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History and Management of the Parasite Fauna of Aral Sea Fishes

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The present study reviews the parasite fauna of fishes in the Aral Sea, before, during and after the recent regression and salinization crisis. The native fish fauna was much depleted compared to the nearby Caspian Sea, comprising only 20 spp., all having a freshwater origin. The parasite fauna was similarly poorer, both in total species number and when considering parasites infesting individual species. Some fish species and parasites were introduced during the 20th century. Species introduction of fish and progressive salinization in the latter half of the 20th century interacted in various ways, occasionally favouring the spread of parasites. During the salinization parasites with endoparasitic lifecycles endured longer than many ectoparasites, the latter being constantly exposed to the salty water. But all parasites eventually suffered when the salinity tolerance of their free-swimming larvae was exceeded. Predation on zooplankton by introduced fish also temporarily impacted the free larvae of crustacean parasites, causing a decline. Alternatively, introduced fish that were prey to larger species could act to transmit parasites. All the parasites in the southern Large Aral Sea ultimately disappeared, either because their hosts were gone or because of an inability to endure high salinity. Many of the original fish species have now naturally repopulated the reconstituted Small Aral Sea, forming the basis of a renewed commercial fishery. As a result, some parts of the original parasite fauna have also reappeared together with some newly introduced species. The present study highlights the complex, sometimes unexpected, manner in which hosts and parasites can interact during a progressive ecological crisis. We emphasize that they must be an integral part of any sustainable ecological management of lakes and reservoirs. In the framework of revived fisheries and emerging aquaculture, we suggest a system for sound monitoring and control of fish parasites in the Aral Sea system.

Keywords: Aral Sea, Fish parasites, Invertebrate fauna, Fish fauna, Alien species , Salinity, Sustainable management

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BACKGROUND

Parasites are increasingly considered as an important element in natural systems. Penetrating studies have demonstrated how they can have surprisingly strong effects on the structure of ecosystems, sometimes even increasing biodiversity. This also entails that parasites must be considered when studying ecological changes, whether natural or human caused, and form an integral part of sustainable management of ecosystems (*e.g.*, Lafferty et al. 2008; Kuris et al. 2008). In fish ecology parasites are highly important (*e.g.*, Lafferty 2008, Kennedy 2009), although unfortunately often ignored (Timi and Poulin 2020). Poulin (2007) even stated that "*the time has come to transform fish parasite ecology from a mostly descriptive discipline into a predictive science, capable of integrating complex ecological data to generate forecasts about the future state of host-parasite systems.*" Here we focus on fish and fish parasites from the Aral Sea during its recent crisis, hoping that the sequence of events described may come to use in such future predictive models.

The virtual desiccation of the Aral Sea is arguably the worst human cause environmental disaster on a local scale and had multiple disastrous effects on the entire area, both in the aquatic system and the surrounding areas. The Aral Sea is a drainless saline lake in the desert zone of Central Asia in Kazakhstan and Uzbekistan, being the terminal reservoir of the Syr Darya and Amu Darya rivers. The history and hydrology of the Aral Sea system was previously reviewed (Boomer et al. 2009; Micklin et al. 2014; Burr et al. 2019; Bortnik and Christyaevaya 1990; Plotnikov et al.

2023). Until the early 1960s, when modern anthropogenic regression started, the state of the Aral Sea was quasi-stable. It was originally a brackish water lake with an average salinity of ~10 g L^{-1}, and conditions remained quite stable until the human caused slow motion catastrophe commenced in the early 1960s (Ahn et al. 2024; Plotnikov et al. 2023; Jabbarov et al. 2024). The Aral Sea consisted of two main parts: the smaller northern part, the Small Aral, received the waters from the Syr Darya flows; the southern part, the Large Aral, received waters from the Amu Darya. These two parts were connected by the narrow and shallow Auzy-Kokaral and Berg straits.

Since 1961 the water level began decreasing and the salinity increased steadily (Bortnik and Chistyaeva 1990), a result of decrease in river inflows attributable to an irrevocable withdrawal of water, primarily for irrigation. The increasing salinity resulted in a drastic decrease in the diversity of all fauna elements, including parasites.

By 1988–1989, the salinity reached 30 g L^{-1}. Due to the decreased water level, both the connecting straits dried up, whereby the Aral Sea was transformed into two residual water bodies with different fates. At the present time, the desiccation and salinization of the Large Aral continues, and it is now reduced to a number of hyperhaline remnants with all ichthyofauna and most invertebrates being lost. The construction of the Kokaral Dam across the former Berg Strait, stabilized the Small Aral and its salinity began decreasing. It is now a stable brackish reservoir. Many of the invertebrate and freshwater fish species that disappeared during the regression crisis have now returned, also including some of their parasites (Plotnikov et al. 2023).

The first studies on fish parasites in the Aral Sea were incidental, with only three species being recorded at the start of the 20th century (Berg 1908). The first comprehensive survey of fish parasites was carried out in 1930 from an expedition led by V.A. Dogiel (Dogiel and Bychowsky 1934). Parasitological studies were renewed in 1951 by S.O. Osmanov, continuing up to 1980, with these studies clarifying the general parasitological situation. The number of parasite species recorded in the Aral fauna reached 213, with attention paid to their biology and life cycles (Osmanov 1971; Osmanov et al. 1976; Osmanov and Yusupov 1985). These studies included trematode parasites of mollusks and their role when transmitted to fish and fish-eating birds (Arystanov 1969 1980; Osmanov et al. 1976). Such research has recently been resumed in the Small Aral, with parasites of some commercially important fish being investigated (Dəuitbaeva and Satybaldieva 2012; Abdybekova et al. 2022).

In this study, we review the parasite fauna of both fish and free-living invertebrates in the Aral Sea, based on previous studies as well as new data records. We elucidate the fauna of fish parasites, their zoogeographical origins and original distribution in the undisturbed Aral Sea, as well as their general biology and hosts. The complex changes to the parasite fauna are investigated, including the effects on their host animals, direct effects on the parasites themselves or more complex interactions involving the entire food web and ecosystem. Finally, we discuss management issues of the fish parasite fauna in the now partially restored Small Aral Sea, with special attention to the potentially emerging aquaculture plants.

Fauna of fish and free-living invertebrates

Zoogeographically, the Aral Sea belongs to the Aral region of the Ponto-Aral-Caspian Province of the Mediterranean subregion of the Holarctic region. It is in direct contact with the Turkestan Province containing the Amu Darya and Syr Darya districts. These two rivers originate in the mountainous Upland-Asian subregion (Shulman 1958; Osmanov 1971).

Fish fauna

Fish are not only the final hosts of parasites but also are intermediate hosts for parasites of fish-eating animals such as predatory fish, birds, amphibians and mammals. The ichthyofauna of the Aral Sea (Tables 1, 2) consists of both native species and some species introduced by humans in the 1930s and 1950s (Karpevich 1975). The native ichthyofauna consisted of 20 species, 12 of them being cyprinids. The introduced fauna element comprised 15 fish species, originating from the Caspian Sea, Baltic Sea and Amur basin (Fig. 1). The majority of fish species, both native and introduced, are of freshwater origin, therefore having migrated for spawning to the relatively low salinity coastal zones or into the rivers (Nikolsky 1940). Exceptions were the stickleback, species from the Amur basin and truly marine species, including gobies, atherines, herring and flounder (Ermakhanov et al. 2013).

Table 1. Comparison of helminth parasite species infesting cyprinid fishes of the Aral and Caspian Seas (based on Osmanov 1971; Semenova et al. 2007)

	Aral Sea		Caspian Sea	
Fish	Total	By taxa	Total	By taxa
Bream	63	Cestoda – 8	166	Cestoda – 13
		Monogenea – 6		Monogenea – 18
		Trematoda – 13		Trematoda – 48
		Nematoda – 12		Nematoda – 20
Roach	54	Cestoda – 5	187	Cestoda – 6
		Monogenea – 7		Monogenea – 18
		Trematoda – 11		Trematoda – 55
		Nematoda – 12		Nematoda – 23
Asp	60	Cestoda – 9	109	Cestoda – 7
		Monogenea – 3		Monogenea – 3
		Trematoda – 11		Trematoda – 33
		Nematoda – 16		Nematoda – 18
Carp	38	Cestoda – 8	168	Cestoda – 11

		Monogenea – 14 Trematoda – 15 Nematoda – 10		Monogenea – 31 Trematoda – 38 Nematoda – 20
Shemaya	28	Cestoda – 6 Monogenea – 3 Trematoda – 8 Nematoda – 8	74	Cestoda – 3 Monogenea – 8 Trematoda – 22 Nematoda – 17
Sabrefish	24	Cestoda 3 Monogenea – 3 Trematoda – 9 Nematoda – 3	92	Cestoda – 5 Monogenea – 4 Trematoda – 34 Nematoda – 11
Crucian carp	24	Cestoda – 3 Monogenea – 3 Trematoda – 9 Nematoda – 3	78	Cestoda – 4 Monogenea – 12 Trematoda – 24 Nematoda – 3

Table 2. Common and scientific names of fishes mentioned in this contribution

Ship sturgeon	*Acipenser nudiventris* Lovetsky
Stellate sturgeon	*Acipenser stellatus* Pallas
Aral trout, Aral salmon	*Salmo trutta aralensis* Berg
Baltic herring	*Clupea harengus membras* (Linnaeus)
Golden grey mullet	*Chelon auratus* (Risso)
Leaping mullet	*Chelon saliens* (Risso)
Pike	*Esox lucius* Linnaeus
Roach	*Rutilus rutilus aralensis* Berg
Ide	*Leuciscus idus* (Linnaeus)
Asp	*Leuciscus aspius* (Linnaeus)
Grass carp	*Ctenopharyngodon idella* (Valenciennes)
Silver carp	*Hypophtalmichthys molitrix* (Valenciennes)
Spotted silver carp	*Hypophtalmichthys nobilis* (Richardson)
Black carp	*Mylopharyngodon piceus* (Richardson)
Turkestan barbel	*Luciobarbus capito* (Güldenstädt)
Aral barbel	*Luciobarbus brachycephalus* (Kessler)
Bream	*Abramis brama* (Linnaeus)
White-eye bream	*Ballerus sapa* (Pallas)
Shemaya	*Alburnus chalcoides* (Güldenstädt)
Sabrefish	*Pelecus cultratus* (Linnaeus)
Crucian carp	*Carassius gibelio* (Bloch)
Carp	*Cyprinus carpio* Linnaeus
Wels, catfish	*Silurus glanis* Linnaeus
Stickleback	*Pungitius platygaster* (Kessler)
Zander, pike perch	*Stizostedion lucioperca* (Linnaeus)
Perch	*Perca fluviatilis* Linnaeus
Atherine, silverside	*Atherina boyeri* Risso
Bubyr goby	*Knipowitschia caucasica* (Berg)
Sand goby	*Neogobius pallasi* (Berg)
Round goby	*Neogobius melanostomus* (Pallas)
Syrman goby	*Ponticola syrman* (Nordmann)
Bighead goby	*Ponticola gorlap* (Iljin)
Tubenose goby	*Proterorchinus marmoratus* (Pallas)
Snakehead	*Channa argus* (Cantor)
Black Sea flounder	*Platichthys flesus* (Linnaeus)

Fig. 1. Central Asia. The Aral Sea lies isolated and originally contained a depleted fish fauna (20 spp.) compared to the Caspian Sea (110+ spp.); all native fish had a freshwater origin; the figure illustrates the extension of the Aral Sea before the regression crisis; the inset its extension at the height of the crisis. All fish have now perished in the virtually desiccated Large Aral Sea; bream, plaice, roach and zander are now commercially important catches in the reconstituted Small Aral Sea.

Most of the Aral Sea native fish were benthic feeders, although predatory ones comprised pike, zander, wells, asp, and Aral salmon. There were no obligate planktotrophes among the native fish, the main consumers of zooplankton generally being omnivorous species such as stickleback, shemaya, sabrefish, fry and juveniles of benthivorous and predatory fish. The introduced species represented a variety of feeding modes. The stellate sturgeon, the black carp and the flounder are benthic feeders. The grass carp feed on aquatic vegetation, while the silver carp feed on phytoplankton. The spotted silver carp feeds on zooplankton, phytoplankton and detritus. Gobies and atherines are polyphagous, consuming both zooplankton and zoobenthos. The Baltic herring is a true planktophage and, similar to atherines, can also eat small fish. The only introduced predator is the snakehead (Karpevich 1975; Mitrofanov et al. 1986 1987 1988 1989).

Free-living invertebrates

The invertebrate fauna exhibits a variety of origins, with the majority being freshwater, although also comprising brackish-water species of freshwater origin, Caspian species and inhabitants of saline and some hypersaline, continental water bodies (Plotnikov et al. 2023). Many of these invertebrates are intermediate hosts in the life cycles of parasites with vertebrates as final hosts. Mollusks are the first intermediate hosts of trematodes. Amphipods, polychaetes and insect larvae participate in the life cycles of nematodes, while cestodes have copepods and oligochaetes as their first intermediate hosts

Fish parasites in the Aral Sea

General characteristics of Aral Sea parasites

The majority of the Aral Sea parasites were Palearctic (32.7%), Ponto-Aral-Caspian (or Mediterranean) (22.1%), or of unclear provenance (29.6%). The remainder of the species were Turkestanic (5.8%), Sino-Indian (2.2%) and marine (0.4%). A significant number (7.1%) were parasites that were introduced together with non-native fish from other basins (Osmanov 1971). Compared to other regions of the Ponto-Aral-Caspian province, the Aral region contained fewer parasite species with this origin (Shulman 1958). The Aral Sea contained neither endemic fish species nor endemics parasites.

The fauna of Aral Sea fish parasites can be seen as a depleted component of the Caspian region parasites (Table 1), with the addition of some Central Asian elements. Parasites from the Black Sea region are absent (Dogiel and Bychowsky 1939; Shulman 1958; Osmanov 1959 1971). Despite the favorable conditions, the native parasitic fauna lacked many northern species present in the Caspian Sea, particularly the crustaceans *Thersitina gasterostei* (Pagenstecher) and *Achtheres percarum* Nordmann. The few parasites of marine origin found in the Caspian Sea were also lacking, except for the trematode *Bunocotyle cingulata* Odhner (Dogiel and Bykhovsky 1934; Osmanov 1971).

The modern ichthyofauna of the Aral Sea consists of limnophilic inhabitants of the ancient Amu Darya and Syr Darya, and the accompanying lakes in their valleys, explaining why most of the fish parasites also have such a lacustrine-riverine origin (Osmanov 1967 1971; Osmanov et al. 1976). This freshwater origin results in an uneven distribution of parasites in the Aral Sea, with most being found in areas affected by river inflows. The main area of the sea with higher salinity contained less than one third of the total species, without any species exclusive to this particular area (Osmanov 1971; Osmanov et al. 1976).

Although exhibiting a freshwater origin, the fish parasites of the Aral Sea react differently to increased salinity in regard to being able to infest and develop in hosts. Osmanov (1975a) divided the native fish parasites of the Aral Sea into three groups, as follows:

Purely freshwater, rheophilic species (~8%): Fish hosts become infested exclusively in rivers during their migrations for breeding. Examples are the myxosporidium *Myxobolus lobatus* (Nemeczeck), the ciliate *Balantidium barbi* (Dogiel et Bychowsky), the monogenean *Dactylogyrus skrjabinensis* Gusev, the nematodes *Rhabdochona gnedini* Skrjabin and *Spirocamallanus siluri* (Osmanov) and the leech *Limnotrachelobdella turkestanica* (Stschegolew) (Osmanov 1975a).

Freshwater limnophilic species (~30%): The major reduction in freshwater areas has decreased distribution of these parasites because they only infest their fish hosts in freshwater-affected areas of the Aral Sea (Osmanov 1975a; Osmanov et al. 1976). This is particularly true for ectoparasites such as the monogenean *Dactylogyrus vastator* Nybelin, and the copepod crustaceans *Lernaea cyprinacea* Linnaeus, *Lernaeocera esocina* (Hermann) and *Lamproglena pulchella* Nordmann, all of which are negatively influenced by salinity even after infestation of the host, thereby explaining their confinement in the freshwater zone. Endoparasites within this group are protected from salinity levels once inside a host, therefore also being found in high salinity areas of the Aral Sea. Examples include the microsporidian *Glugea dogieli* Gasimagomedov et Issi and the trematodes *Posthodiplostomum cuticola* (Nordmann), *Hysteromorpha triloba* (Rudolphi) and *Bolbophorus confusus* (Krause).

Limnophilic species in the Aral Sea conditions: These parasites infest in both fresh and sea water but react differently to increased water salinity. Many monogenean and some crustacean parasites were found both in the freshwater zone and at salinities ranging up to 12 g L^{-1}. They include *Dactylogyrus wunderi* Bychowsky, *D. affinis* Bychowsky, *D. linstowi* Bychowsky, *D. kulwieci* Bychowsky, *D. crucifer* Wagener, *D. chalcalburni* Dogiel et Bykhovskii, *Ancyrocephalus paradoxus* Creplin, *Diplozoon paradoxum* Nordmann, *Paradiplozoon pavlovskii* (Bychowsky et Nagibina), *P. homoion* (Bychowsky et Nagibina), *Ergasilus sieboldi* Nordmann, *Caligus lacustris* Steenstrup et Lütken and *Argulus foliaceus* (Linnaeus). Other species within this group can only tolerate salinity up to 10 g L^{-1}. This is probably true for the ciliates *Ichthyophthirius multifiliis* Fouquet and *Trichodina luciopercae* Lom and the monogeneans *Dactylogyrus falcatus* (Wedl), *Thaparocleidus siluri* (Zandt), *Th. vistulensis* (Sivak) and *Paradiplozoon sapae* (Reichenbach-Klinke), noting that, as the salinity increased, the habitats of this group of parasites decreased in size (Osmanov 1975a; Osmanov *et al.* 1976). Among the native fauna, no parasites were confined only to "marine" areas (Dogiel and Bychowsky 1934; Osmanov 1959, 1975a), dovetailing a lake-river origin of both ichthyofauna and their parasites (Nikolsky 1940; Osmanov 1967 1975a).

The Baltic, Caspian and Aral Seas exhibit pronounced salinity gradients. Ranging from practically fresh water at rivers mouths to significantly brackish water away from the rivers. In the Baltic Sea, marine and freshwater components of the parasite community can be clearly distinguished. In the brackish waters off the coast of Germany, 43% of all species of fish parasites were trematodes, but only represented 17% in the much less saline Gulf of Bothnia. On the other hand, cestodes of predominantly freshwater origin comprised 33% in the Gulf of Bothnia, while only 18% on the German coast (Zander et al. 1999; Valtonen et al. 2001). The decreasing numbers of fish parasite species as the waters become fresher primarily affect marine species of trematodes due to the loss of suitable intermediate hosts. The situation is rather the opposite in the Aral Sea, noting that with the fish fauna being predominantly freshwater, the greatest diversity of parasites occurs in less saline areas.

Parasites in the Aral and Caspian seas

The Aral Sea contains only 20 fish species, two thirds being cyprinids, compared to 110+ species from 15 families in the Caspian Sea (Fig. 1). When the Aral Sea was still undisturbed, nearly simultaneous studies found 70 fish parasite species were found in the Aral Sea (1930), compared to 174 parasite species in the Caspian Sea (1931–1932) (Dogiel and Bychowsky 1934, 1939). This difference is primarily due to the much richer Caspian ichthyofauna (Bogutskaya and Naseka, 2013). The pronounced ichthyofauna difference indicates a direct comparison of parasite diversity in the two water bodies would be incorrect. It is more informative to compare the parasite fauna of individual fish species. Carp are the most species-rich group in the Aral Sea (Table 1). Comparing the parasites on some of these with the situation in the Caspian Sea shows a marked depletion in the Aral Sea numbers. This depletion primarily concerns trematodes and monogeneans, the difference being less for cestodes. Dogiel and Bykhovsky (1934, 1939) suggested this situation was due to a decrease in parasite fauna close to the boundaries of the host ranges.

Ship sturgeon is the only native sturgeon in the Aral Sea. When comparing its parasites load with those present on it in the Caspian none of the following were noted (Dogiel and Bychowsky 1934, 1939; Semenova et al. 2007): the protozoans *Cryptobia acipenseris* (Joff, Lewaschow, Boschenko), *Hexamita truttae* (Schmidt), *Haemogregarina acipenseris* (Nawrotzky), *Pleistophora sulci* (Rasin); the cnidarian *Polypodium hydriforme* Ussow; the nematodes *Capillospirura ovotrichuria* Skrjabin, *Cucullanus sphaerocephalus* (Rudolphi), *Cyclozone acipenserina* Dogiel, *Hysterothylacium bidentatum* (Linstow), *Cystoopsis acipenseris* Wagner; the monogeneans

Diclybothrium armatum Leuckart, *Nitzschia sturionis* (Abildgaard); the trematodes *Skrjabinopsolus semiarmatus* (Molin); the cestodes *Amphilina foliacea* (Rudolphi), *Bothrimonus fallax* Lühe, *Eubothrium acipenserinum* (Cholodkovsky).

Parasites and the history of the Aral Sea

The depleted fauna of fish parasites is related to a similarly low species number of both fish and invertebrates, compared to other large basins in the Ponto-Aral-Caspian zoogeographic province, with this difference possibly having several causes. First, the young age of the Aral Sea, barely exceeding 17 thousand years (Burr et al. 2019), has left insufficient time to evolve any endemic parasite species. In contrast, the Caspian Sea lost contact with the world ocean several million years ago and now contains numerous endemic parasites (Bogutskaya and Naseka 2013). Second, the Aral Sea has exhibited several salinity changes that far exceed those experienced by the Caspian Sea. These salinity changes were caused by water level regressions and transgressions, including a drop below +40 m, accompanied by the division of a single water body into two or more reservoirs with different salinity conditions. Over the past two thousand years, there have been two large regressions during the 1st–5th Century, followed by transgressions. The last and most extensive regression occurred in the 20th and 21st centuries and was entirely human caused (Sorrel et al. 2007). Salinity increases negatively affected the numbers of both fish species and their parasites. Changes in ectoparasites fauna began even before the complete extinction of their hosts in the sea. During sea level transgressions, fish species returned from the inflowing river systems as is now happening in the Small Aral, and this explains the freshwater nature of the fish parasites in the Aral Sea.

Introduced parasites in the Aral Sea

In the 20th Century, 15 non-native fish species were introduced by humans, carrying new parasites to the Aral Sea, resulting in a 10% increase in parasite diversity compared to the situation before the regression crisis (Table 3). During 1927–1934, an unsuccessful attempt to acclimatize stellate sturgeon from the Caspian Sea (Karpevich 1975) entailed the introduction of two new sturgeon specific parasites that soon switched to the native ship sturgeon (Dogiel and Bychowsky 1934; Dogiel and Lutta 1937; Dogiel 1939; Osmanov 1959 1967 1971). They were the monogenean gill parasite *Nitzschia sturionis* (Abildgaard) and the aberrant oocyte infesting coelenterate *Polypodium hydriforme* Ussow, (Osmanov 1959 1967 1971; Trusov 1947; Raikova 2002). An additional sturgeon specific parasite, the nematode *Cystoopsis acipenseris* Wagner, was discovered during 1954–1956 (Osmanov 1958 1971) after a renewed attempt to introduce stellate sturgeon after 1948.

Table 3. Parasites that appeared in the Aral Sea with introduced fishes (Osmanov et al. 1976)

Taxa	Stellate sturgeon	Round goby	Bighead goby	Sand goby	Syrman goby	Bubyr goby	Black carp	Grass carp	Silver carp	Spotted silver carp
MICROSPORIDIA										
Glugea shulmani Gasimagomedov et Issi		+								
Nosema sp.		+								
MYXOZOA										
Chloromyxum cyprini Fujita								+	+	+
CILIOPHORA										
Trichodina domerguei domerguei (Wallengren)		+	+		+					
Trichodina jadranica (Raabe)		+		+						
Balantidium ctenopharyngodonis Chen								+		
CNIDARIA										
Polypodium hydriforme Ussow	+									
NEMATODA										
Cystoopsis acipenseris Wagner	+									
MONOGENEA										
Gyrodactylus bubyri Osmanov						+				
Nitzschia sturionis (Abildgaard)	+									
Dactylogyrus aristichthys Long et Yu										+
Dactylogyrus ctenopharyngodonis Achmerow								+		
Dactylogyrus hypophthalmichthys Akhmerov									+	
Dactylogyrus lamellatus Akhmerow								+		
Dactylogyrus magnihamatus Akhmerov								+		
Dactylogyrus nobilis Long & Yu										+
Dactylogyrus skrjabini Akhmerov									+	
Dactylogyrus suchengtaii Gusev									+	
Dactylogyrus wuhuensis Lee									+	
Sindiplozoon strelkowi (Nagibina, 1965)								+		
CESTODA										
Bothriocephalus opsariichthydis Yamaguti								+	+	+
COPEPODA										
Paraergasilus longidigitus Yin, 1954								+	+	+

The Baltic herring *Clupea harengus membras* was introduced during 1954–1959 from the Baltic Sea, causing a serious environmental disturbance by critically depleting the zooplankton. Luckily, the species were imported as fertilized eggs, preventing the introduction of any Baltic Sea parasites (Bykov 1964).

During the unsuccessful introduction of mullets from the Caspian, six new parasites appeared, including *Glugea schulmani* Gasimagomedov et Issi and *Nosema* sp., the ectoparasites *Trichodina domerguei* Wellengren, *T. jadranica* (Raabe) and those specific to bubyr goby *Gyrodactylus bubyri* Osmanov (Karpevich 1975; Osmanov 1967 1971; Osmanov et al. 1976; Yusupov and Urazbaev 1980).

During the first half of the 1970s, the nematode *Dichelyne minutus* (Rudolphi) (Osmanov, 1975b) was found in Aral Sea gobies. This nematode is widespread in the Atlantic including the

Mediterranean, Black, Baltic and White Seas, and also occurring in the Caspian Sea. This parasite infests a broad range of host species, also being common in the flounder *Pleuronectes flesus* Linnaeus (Janiszewska 1939; Osmanov 1940; Shulman and Shulman-Albova 1953). Its first intermediate host is the polychaete *Hediste diversicolor* (Müller) (Osmanov 1975a; Ivashkin and Khromova 1975), with its larvae being found in these hosts in the Black Sea (Pronkina et al. 2017). Experimental studies with materials from the Black and Baltic Seas indicated the larvae cannot infest crustaceans as a possible first intermediate hosts, nor can they directly infest fish (Køie 2001; Pronkina et al. 2017). It is suggested *D. minutus* was not introduced together with gobies, but only later along with the already-infested *H. diversicolor* introduced during 1960–1961 from the Sea of Azov in order to provide a new food source for Aral Sea fishes (Karpevich 1975). *H. diversicolor* was not introduced to the Caspian Sea until 1939–1941 (Karpevich 1975) and, in line with this *D. minutus*, was not present in the 1931–1932 survey of this basin (Dogiel and Bychowsky 1939).

Most of the parasites characteristic of atherines in the Caspian Sea did not follow them into the Aral Sea (e.g., the monogenean *Gyrodactylus atherinae* Bychowsky, the trematode *Ascocotyle calcostoma* (Looss), and the copepod *Thersitina gasterostei* (Pagenstecher)). When introduced and acclimatized to the Aral Sea, fishes from the Far Eastern Amur region (grass carp, silver carp and snakeheads) also lost most of the parasites found in their home range. Black carp and snakeheads, both imported in small numbers and now very rare in the Aral Sea, have lost all their home range parasites. In contrast, Far Eastern cyprinids retained their specific ectoparasites – the monogeneans *Dactylogyrus* spp., *Gyrodactylus* spp. and *Sindiplozoon strelkowi* (Nagibina) and the copepod *Paraergasilus longidigitus* Yin. For carp endoparasites, only the myxosporidium *Chloromyxum cyprini* Fujita, the cestode *Bothriocephalus opsariichthydis* Yamaguti and the grass carp specific ciliate *Balantidium ctenopharyngodonis* Chen were carried into the Aral Sea. Both *Ch. cyprini* and *B. opsariichthydis* later spread both to local cyprinids and to fish from other families.

Patterns in parasite introductions

The composition of the parasite fauna on fish introduced into the Aral Sea corresponds to previously established patterns (Petrushevsky 1958; Osmanov et al. 1976). Their parasite fauna became poorer in the Aral Sea than that they exhibited in their native water bodies. When entering the Aral Sea they lost many, and in some cases all, of the native parasite species. They mainly retained monogeneans, such as *Gyrodactylus*, *Dactylogyrus*, and *Diplozoon*. In turn, some local, more generalist parasite species absent in their native water bodies were passed to the introduced fish.

Of the parasites carried to the Aral Sea by alien fish, 85% had direct development, with 55% being monogeneans such as *Gyrodactylus*, *Dactylogyrus*, and *Diplozoon*. Such species are highly resistant during transportation, and their single-host life cycle facilitated their introduction.

The disturbance to Aral Sea food webs attributable to alien fish had some rather complex effects on the parasite fauna. Planktonic copepods are an intermediate hosts of many cestodes and parasitic nematodes. Introduction of zooplankton-consuming fish (*e.g.*, herring, atherines, gobies) resulted in a dramatic decrease in the copepod zooplankton which, in turn, was followed by a decrease in the cestode and nematode fish parasites, apparently because of a critical scarcity of intermediate hosts. The alien gobies and silversides became permanently established in the Aral Sea, consuming large quantities of crustacean zooplankton, but were not much preyed upon by fish eating birds. This resulted in a dead end in the life of some cestodes, because they were never transferred to their final bird host. The forage on zooplankton also affected nauplii and copepodites of parasitic crustaceans, particularly *Ergasilus sieboldi*, leading to decreased infestation levels of their hosts (Osmanov et al. 1976; Osmanov and Yusupov 1985). In contrast, the increasing quantities of gobies and atherines rendered them a new food item for predatory fish such as catfish, asp and perch. Since prey fish are intermediate hosts of the nematodes *Contracoecum rudolphii* and *C. microcephalum*, they now became a more effective link from the first intermediate host, copepods, than were the juveniles of the native cyprinid fish. Therefore, despite the decline in planktonic copepods, gobies and atherine ensured the maintenance of a high level of infection of predatory fish by said nematodes.

Threats to native fish

Most introduced parasites (75%) are host specific, being found only on the fish with which they entered the Aral Sea (i.e., their primary hosts), but some also spread to native fish species, thus causing potential disturbance to the ecosystem. The cestode *Bothriocephalus opsariichthydis* and the nematode *Dichelyne minutus* both migrated to various native fish. The monogenean *Nitzschia sturionis*, the nematode *Cystoopsis acipenseris* and the cnidarian *Polypodium hydriforme* (Osmanov et al. 1976) all spread to the ship sturgeon, which is a very important native species. *P. hydriforme* infests oocytes, resulting in decreased host fertility. *C. acipenseris* releases eggs into the water from its cysts by rupturing through the body wall, leaving deep wounds. These wounds provide access for pathogenic bacteria and fungi. The last three parasites are strictly specific to sturgeon fish. Therefore, the spread of these parasites to non-sturgeon native fish is impossible. The cestodes *Bothriocephalus opsariichthydis* and *Khawia sinensis* were introduced with cyprinid fish from the Far East. Both are are intestinal parasites, and at high infestation intensity they cause intestinal obstruction and inflammation. It is known that they pose a danger to fish kept in ponds, but there is as yet no data on the extent of harm they cause to their hosts in the Aral Sea itself. As yet, introduced parasites may not have caused serious disturbance to the native fish fauna, but it is clear that this is an issue that needs to be kept under very close surveillance.

Changes to fish parasites during the salinization

Changes in the hydrological regime of the Aral Sea had serious effects on the ecosystem, resulting both in a decrease in the infestation of fishes, and eventually the complete disappearance of parasite species in the southern Large Aral Sea. The situation in the now partially reconstituted Small Aral Sea is discussed separately below. During the regression crisis, host-parasite interactions were complex, mostly causing decreased infestation levels, but occasionally also leading to a temporary increase. The main reason for the changes was the salinization, which negatively affected both the intermediate and final parasite hosts, thereby impeding their life cycles. Salinization also directly affected the parasites because most had a freshwater origin, principally concerning free-swimming larval stages of the parasites. For ectoparasite such as monogenean trematodes, it included their exposed adult stages. More complex and unexpected was predation on the larval stages of crustacean parasites by introduced fish, a side effect of the much larger effects on free-living zooplankton. A population surge in small-size introduced fish occasionally resulted in increased infection levels because being prey for larger fish, they acted as paratenic hosts (for definition, see: Anderson 1988). As for the Aral Sea itself, the parasite fauna in the lower reaches of the Amy Darya delta also declined during the crisis, possibly of benefit to fish farms (Allamuratova et al. 2021). A decline in fish parasites also occurred in the South Priaralie natural park, located in the southern Aral Sea region in the Republic of Karakalpakstan, Turkestan. This is of concern if the goal is to retain the original fauna in the area to the maximum degree (Kurbanonaand Kurbanov 2021). Finally, effects on parasites in the Aral Sea were not confined only to aquatic issues. For species for which fish-eating birds are the final host, the shore conditions became an issue. The salinization also caused serious changes to the wetlands and shore vegetation around the Aral Sea used by water birds for resting and breeding (Micklin et al. 2014; Plotnikov et al. 2023). The changes by parasite taxon are reviewed in appendix 1.

Fish parasites in the modern Small Aral sea

The Small Aral Sea has again become a brackish water body. Many invertebrates and freshwater fish species that previously disappeared because of increased salinity have now returned to this partially reconstituted basin. Commercial fisheries have also rebounded, benefiting the local population (Plotnikov et al. 2023). And not unexpected, the fauna of fish parasites has also partially recovered (Table 4). Parasite diversity is now dominated by trematodes that use fish as second intermediate hosts, including *Diplostomum helveticum*, *D. gobiorum*, *D. mergi*, *D. spathaceum*, *D. volvens*, *Tylodelphys clavata*, and *Ichthyocotylurus variegatus*. Their intermediate hosts, as well as those of the widespread nematode *Contracaecum microcephalum*, are freshwater mollusks and insect larvae. Since they do not inhabit most of the sea, infection likely occurs either in the freshwater part of the sea, or during migration to the Syr Darya during the breeding season. The low trematode diversity in the modern reservoir indicates the present parasite fauna is derived from outside its borders and being even now more freshwater in nature than before the regression crisis.

A 2010 survey in the Small Aral concerned only monogeneans. In six commercially caught fish species, including roach, bream, carp, asp, zander and flounder (Dəuitbaeva and Satybaldieva 2012), a total of 13 monogenean species were found, although none in flounder. *Dactylogyrus minutus* Kulwiec was found in carp but had previously been observed only in fish farm ponds, reservoirs and in the Syr Darya River (Osmanov 1971).

Table 4. Parasites of fish in the modern Small Aral Sea (by: Dəuitbaeva and Satybaldieva 2012; Abdybekova et al. 2022)

Taxon	Roach	Carp	Bream	Asp	Sabrefish	Shemaya	Crucian carp	Zander	Pike	Snakehead
Nematoda										
Capillaria brevispicula (Linstow)			+							
Piscicapillaria tuberculata (Linstow)	+				+					
Camallanus lacustris (Zoega)					+					
Contracaecum microcephalum (Rudolphi)	+		+	+				+		
Nematoda larvae	+		+	+				+		
Trematoda										
Diplostomum gobiorum Shigin	+							+	+	
D. helveticum (Dubois)	+		+					+	+	
D. mergi Dubois									+	
D. spathaceum (Rudolphi)	+		+		+		+	+	+	+
D. volvens Nordmann	+		+		+				+	
Tylodelphys clavata (Nordmann)	+		+		+			+	+	
Ichthyocotylurus variegatus (Creplin)	+									
Monogenea										
Dactylogyrus auriculatus (Nordmann)			+							
D. crucifer Wagener	+									
D. extensus Müller et Van Cleave		+								
D. falcatus (Wedl)			+							
D. minutus Kulwiec		+								
D. pavlovskiy Bychowsky				+						
D. rarissimus Gusev	+									
D. simplicimalleatus Bychowsky					+					
D. sphyrna Linstow	+									
D. tuba Linstow				+						
D. wunderi Bychowsky			+							
D. zandti Bychowsky			+							
Gyrodactylus cernuae Malmberg								+		

G. elegans Nordmann			+					
G. gasterostei Gläser	+							
G. medius Kathariner		+						
Gyrodactylus sp.	+				+			+
Diplozoon paradoxum Nordmann	+		+		+	+		
Diplozoon sp.								+
Paradiplozoon pavlovskii (Bychowsky et Nagibina)	+			+				+
P. rutili (Gläser)	+							+
P. vojteki (Pejčoch)					+			
Paradiplozoon sp.			+		+			
Ancyrocephalus paradoxus Creplin								+
Cestoda								
Khawia sinensis Hsü			+		+			
Crustacea								
Ergasilus sieboldi Nordmann	+		+	+	+			+
E. briani Markevich	+		+		+	+		
Sinergasilus major (Markevich)	+		+			+		
Argulus japonicus Thiele	+							
Lernaea sp.			+					

A larger-scale survey in 2020–2021 (Abdybekova et al. 2022) included monogeneans, nematodes, trematodes, cestodes and parasitic crustaceans in zander, asp, carp, bream, sabrefish, roach, shemaya, crucian carp, pike, white-eye and snakehead. Only 32 of the parasites found were identified to species level. Among these and previously unknown for the Aral Sea were the following: metacercariae of *Diplostomum volvens* Nordmann in bream, sabrefish, roach and pike; *D. gobiorum* Shigin in pike perch, roach and pike, a parasite usually common in gobies; the monogeneans *Dactylogyrus pavlovskiy* Bychowsky in asp; *Gyrodactylus gasterostei* Gläser in roach; *G. cernuae* Malmberg in pike perch; *Paradiplozoon rutili* (Gläser) in pike perch and roach; and *P. vojteki* (Pejčoch) in sabrefish; the cestode *Khawia sinensis* Hsü in bream and sabrefish; the crustaceans *Ergasilus briani* Markevich in bream, sabrefish, roach, shemaya and *Sinergasilus major* (Markevich) in bream, roach and shemaya. *K. sinensis* was previously brought to fish farms in the Aral Sea region from the Far East, along with carp. It spread from the farm ponds to the Syr Darya and subsequently to the Small Aral. *S. major* was introduced together with grass carp (Osmanov 1971) being recorded in the Amu Darya in the early 1970s (Osmanov et al. 1976). A new species found by Abdybekova et al. (2022) in Aral Sea was the nematode *Piscicapillaria tuberculata* (Linstow) in bream. Bream, roach, sabrefish, zander and pike, which now form the basis of the recovered fishery in the Small Aral, were most heavily infested by parasites. In contrast, no parasites were found in 51 carp specimens. The only parasites found in crucian carp and snakehead were metacercariae of *Diplostomum spathaceum* (Abdybekova et al. 2022).

Parasite caused disease and mortality in Aral Sea fishes

It is clear that parasites can severely affect fish, leading to such negative impacts as reduced health, reduced fertility or death (Fig. 2; Sinderman 1987). Parasites occasionally can even cause mass mortality in fish populations, with several such events having been observed in the Aral Sea. Such events will obviously impact on commercial fisheries. The increasing importance of aquaculture in the area also poses a problem. There are as yet no regular surveys of fish parasites in Kazakhstan, and lack of controls when fish are moved between sites will increase the risk of accidental spread of parasites both between plants and into the wild (Abdybekova et al. 2022). All of this creates a need for effective management of aquaculture and fish parasites and below will discuss this issue in detail.

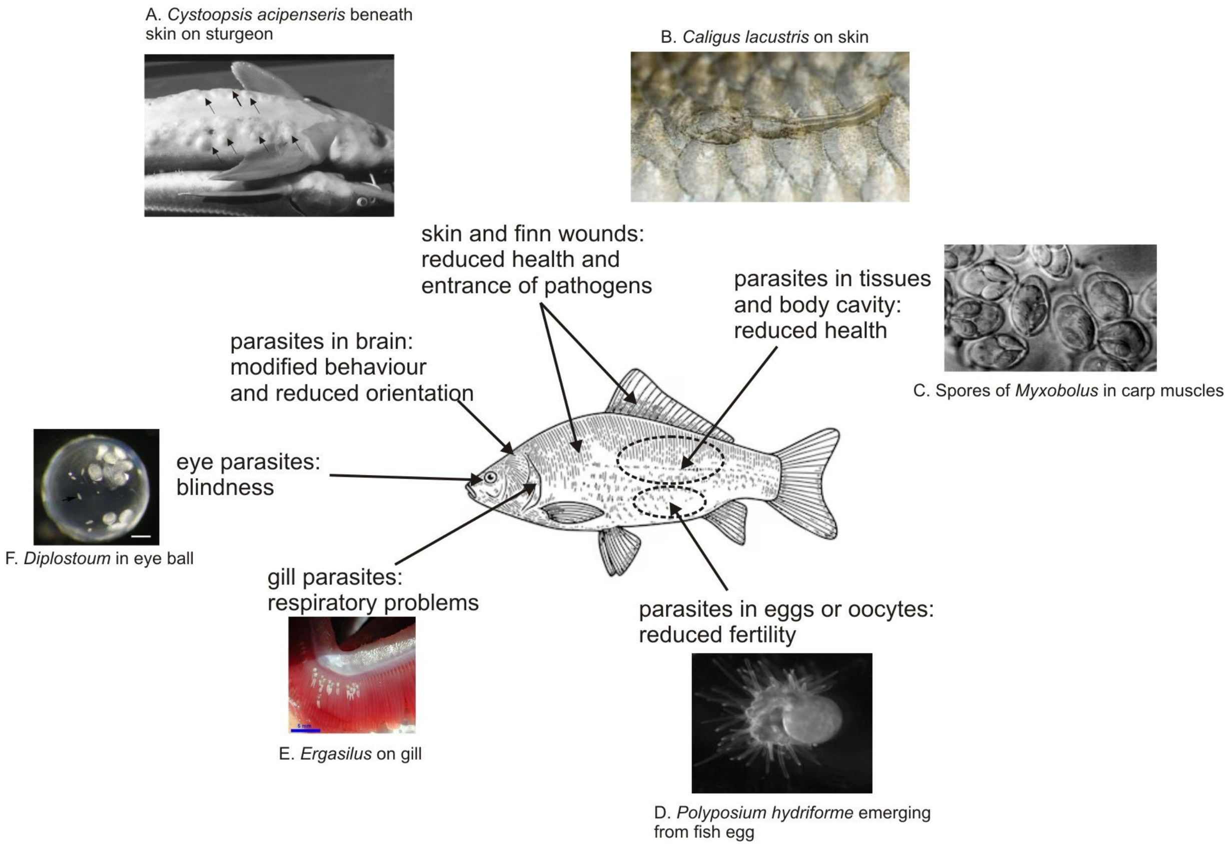

Fig. 2. Examples of parasites causing serious health effects on fish. Sources: A. Molnar et al. (2006); B: Shutterstock.com; C: Molnar et al. (2002); D: Chang (2013); E: Wikipedia.org; F: Scharsack and Kalbe (2014).

Parasites in Tissues and Body Cavities

The myxosporidium *Myxobolus musculi* Keysselitz infest muscles, mainly of barbels and most severely in juveniles. The larvae of the nematode *Contracaecum rudolphii* (Hartwich) infest the body cavity of various fish, feeding on tissues and juices. The infested fish are seriously weakened, becoming easy prey for fish-eating birds, the definitive hosts of this parasite. A very serious *C. rudoplhii* infestation of juvenile catfish occurred in 1955. Further, parasites infesting the brain represent a special case, potentially leading to "tumble disease" and subsequent death. Some digeneans can enter the brain and change behaviours, rendering the fish more prone to predation and, therefore, also favouring transmission to the next host, such as water birds. Although such cases were not observed in the Aral Sea, they have been noted in Californian salt march habitats, affecting a much richer fauna of water birds than if these parasites were absent (Shaw et al. 2009).

Infestation of Eggs

This can result in reduced fertility of the host. It occurs in the myxosporidium *Henneguya oviperda* (Cohn) infesting pike eggs (Dogiel and Bychowsky 1934; Osmanov 1971), and in the aberrant coelenterate *Polypodium hydriforme* infesting oocytes of sturgeons (Raikova 2002).

Damage to Gills

This can lead to respiratory and homeostasis problems. The monogenean *Nitzschia sturionis* is a blood feeding gill parasite that causes acute inflammation of the respiratory tissue, resulting in severe exhaustion and even death of the host. *N. sturionis* caused mass death of the ship sturgeon in 1936, attributable to infestation levels reaching 600–1000 parasites per fish (Trusov 1947). The crustacean *Ergasilus sieboldi* can destroy the gills, again causing respiration problems and emaciation of the fish host. In 1953, there occurred an infection by *E. sieboldi* causing mass disease and death occurred there in many species of commercially caught fish.

Eyes damage

Metacercariae of *Diplostomum* spp. trematodes infest the eyes of fish, causing lens clouding. At high infection levels this can lead to blindness, with the affected fish perishing when losing the ability to find food.

Skin wounds

These are particularly dangerous to fish because they act as direct pathways for entrance of pathogenic bacteria and fungi. The nematode *Cystoopsis acipenseris* Wagner, 1867 release eggs into the water from its cysts by rupturing through the body wall and leaving deep wounds. A similar situation is caused by the temporary parasitic leeches *Piscicola geometra* (Linnaeus) and *Limnotrachelobdella turkestanica* (Stschegolew). Their feeding on host blood leaves open wounds in the skin and, aggravating this situation, leeches are carriers of flagellates that parasitize on the blood of fish. The crustacean *Caligus lacustris* attacks the fins with ulcers forming at the attachment sites. This caused serious disease and death of carp and roach in 1953.

Multiple effects

The temporary ectoparasitic crustacean *Argulus foliaceus* attaches on the skin of the host, feeding on its blood. This leads not only to inflammation and hemorrhage at the attachment site, but *A. foliaceus* seemingly also produce secretions that slow or hinder blood clotting and cause irritation. Due to the large size of this parasite, juvenile fish are particularly vulnerable and there was a mass disease and death of one-year and two-year-old carp in 1953 (Osmanov 1964 1971).

Conclusions on Aral Sea fish parasites

In the original Aral Sea, the ichthyofauna, invertebrates and fish-infesting parasites exhibited a very low species diversity, due to the young age of the water body and its geographic isolation. All fauna components, including parasites, are absolutely dominated by species with a lacustrine-riverine origin. The low diversity of fish parasites is related to the low diversity of the available intermediate and final hosts, a situation very different from other large basins in the Ponto-Aral-Caspian zoogeographic province.

The Aral Sea has undergone very significant changes since the 1930s as a result of human activities in its drainage basin. Until the early 1960ts, these changes primarily concerned both the intentional and accidental introduction of fish species new to the Aral Sea, which also entailed the introduction of alien parasite species. Some fish parasites were from the Far East, being initially found only in fish farm ponds. However, over time they spread to the Aral Sea itself, a process that may still be ongoing.

The anthropogenic regression in the 1960s and the resulting salinization affected the entire fauna. The increased salinity directly affected parasites with direct development. In the case of endoparasites with several host changes, the number and distribution areas of parasites depended on the salinity tolerances of both the intermediate and final hosts, all being vital links in the parasite life cycle.

The areas of parasite distribution had generally shrunk, and infestation decreased by the end of the 1960s. There subsequently was a sharp depletion in parasite fauna during the 1970s attributable to a massive loss of most invertebrates that acted as intermediate hosts. A certain number still persisted in the few remaining areas containing relatively fresh water, but only a few of the original fish parasite species remained in the then seriously disturbed Aral Sea by the end of the 1970s.

The main trends in the dynamics of the Aral Sea ichthyoparasites consist of a progressive decrease in the distribution areas of many species due to the constant reduction of river flow and the resulting progressive salinization of the Aral Sea, followed by a decrease in the number of species, attributable primarily to a reduced numbers of their hosts (Osmanov et al. 1976). Freshwater fishes and freshwater free-living invertebrates completely disappeared in the 1980s, including all of their parasites. Due to a cessation of parasitological studies, however, what parasites may have remained on euryhaline fish that survived salinity is unknown.

Freshwater fish returned to the reconstituted Small Aral Sea from the refugia of the Syr Darya River and the lakes along its lower reaches in the 2000s. The fish parasite fauna, however, is still much depleted compared to the past, especially in regard to helminth and crustacean species (Abdybekova et al. 2022). Inadequate data in recent years renders the situation unclear for other parasitic taxa.

Fish parasite management in the Aral Sea system

Before the Aral Sea regression crisis climaxed, the parasite fauna of its ecosystem system consisted of native and accidentally introduced species, the latter mainly on introduced fish. As explained above, the native fauna was poor when compared to systems in the Caspian Sea, mainly due to the isolated geographic location and lack of interconnecting watersheds. During the crisis, several parasite species vanished, either due to disappearance of their host or due to direct effects from the critical increase in salinity. Following the crisis, the Aral Sea must be treated as two separate systems (Plotnikov et al. 2023). In the south, the increasing amount of Amu Darya waters diverted for irrigation purposes leaves only a small and irregular amount of freshwater to flow directly onto the salt flat area (now constituting the southern Aral Sea). As a direct consequence, by 1990 this water body was completely devoid of fish. The southern part now only consists of the affluent Amu Darya, with freshwater-dominated ecosystems and some brackish parts near the river mouth (Fig. 1). The northern system is much more complex and somewhat resembles the situation before the crisis. Here, the affluent Syr Darya terminates into the reconstituted Small Aral Sea, and thus the system comprises both the brackish waters of the Small Aral and the freshwater river with its smaller water bodies.

The Small Aral Sea system

The present fish parasite fauna is a mix of species present before the crisis that have re-entered the area as it began to restore in size, and species parasitizing on newly introduced / non-native fish species. The native fish and their parasites have a long history of co-evolution and had, assumedly reached largely stable co-existence before the crisis. These host / parasites systems are thus an integral part of the original system and must be included in any preservation plans for the area. Inevitably, there will be episodes of new parasites and parasitic diseases spreading from aquaculture into the native ecosystem, but proper management, containment and vigilance by the aquaculture industry is hopefully enough to prevent major damage to the native fish fauna.

Fisheries and aquaculture in the Small Aral System

There is now a revived and vibrant commercial fishery in the open waters of the Small Aral Sea (Plotnikov et al. 2023). Mostly conducted from small vessels, this fish trade yields an important financial and cultural benefit to the local population, which has traditionally relied on fish as their principal source of protein and income. An important fish species is the non-native (introduced) flounder, which now has a firmly established stock. Lacking the knowledge of fishing methods of this non-native species, the local fishermen established a rewarding cooperation with Danish fishermen from the Baltic Sea, where the flounder is abundant. This is an excellent example of a successful and sustainable introduction of a commercial species and of fruitful international cooperation (Plotnikov et al. 2023).

Currently several fish processing plants can be found in the Aralsk district of the Kyzylorda region (Kazakhstan). At the time of writing, there are no active aquaculture enterprises raising fish to marketable size, but there has been an emerging interest in building facilities within the reservoirs of the Small Aral basin, and small aquaculture enterprises are emerging gradually (personal message – head of Aralsk administration, Erbol Talekenov). In 2020, the local public association “Kazaly Oasis” created an incubation workshop and a pond farm for growing commercial fish fry to be introduced into the open sea in the village of Akshatau in the Aralsk district (Living Asia 2020). This initiative included education and training of the local fishermen, which is essential for establishing a sustainable and commercially viable stock.

Unfortunately, the fisheries in the Small Aral Sea as well as any aquaculture using its water face the problem of pollution. The Syr Darya water contains high levels of agricultural runoff including pesticides, fertilizers, industrial waste and other contaminants. In the southern Kyzyl-Orda region, warnings have been issued that crops grown on local water resources are not safe for human consumption (Iyas 2015). So far, no detailed studies of the precise nature and amount of pollution in fish from the Small Aral Sea are available. However, the need for such studies and constant monitoring is urgent if the growing commercial fisheries in the Sea are to continue in a safe way.

There is great promise for commercial aquaculture in the Small Aral Sea, as it presents a perfect opportunity to establish systems based on best practices in sustainability from all over the world. The most modern and eco-friendly production methods, e.g., closed tank or land based re-circulating systems are prohibitively expensive for the Small Aral Sea producers. Thus, the more traditional methods of near shore open top net pens or on shore pond systems are the most likely to be chosen. However, care must be taken to find the fish species best suited for the brackish waters, with most commercially produced fish being either purely fresh water or marine species. The seasonal formation of ice on the Small Aral Sea would increase costs and reduce net pen production, but probably also offer an easy way of ensuring a lower parasite load. Another very important and complicating issue is the current discussion of building a dam splitting the Small Aral Sea into two basins. If built, the part directly receiving the Syr Darya river water would rapidly decrease in salinity, making it better suited for purely freshwater aquaculture, but then also freeze over more rapidly (Plotnikov et al. 2023). Even if on shore pond culture is occurring along the lower Syr Darya, the problems with containing the nutrient rich wastewater (sometimes also containing residual chemicals) are serious and costly to remedy, rendering this type of production a poor choice for the future. All in all, the local and regional authorities all need to take their responsibility seriously and set up regulations and control / monitoring systems to help and guide the producers in order to keep the production safe and environmentally friendly.

Parasites and other threats to Aral Sea aquaculture

Open pen cage aquaculture exposes the fish to the full parasite fauna of the water body. The high fish density in the cages increases infection and transfection rates significantly.

In pond culture the main threats to fish health are fish-specific (ecto)parasites and bacterial and viral infections, as these spread extremely quickly. Fish specific parasites include monogeneans *Gyrodactilus* and *Dactylogyrus* spp. and flagellates like *Ichthyobodo necator*. All of these parasites cause severe damage to gills and/or skin and increase mortality dramatically.

There is a number of ectoparasitic crustaceans causing problematic damage to cultivated fish, including copepods such as *Ergasilus sieboldi* Nordmann, *Sinergasilus major* (Markevich), *Lernaea cyprinacea* L., *Caligus lacustris* Steenstrup et Lütken, as well as the branchiuran *Argulus foliaceus* (L.). Their feeding on the fish skin leaves severe skin lesions open to secondary infections and often affect the gills severely. In the case of *A. foliaceus*, the females deposit up to 200 eggs on underwater leaves or smooth surfaces in the ponds, making it extremely difficult to manage without introducing chemical control measures.

Another major risk is indirect infections from feed copepods (see below) carrying procercoids of tapeworms such as *Ligula intestinalis*, causing Ligulinosis, or *Bothriocephalus acheilognathi Yamaguti, 1934 (syn. B. opsariichthydis* Yamaguti*, B. gowkongensis* Yeh) causing bothryocephalosis. Both parasites severely damage the intestines and gonads of the fish. In extreme cases, this type of infection can cause complete population collapses in aquaculture (Sohn et al. 2016; Gabagambi and Skorping 2018). Finally, the threat to any commercial aquaculture from bacterial and viral infections such as *Pseudomonas* and SCV (Spring carp viremia) should not be underestimated, but a thorough treatment of this falls outside the scope of this paper (Ahne et al. 2002; Senthamarai et al. 2023)

Fish for aquaculture and their parasites

The fish species of primary interest for aquaculture in the Small Aral Sea are grass carp, carp and bream.

Grass carp (*Ctenopharyngodon idella*). In several areas of the world, this species is the most common in aquaculture, outnumbering other species. It was previously acclimatized in the Syr Darya River, but is an unlikely candidate for fish farming in the open Aral Sea, due to a low salinity tolerance of the fry, although juveniles are more resistant (Kirillov 2008). It is obviously better suited for pond aquaculture in the freshwater floodplain lakes of the affluent Syr Darya River, although no such plants exist yet.

The tapeworm parasite *Bothriocephalus acheilognathi* has already been introduced to Kazakhstan with imported fish, and has since survived in the reservoirs of the Syr Darya River basin. Bothriocephalosis is one of the more dangerous and widespread fish diseases also afflicting grass carp. The fish are infected by eating copepods acting as intermediate hosts, carrying the procercoids of the helminth. In older fish the invasion is asymptomatic, but in fry and yearlings acute bothriocephalosis causes severe damage to the intestines and gonads. With the transition of fish to benthos feeding, the infection rate decreases sharply (Khorosheltseva 2022). In high density grass carp stocks in aquaculture, this parasite can cause an epidemic with a high risk of spreading to the natural fish populations, *e.g.*, in the Syr Darya River and the Small Aral Sea.
The ”Hook worm” *Lernaea cyprinacea* (Lernaeida, Copepoda) parasitizes all cyprinids and can cause significant damage to the skin of the infected fish. Typically found on the gills, they can be very numerous and cause hemorrhaging and severely reduced respiratory and osmoregulatory

functions. Several other parasites also threaten grass carp aquaculture, such as *Ichthyobodo necator*, and the gill fluke, *Dactylogyrus* sp.

Bream (*Abramis brama*) is usually bred in polyculture with carp. Young Bream fry mainly feed on benthos and are cultured in shallow reservoirs or lakes. Currently, the tapeworm *Khawia sinensis* has been found in bream in the Small Aral Sea (Abdybekova et al. 2022). Like other tapeworms, this parasite is known to cause severe damage (e.g., hemorrhagic enteritis and gonad damage here termed khaviosis). In the Azov-Black Sea basin, the parasite has reached epidemic levels in a few cases, and very high parasite loads have been observed (Khorosheltseva 2022). *K. sinensis* has also been found on cyprinids (Oros et al. 2009), and by considering the situation in the Azov-Black Sea basin, it must be assumed to be a significant threat to aquaculture in the Smal Aral Sea also.

The Copepod *Ergasilus sieboldi* is known to attack Bream also, although typically not in very high intensity. However, they can cause a significant decrease in the fish fitness causing slower growth and higher susceptibility to diseases or other parasites (Dezfuli et al. 2003). Carp louse, *Argulus foliaceus*, can also cause damage to both cyprinids and bream. It causes damage to the skin, which can weaken the immune system and lead to secondary infections.

In marine aquaculture some of the most commonly used live foods for fry are brine shrimp (*Artemia* spp.) or rotifers (*Brachyonus* spp.), which incur no parasitological risk. But as both are of non-marine origin, their nutrient value is not optimal for marine fish. This has led to a recent increase in popularity of using cultured copepods as food in marine systems, with promising results. Also, new investigations into adapting the systems for freshwater aquaculture have shown interesting results (Hansen 2017; Hansen et al. 2022). Modern systems based on copepods are very environmentally friendly, e.g., producing much less residual nutrients in their runoff, which would be ideal for the future of aquaculture in the Small Aral Sea. Obviously any such live food used in aquaculture plants must be assuredly free of parasites that can be transmitted to the fish.

Parasite management for the Small Aral Sea

Developing and applying a robust strategy for prevention and establishing good management practices is the cornerstone in all parasite management.

The basic way to prevent parasites is the classic five steps (based on FAO guidelines):

1. Ensure good water quality
2. Keep the pond ecosystem in balance
3. Keep the fish in good condition
4. Prevent parasites and diseases from entering by strict monitoring and relevant measures

   a. In case of infection / disease, prevent the spreading of the parasites to the whole plant
   b. Prevent parasites / diseases spreading to the environment / local ecosystem
5. Set up a monitoring system for fish health assessment and an action plan for parasite invasions

Steps one to three are dependent on the local management of the plant, but to enable steps four and five, a constant and consistent monitoring scheme of the prevalent fish parasite fauna must be implemented. Based on experience from other major aquaculture sites, local and regional authorities must develop regulations on the relevant sampling level and sampling methods. But regular large-scale sampling with visual identification of the parasites is time consuming and expensive, and therefore modern methods such as eDNA analysis/identification could be interesting to implement. Already in the planning and building of aquaculture plants, steps 4a and b must be considered. If regular restocking of the plants is planned, the danger of introducing non-native parasites is high, causing potential damage and fatal epizootics. Screening of the fish and adequate quarantine measures before introduction in farms need to be in place. A prerequisite to this is of course ample knowledge of possible parasites and diseases in the home range of introduced fish, so potential risk species are known.

The monitoring system must follow the local and regional regulations and include some or all of the following measures:

Parasite quantification

Where possible and applicable, standards must be set and enforced for the permissible number of parasites per fish, using a standardized sampling method. Inspiration and knowledge could be gleaned from Norwegian salmon farms, where the caligid copepod *Lepeophtheirus salmonis* is a serious threat to production and very detailed management and monitoring regimes have been enforced successfully for many years (Larsen 2025; Johnsen 2021).
Outbreak action plans. Taking inspiration from aquaculture systems all over the world, a specific set of action plans need to be in place in the event of an outbreak of disease or parasitic invasion. These must include all measures and actions to be taken by the management of the affected plant as well as the roles and actions taken by the local authorities. Such plans must also consider which types of chemical therapeutics and drugs are allowed and set up specific limits for their use. Finally, the specific criteria for defining the end of an outbreak are also highly important, as the principle of minimal use of drugs and chemical agents must be applied strictly.

For a proper management strategy of aquaculture to succeed in the Small Aral Sea system it is crucial that regulations and oversight plans are clearly understood, agreed to and followed by both aquaculture farm operators and local fishermen. It is critical to raise the awareness of the consequences for themselves and the entire ecosystem if the regulations are not adhered to. Educating the local population on proper and sustainable management, including fish parasites, can be facilitated by meetings that include all respective stakeholders, including parasitologists, local and regional government officials, fishermen and managers and staff from the aquaculture farms. In such meetings a consensus on adherence to an efficient, effective and ecologically sound parasite management plan benefitting both fishermen, fish farmers and surrounding aquatic ecosystem can be reached. The relevant stakeholders also need to be trained in the scientific and technical side of parasite management, e.g., by using relevant literature and receive training in identification methods and plant management skills. Such training should use manuals in the local language, designed in text and figures so as to be easily applicable for the non-professional. Modern smart phone applications for identifying parasites and report outbreaks would be an obvious avenue to pursue. Initiatives like these are already starting at a small scale, but their current scope is too narrowly focused on production and not embracing the whole system including parasites, sustainability and the danger of pollutants in the fish catch (Living Asia 2020).

Parasite control

Despite all efforts of prevention, parasites still get introduced into plants, typically during restocking. This damages production (as described above) and entails the risk of the parasites spreading into the local ecosystem. Also, some of the tape worm species mentioned above have humans as their final host, which amounts to a considerable health risk to consumers both local and elsewhere (dos Santos and Howgate 2011). Thus, parasitic control measures are unavoidable and often these include chemical therapeutics or even specific drugs (Buchmann 2012). In aquaculture systems management and administration of chemical or medical agents is much more difficult than in terrestrial systems. Whether put into food or administered to directly to the water, the agents will necessarily end up in the general aquatic system. It is therefore critical that agents used are either broken down very quickly by natural processes or are assuredly not harmful to the environment. Additionally, they must not be dangerous when the fish are used for consumption, and specific limits for residuals need to be enforced, again learning from the example set by Norway, where monitoring of residuals is very strict (Bernhard et al. 2023). For the Small Aral Sea, it is of high importance to avoid chemicals leaking out in large amounts, whether associated directly with antiparasitic treatments or from elsewhere. The sea itself is now of such a small size that the cumulative effects to the surrounding ecosystem are almost certainly negative.

Giving a complete overview of all the various control methods in aquaculture falls outside the scope of this paper, but an excellent review can be found in Buchmann (2022). When it comes to the Small Aral Sea system, setting up a strict regime for use of chemical agents and veterinary drugs in aquaculture is of the greatest importance, due to the fragile ecosystem. Moreover, some of the known parasites e.g., monogeans like *Dactylogyrus* can be treated with specific chemicals (or salt baths), but flagellates such as *Ichthyobodo necator* are almost impossible to control once they manifest themselves. This again underlines the need for a solid system of preventive measures to be put in place.

Recent research has shown it possible to identify candidate target proteins by combining genomics, transcriptomics and proteomics (so-called OMICS Strategies) to successfully control parasites in aquaculture (Natnan et al. 2021; Marnis and Syahputra 2025). Also, as finfish possess a "true" adaptive immune system, they can be successfully vaccinated, and this has been a major subject of research for many years. Ultimately, such efforts may eventually lead to effective fish parasite vaccinations, bringing aquaculture on par with terrestrial animal farming (Buchmann and Secombes 2022; Mondal and Thomas 2022; Du et al. 2022).

Summary Suggestions for parasite management

- National, regional and local authorities must set up a solid set of science-based regulations and principles for sustainable aquaculture in the Small Aral Sea system.
- Aquaculture plants must be built with a strict focus on the FAO guidelines on:
  Water quality, pond/plant ecosystem health, fish health, parasite prevention, precise and regular control measures for fish health, environmental impact, residual chemicals etc., specific action plans for disease outbreaks and/or parasitic infections
- Education and training of the local stakeholders is of primary importance. It serves to increase their involvement in, and understanding of local ecosystems and is a prerequisite for long-term sustainable aquaculture in the region. The development of easily available instructions and manuals for local staff is also a key point, along with continuing training and evaluation of methods and measures.
- In summary, well-trained, highly skilled and dedicated local stakeholders working within a solid, evidence-based framework of regulations and management principles will enable the Small Aral Sea system to develop a thriving and sustainable aquaculture

The Amu Daria system

Although the southern Large Aral Sea has now vanished, there is intensive fisheries along the Amu Daria river, but this to a high degree involves introduced species (Plotnikov et al. 2023). Being completely freshwater and not including a terminal sea, the Amu Daria system should in principle be easier to manage than the Small Aral system, but generally the same monitoring and preventive measures should apply. In the Amu Daria river and its delta system, a 2019-2023 survey has documented a significant decline in fish parasitofauna, primarily due to anthropogenic effects such as water pollution and declining water levels due to irrigation (*e.g.*, Barthrem et al. 2024). While this may proximally benefit the fish fauna it bodes ill for the general health of the ecosystem (Kurbanova 2024). Politically, the Small Aral Sea system and the Amu Daria system are now separated. Therefore, just as for the Aral Sea system in general, it is vital also for parasite management that close international cooperation is established and that this benefits from the best possible expertise from countries that have long term experience in managing the parasitological and also general ecological issues involved in aquaculture.

CONCLUSIONS

The original, pristine and in many ways still unique Aral Sea that is still in a recovery mode with respect to its northern part. Among the central Asian countries concerned, many ecological management measures have been implemented, although not always in an ideal form, mainly due to lack of regional planning both within and across national borders (Bao et al. 2024). Stronger international cooperation is therefore urgently needed (*e.g.*, Allaberganov 2024; Quizi 2024). Fortunately, much of the original invertebrate and teleost fauna has survived in the northern part; fisheries is again an important trade, much valued by the local populations, while aquaculture is still at a very incipient stage. The present study emphasized that parasites are natural parts of ecosystems and, therefore, must be taken into serious consideration when attempting to manage aquatic systems. We have reviewed the many, often complex interactions between fish and their parasites during the Aral Sea regression crisis and its partial recovery and offered some “a posteriori” explanations for the events. The hope is that future models may be able to predict such changes before they occur, thus assisting ecosystem management (Poulin 2007). Because disturbance of the parasite fauna can change an ecosystem, they must therefore be monitored and protected in the same manner as with other organisms. This includes caution in accidentally transporting parasites to new habitats, with possible detrimental effect on either the natural fauna or aquaculture. For sustainable environmental management of this unique habitat, including its fisheries and emerging aquaculture the situation is still open for development and implementation of sound rules and management in cooperation with the local population, as outlined here.

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Supplementary materials

Appendix 1. Changes to specific parasite taxa during the regression crisis. (download)