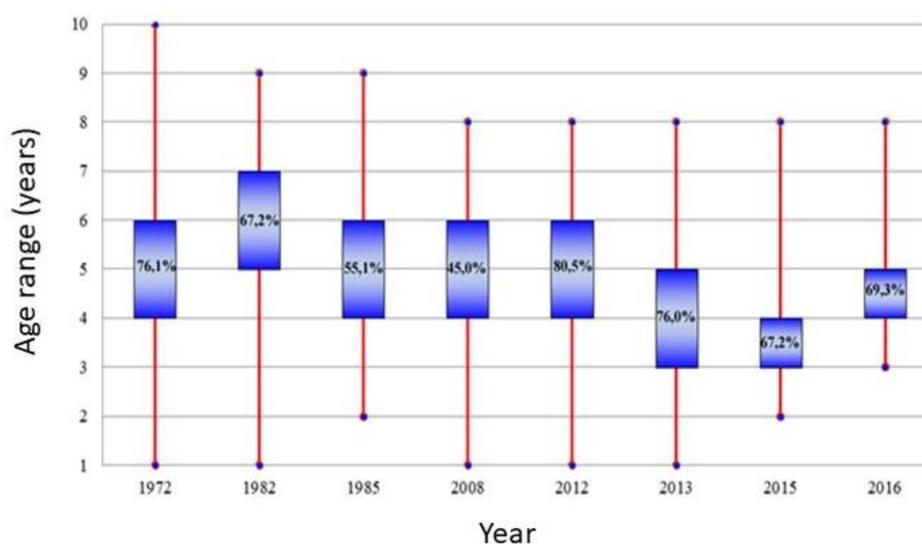


Figure 6. Dynamics of the age structure of freshwater bream from Lake Balkhash between the years 1972 and 2016. For each year, the red vertical line indicates the age range of the catch, and the blue box defines the percentage of the catch falling within the age range defined by the box. Pre-1985 data are from [58].

Beginning in 2008, the age structure of freshwater bream did not exceed 8+ years, and in 2015 and 2016, it was even less (Figure 6). Freshwater bream between the ages of 4 and 6 years dominated the catch in 2008 and 2012, but 3- to 5-year-old fish did so in 2015. Almost 70% of the 2016 catch from Lake Balkhash was composed of 4- to 5-year-old fish. Length varied from 180 to 275 mm, body weight from 116 to 426 g, and age from 3+ to 8+. Table 2 summarizes data on the lengths and weights of 3- to 8-year-old freshwater bream captured from Lake Balkhash during seven sampling periods from 1973 to 2016. Although there is considerable variation in the measurements of younger fish, 6- to 8-year-old fish sampled between 2007 and 2016 were uniformly smaller in both weight and length when compared with fish sampled in the 1970s and 1980s (Table 2, shaded areas).

Table 2. Length–weight relationships of freshwater bream captured in Lake Balkhash during seven sampling periods between 1973–1984 and 2016. Pre-1985 data are from [58].

Sample Period	Mean Length (mm) of Fish of a Given Age					
	3 Years	4 Years	5 Years	6 Years	7 Years	8 Years
1973–1974	198	217	237	253	277	287
1980–1984	153	187	216	245	260	280
2007	158	188	205	224	239	260
2008	153	184	201	218	239	266
2009	154	176	196	213	233	252
2015	152	195	218	224	241	272
2016	180	193	208	229	245	266

Sample Period	Mean Weight (g) of Fish of a Given Age					
	3 Years	4 Years	5 Years	6 Years	7 Years	8 Years
1973–1974	159	210	267	343	426	570
1980–1984	75	136	177	306	383	486
2007	79	135	179	231	288	347
2008	72	121	158	199	262	338
2009	72?	110	146	187	246	316
2015	83	111	135	186	243	293
2016	132	136	171	241	293	374

7. Discussion

There were no commercial fisheries in Kazakhstan before the 20th century, and it was not until the 1960s that intensive commercial development of fisheries began [59]. Thus, fishing did not play a significant economic role until rather recently, but it has now become widespread in the area of the Syr Darya River and the Aral Sea, as well as the Ural, Irtysh, and Ili Rivers and Lake Balkhash [60]. The origins of the formation of industrial fishing on Lake Balkhash and the lower reaches of the Ili River date back to 1929 [1], when local fishermen were organized into commercial fishing cooperatives. The subsequent development of industrial fishing on Lake Balkhash can be divided into five periods, three of which preceded dam construction and two of which followed it (Figure 3).

The first period, from 1929 to 1941, corresponds to the initial establishment of a commercial fisheries industry on the lake. Carp, which accidentally entered the river in 1905 and reached the lake in 1910 [1], predominated, along with low commercial value fish of indigenous species. Annual catches reached nearly 15,000 tons after only two years of commercial fishing and remained high through the 1930s, reaching a maximum of 18,650 tons in 1941. The second period, from 1942 to 1961, saw the annual catch decrease and stabilize at levels that averaged only half of that achieved in 1941. Catches increased progressively during the third period, from 1962 to 1968, likely because populations of newly introduced species [6] were becoming established. The maximum catch ever recorded, 23,930 tons, was achieved in 1968.

The fourth period, which extended for roughly two decades from 1969 to 1990, encompasses the time during which the reservoir was being filled, as well as a few years thereafter. The total catch was relatively stable, but harvests of carp dropped precipitously (Figures 3 and 4) as spawning and feeding areas were damaged by falling water levels [1]. Harvests of freshwater bream, another introduced species, increased and stabilized. The fifth period begins with Kazakhstan's independence in 1991 and extends to the present (Figure 3). Reported catches declined over the first ten years, a time when under-reporting of harvests was widespread. This ceased in 2002, after which catches increased for a few years, but then decreased again. Since 1991, catches have been consistently low by historical standards and continue to decline [59]. Fish harvest from Lake Balkhash decreased by 17% between 2010 and 2017, and that of carp and pike-perch declined by 47% and 42%, respectively, during the same period [8]. Freshwater bream harvest declined by only 5%, but weight and length measurements (Table 2) indicate that the population is stressed in comparison to the 1970s and 1980s.

Over-exploitation of fish stocks is being increasingly recognized as a problem for Eurasia [61,62], and indeed, Kazakhstan's current fisheries complex suffers similarly and can be realistically described to be in a state of crisis. At the peak of its productivity, between 1965 and 1969, it provided nutrition for more than 1.5 million people, based on estimates of annual fish consumption at that time. It also secured employment and other economic activity for local people in the Lake Balkhash region. The collapse of the Soviet Union turned the new republic's attention away from fisheries and fragmented the fleet into many small, private enterprises that were difficult to monitor as enforcement was relaxed [8]. Today, the rules regulating fisheries are being systemically broken by fishing firms, poachers, and anglers interested primarily in financial gain. Registered enterprises catch fish with legally authorized gear, but they often exceed quotas. Poachers use prohibited gear and fishing methods, and they harvest at prohibited times, particularly during the sensitive spawning season. Ineffective regulation has allowed these activities to proliferate and intensify, and as a result of this shadow economy, stocks of commercially valuable fish in Lake Balkhash are being rapidly depleted. Catches are consequently reduced, and decreased length–weight relationships of caught fish are evident.

Inadequate supplies and seasonal shortages of water, increasing levels of pollution [4,40], and the effects of climate change also emerge as major risk factors [10,26,63], not just for Lake Balkhash fisheries, but also for other water-dependent activities: irrigated agriculture, generation of hydroelectric energy, and preservation of natural areas in the surrounding ecosystem [3]. These interrelationships underscore the fundamental importance to the lake and river of tradeoffs associated with the water, energy, and food [64,65]. They also highlight the need for comprehensive environmental monitoring, robust experimental data, and systematic analysis and interpretation of the sort that informs management decisions.

As indicated above, our knowledge of Ili River flow rates and the impact of Kapchagai dam on seasonal water cycles is relatively good, but this contrasts with a much more limited understanding of interrelated environmental factors of significance to aquatic fauna in the estuary and Lake Balkhash. The temperature of Ili River water well upstream of the dam is known, for example, to be influenced by hydraulic changes to the river that are even further upstream. Both temperature extremes and fluctuations are perturbed, with potentially significant impacts on fish and other biota [21]. Yet little is known of how impounding spring floodwaters and their subsequent counter-seasonal release influence temperature regimes of water flowing below Kapchagai dam.

The deposition of solids provides another example. It is well-documented that the Ili River carries almost 10 million tons of suspended solids annually [66]. Under natural conditions, they were delivered to the estuary and lake, but sediments now accumulate in and above Kapchagai reservoir [67], with poorly understood consequences for downstream areas. Much more also needs to be understood about the effects of water impoundment and diversion on the salinity and mineralization of Lake Balkhash and the lower reaches of the river. Baseline measurements of the lake's salinity are available from 1929, albeit from a limited number of sampling sites and with significant temporal gaps [68]. Nevertheless, there is evidence of progressively elevated mineralization of Lake Balkhash during the second half of the 20th century, as well as increased salinization and changes in the concentration of other minerals in drainage water reentering the river from irrigated fields [1,12,19,40,66]. Little is understood of how temporal and spatial changes to any of these environmental factors influence fish populations in downstream areas, and indeed, such populations have for the most part been inferred from reports of commercial fish capture. Additional environmental analysis and systematic studies of fish populations would provide answers to pressing, yet overlooked questions about the lake's environment, how trophic levels are changing, and the impact on the lake's ichthyofauna.

Although the endorheic nature of Lake Balkhash and its position within a very arid, disturbed, and transboundary ecosystem [1,69–73] are unusual, analysis of the current situation provides lessons for those seeking to preserve fish as components of other potentially threatened ecosystems. Experience with Lake Balkhash underscores the desirability of having a robust suite of environmental monitoring systems in uninterrupted operation prior to ecosystem disturbance. As much experimental data as

possible should also be obtained concurrent with environmental monitoring, so that baseline function under natural conditions can be established. Neither of these conditions was fulfilled with Lake Balkhash, and it has consequently been difficult to move beyond correlation to an understanding of cause and effect as the ecosystem has been altered.

Finally, it is important to be cognizant of undesirable tradeoffs, for example, when one important source of food (fish) becomes jeopardized in an effort to increase availability of another (irrigated crops). Indeed, and as we have pointed out earlier [64], steps to increase crop production along the Ili River have involved tradeoffs with yet a third significant source of food (animal agriculture). It is important to recognize the existence of such tradeoffs [74,75], which characterize not just food issues, but also interrelated and competing demands for provision of water and energy.

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